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Beyond Traditional Healthcare: The Expanding Role of eHealth and Telemedicine in the Digital Era

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Abstract: Over recent decades, healthcare has undergone transformation through digitalization, and systematic data exchange. These developments have contributed to the emergence of Healthcare 4.0 and have changed the organization, delivery, and monitoring of healthcare services. Modern healthcare systems increasingly rely on interconnected technologies that link patient-based and hospital-based components into broader digital ecosystems, supporting communication, structured data sharing, and more continuous healthcare delivery. Wearable and sensor-based technologies have expanded home-based patient monitoring by enabling the collection and transmission of health-related data outside traditional clinical settings. This data may be shared with healthcare professionals and incorporated into the electronic health record (EHR), a one of the key components of modern eHealth infrastructure. However, clinical usefulness depends on effective integration, interoperability, and interpretation within healthcare information systems. Telemedicine platforms enable remote communication between healthcare professionals and patients and may provide access to selected clinical data in real time. This concept can support individualized counselling, continuity of care, and adherence to therapeutic recommendations. Nevertheless, telemedicine should not be understood as an isolated service, but as part of a broader digital healthcare ecosystem. Artificial intelligence (AI) has further expanded the potential applications of telemedicine across medical specialties and may contribute to improved healthcare efficiency. This article provides an overview of current eHealth systems and telemedicine, with attention to their integration into digital health infrastructure and future perspectives in the transition from Healthcare 4.0 toward Healthcare 5.0.

Keywords: HEALTHCARE, TELEMEDICINE, EHEALTH, DIGITALIZATION

1 Introduction

Telemedicine and electronic healthcare (eHealth) represent major components of modern healthcare systems, primarily through the implementation of information technologies. While eHealth broadly refers to the use of digital tools and IT infrastructure in healthcare delivery, telemedicine specifically involves the provision of medical care at a distance through electronic communication between healthcare professionals and patients. The primary aim of telemedicine is to reduce the need for direct physical contact, while enabling the transmission of clinical information regardless of geographical distance. Furthermore, by overcoming spatial barriers, telemedicine may improve access to healthcare services and support more efficient communication within modern healthcare systems. [1]

This concept of healthcare encompasses a broader spectrum of digital solutions aimed at monitoring patients, managing healthcare processes, and optimizing the provision of medical care. It includes the integration of electronic health records (EHR), the use of mobile health technologies (mHealth), sensor-based systems, artificial intelligence (AI), and the Internet of Things (IoT). When applied in the medical field, it is commonly referred to as the Internet of Medical Things (IoMT). While these technologies differ in their specific functions, they collectively contribute to the digital transformation of healthcare. Furthermore, their implementation enables more effective coordination of medical processes and may contribute to an improvement in the overall quality of healthcare delivery. [2-3] The significance of telemedicine and eHealth increased dramatically during the COVID-19 pandemic, which accelerated the implementation of these systems as essential tools for maintaining continuity of medical care under conditions of limited physical contact. Telemedicine systems use a broad spectrum of information technologies, ranging from short-range wireless communication technologies, such as Bluetooth and Wi-Fi, to mobile network technologies, including 3G, 4G, and 5G. As a result, these systems enable both real-time communication and asynchronous data transmission, also supporting continuous patient monitoring. [4] Current eHealth structures consist of complex information systems and infrastructure, including data storage solutions, interoperable platforms, and control systems implemented at the level of healthcare organizations as well as within national healthcare systems. The implementation of these systems is associated with improved availability of healthcare services, increased efficiency, and potential cost reduction. Despite these benefits, eHealth also introduces several significant challenges, including problems related to interoperability, cybersecurity, data protection, and unequal levels of technological readiness among different countries. [1, 5]

In the context of future healthcare system development, telemedicine may currently be considered an application layer within the broader eHealth ecosystem. This ecosystem is progressively moving towards fully integrated digital solutions. However, one of the key future challenges remains the transition from multiple fragmented platforms to interoperable systems that enable continuous data flow across different levels of healthcare delivery. Furthermore, another important trend is the gradual shift from conventional medicine towards personalized medicine, supported by large-scale data analysis and the application of AI systems. These systems may enable not only a reactive approach to disease treatment, but also a predictive model of healthcare focused on early risk identification and prevention. Nevertheless, the implementation of these technologies will require careful attention to cybersecurity risks, ethical considerations, and regulatory limitations. Ultimately, these factors are likely to determine both the scope and the pace of integration of modern digital technologies into clinical practice. [1,3]

2 Healthcare 4.0, way from 1.0. to 4.0, role of eHealth

Over recent decades, substantial progress has been observed in information and communication technologies (ICT). This progress has involved not only advances in processing technologies and hospital equipment, but also the development of electronic devices, data sharing, and data collection. Although eHealth has recently been enhanced by several technologies associated with the concept of Industry 4.0, it remains a relatively established concept rather than an entirely new phenomenon. Among the most important technologies currently integrated into eHealth are Big Data, the IoMT, sensor-based systems, AI, and other digital solutions. While earlier interpretations of eHealth were primarily focused on enabling healthcare users to access and use information related to health conditions, the contemporary concept is considerably broader. It also includes the organization and support of prognostic, diagnostic, research, auxiliary, and other medical services and procedures. Thus, modern eHealth may contribute to the provision of comprehensive services for both healthcare users and healthcare professionals. Figure 1 shows the evolution of healthcare across the past decades. [7]

One of the key features of this system is the provision of easy access to patient data across healthcare institutions, with a very low probability that relevant clinical information will be unavailable when required. Consequently, this concept may substantially

improve the efficiency of healthcare delivery, reduce costs, and support earlier, more accurate, and safer medical interventions. [8] However, despite the presence of many benefits, this concept also has several limitations and shortcomings. One of the major challenges is the need to integrate all relevant data into existing healthcare information systems. Based on previous experience, successful implementation requires that several essential conditions be fulfilled. These include the development of a comprehensive framework involving several key steps, such as electrification, system integration, medical hardware innovation, and the development of modern electronic devices. Furthermore, these devices form part of a complex infrastructure that can be used to monitor patients' health status and educate healthcare users. Nevertheless, for such systems to function effectively, all collected data must be systematically processed, securely stored, and managed within large databases. [9]

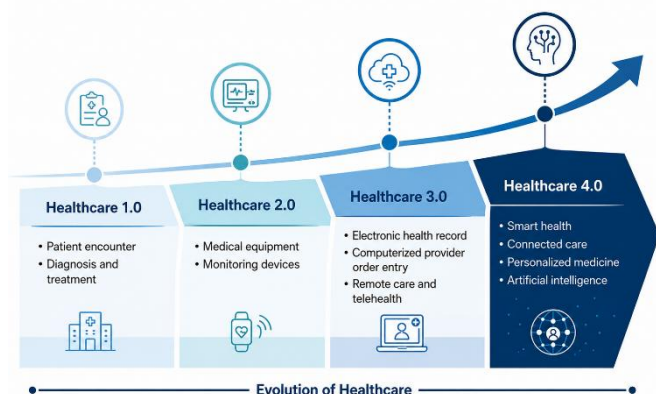


Fig. 1 Revolution of Health Care from Health Care 1.0 to Health Care 4. [7]

A major milestone in the development of eHealth was the widespread adoption of smartphones. These devices integrate various specialized sensors that can be used to monitor health-related parameters. Furthermore, smartphones can be connected to a range of medical and wearable devices through dedicated applications that are easily accessible and downloadable. Such devices include smartwatches, heart rate monitors, continuous glucose monitors (CGMs), insulin pumps, and many others. [10] Thus, smartphones have become an important interface between patients, medical devices, and digital healthcare systems. Internet connectivity plays a significant role in the sharing and transmission of healthcare data. It enables not only the exchange of patients' clinical information, but also the remote sharing and support of entire medical procedures and interventions. Furthermore, this concept has important applications in modern surgical practice, particularly within the framework of Surgery 4.0. Thus, internet-based connectivity represents an essential component of digitally supported healthcare and advanced medical procedures. [11] Together with the development of Industry 4.0, robotics has also found important applications in healthcare. Modern robotic systems, such as the da Vinci Surgical System and others, are increasingly used in routine clinical practice. Furthermore, various expert systems supported by artificial intelligence AI may contribute to more effective decision-making by providing clinically relevant outputs that can be considered by healthcare professionals. The importance of a well-functioning eHealth system becomes particularly evident in situations where there is an insufficient number of medical staff to adequately respond to patient needs. In this context, digital healthcare solutions may improve daily healthcare operations by making them more efficient, less time-consuming, and better adapted to increasing demands on healthcare services. [1]

Within the field of eHealth, a new concept referred to as the eHealth Architecture Model (e-HAM) is currently being discussed. e-HAM describes various component categories that together form a functional digital healthcare system. The main component categories include Foundation ICT Infrastructure, which comprises servers,

software technologies, common standards, and procedures managed by IT professionals. Another important component is the Foundation eHealth Infostructure, which includes data warehousing, consent and access control, management of data exchange, and the integration of electronic records and registers. Furthermore, the Health Process Domain Components are focused on managing patients' access to healthcare services when medical care is required. These components support the continuum of care, including clinical assessment of health problems, diagnostic evaluation, treatment, patient education, and other related aspects of medical care. Finally, the component of Governance and National Ownership encompasses organizational and governance structures, including funding mechanisms as part of a national healthcare program. Thus, the main objective of e-HAM is to maximize the efficiency, productivity, and cost-effectiveness of the healthcare system. [1, 12]

2.1 eHealth Infrastructure

With the development of ICT, there has been a growing trend towards connecting technologies within networks, giving rise to IoT. In the context of healthcare and medicine, this development represents an important challenge, particularly in relation to establishing fast, secure, and reliable communication between devices that collect health-related information and databases that store these data. Thus, the effective functioning of eHealth infrastructure depends not only on the availability of connected devices, but also on the quality, security, and interoperability of the systems that manage data transmission and storage. [13] Several of the most frequently discussed advantages of these systems include effective monitoring of users' health status and the possibility of real-time patient observation. With the successful interconnection of multiple medical devices, a new concept known as the IoMT has emerged. IoMT refers to a connected network of active medical devices that monitor the health status of users or patients. Furthermore, these devices can continuously collect and transmit clinically relevant information to healthcare professionals in real time. Thus, IoMT may support earlier clinical assessment, improve patient monitoring, and contribute to more efficient healthcare delivery. [14] The effectiveness of this system has been demonstrated in several studies. However, despite its potential benefits, the system also has important limitations. These include the requirement for a constant power supply, the need for a large number of microchips, and the need for a certain degree of autonomous functioning. Furthermore, cybersecurity remains a significant concern, as connected medical devices and data-sharing platforms may be vulnerable to unauthorized access or misuse. Therefore, these technical and security-related limitations must be carefully addressed before broader implementation in clinical practice. [13, 15-17]

2.2 e-Health Composition and Infostructure

An effective electronic healthcare system consists of multiple medical devices connected within a common network and linked to a central database. In such a system, it is essential that data related to the health status of the medical device user can be accessed from the database at any time by an authorized operator. In this context, the term operator refers mainly to healthcare practitioners and therapists. Furthermore, the system not only provides medical staff with information about the patient's health condition, but more advanced systems may also support clinical decision-making related to diagnosis and subsequent treatment. This type of advanced digital tool is referred to as a Clinical Decision Support System (CDSS). With the use of mobile technologies for communication between healthcare practitioners and patients, the concept of mHealth has been established. Within this framework, smartphones may collect data from various medical devices and transmit them through databases directly to healthcare professionals. Thus, mHealth represents an important step towards fully functional telemedicine, as it enables remote data collection, communication, and patient monitoring. [18]. Today's use of AI helps healthcare workers collect and analyze the data in a quicker way, helping them also considerably facilitate the diagnosis and helps them make a faster decision. [19] In

recent years, more than 20 interconnected eHealth systems have been implemented across several European countries, including Germany, Denmark, Poland, Italy, and others. These systems have been successfully linked to healthcare organizations and are currently used to support medical staff in patient monitoring, clinical decision-making, and treatment management. However, their practical benefits, several challenges remain. The most important limitations include the financial costs associated with implementation and the need to provide adequate technological training for healthcare professionals. [20]

2.3 eHealth Components

Currently, smartphones represent one of the key standard tools for data collection within eHealth systems. They can be connected to various medical devices capable of detecting and monitoring multiple physiological parameters and health-related indicators in patients. Furthermore, smartphones serve as an important interface between patients, medical devices, and healthcare information systems, thereby supporting continuous data collection and remote patient monitoring. [21] Nowadays patients use many wearable devices such as smart watches, or smart rings to monitor heart rate, physical activity, sleep patterns, or more specialized devices such as CGMs. [22] Home-based medical devices, such as blood pressure monitors, glucometers, spirometers, and thermometers, can also be connected to smartphones and used for telemonitoring. Furthermore, in daily hospital-based clinical practice, one of the most widely used digital solutions is the Clinical Information System (CIS), which collects data from bedside medical devices. Thus, both home-based and hospital-based devices contribute to continuous data acquisition and support the integration of patient information within eHealth systems. [23] Patient's (bedside used) monitoring systems like, EKG, heart rate, blood oxygen, blood pressure meters are lately most common devices currently linked to CISs. [24] The field of clinical biochemistry involves the collection and management of various biochemical, hematological, and microbiological patient data through specialized Laboratory Information Systems (LIS). These systems are usually connected separately to CIS, as well as to the broader eHealth infrastructure. Thus, LIS represents an important component of digital healthcare systems, as they enable structured laboratory data processing, integration, and availability for clinical decision-making. [25] In the field of radiology, radiographic images are collected, stored, and managed through Picture Archiving and Communication Systems (PACS). These systems allow imaging data to be viewed not only within different departments of the same hospital, but also at other medical workplaces for consultation purposes. Thus, PACS support more efficient image sharing, interdisciplinary cooperation, and diagnostic decision-making.

Furthermore, an important category of medical devices is represented by implantable medical devices, such as cardiac pacemakers, implantable cardioverter-defibrillators (ICDs), and implantable sensors used for various clinical purposes. These devices enable continuous monitoring of selected vital functions and may provide clinically relevant data over extended periods. In addition, Patient-Reported Data Systems are increasingly discussed as part of modern eHealth infrastructure. These systems allow patients to report subjective information, including symptoms, perceived health status, and quality of life. While these data cannot replace objective clinical assessments, they may support earlier diagnostic evaluation and long-term monitoring, particularly in patients receiving chronic medication or long-term care. [26-27]

2.4 Governance and Electronic Health Records (EHRs)

Many countries are currently developing national eHealth systems and establishing regulatory frameworks to support their implementation and operation. Within these national systems, EHRs play a key role. An EHR can be defined as a digital system used for the collection, storage, and processing of medical records over time

and across different levels of healthcare. Furthermore, EHRs contain data recorded by various healthcare professionals working in different clinical settings, including primary, secondary, and tertiary healthcare. Thus, they enable the integration of patient information from multiple medical workplaces and may support continuity of care, clinical decision-making, and more efficient healthcare management. [28] EHRs represent a crucial component of an effective healthcare information system. With a functional EHR system, healthcare practitioners can establish a coordinated network for sharing clinical knowledge and relevant patient information. Furthermore, such systems may contribute to the standardization and improvement of eHealth practices across national healthcare institutions. Thus, EHRs support better continuity of care, interdisciplinary cooperation, and more efficient healthcare management. [29]

3 Telemedicine and Its Role in the eHealth System

Telemedicine provides medical care through ICT, regardless of the geographical distance between the patient and the healthcare professional. It includes various forms of electronic communication that enable the transmission of medical information, support diagnostic processes, and facilitate remote consultation. In a broader sense, telemedicine represents a method of delivering medical services and sharing professional knowledge without the need for direct in-person contact. Furthermore, by using modern communication technologies, it may improve the accessibility of healthcare services, increase the effectiveness of care delivery, and reduce the time required for selected healthcare processes. [27] A functional telemedicine system may be described as a complex structure composed of several interrelated components. These typically include a user interface device, such as a smartphone, which enables access to the telemedicine system; a communication device, which establishes the communication link; and a communication channel, which serves as the pathway for data transmission. Furthermore, the system may incorporate a video conferencing device to support real-time interaction between patients and healthcare professionals. In addition, a control unit is required to ensure secure data transfer, while a protocol defines the rules governing information exchange. A backplane or similar integrating component connects the individual parts of the system and enables their coordinated operation. The system may also include a virtual medical device, designed to simulate selected functions of physical devices, as well as a medical device used for examination and diagnostic assessment. Finally, EHR and data storage form an essential part of the system, as they ensure the collection, storage, and availability of patients' medical history. Thus, telemedicine functions as an integrated digital environment that supports remote healthcare delivery through coordinated technological components. [30]

3.1 Components of Telemedicine Systems

Telemedicine systems consist of a wide range of interconnected components. In general, these components may be divided into patient-based elements, monitoring devices, and transmission technologies. Patient-based components primarily include devices used for collecting health-related data, while transmission technologies enable the transfer of these data between patients, healthcare professionals, and healthcare information systems. Furthermore, transmission technologies can be classified according to their communication range. Short-range communication technologies are commonly used for local data transfer between medical devices and user interface devices, such as smartphones or tablets. The most frequently used short-range technologies include Bluetooth and Wi-Fi. On the other hand, long-range communication technologies enable data transmission over greater distances and support remote patient monitoring and consultation. These include mobile and internet-based technologies such as 3G, 4G, 5G, LoRaWAN, and GSM. Thus, both short-range and long-range communication technologies are essential for the effective functioning of telemedicine systems. [31]

3.2 Patient-Based Components

Patient-based systems, including biosensors and wireless technologies, together form a Wireless Body Area Network (WBAN). A patient's WBAN consists of small biosensing devices that can collect, transmit, and, in some cases, temporarily store health-related data. In general, these biosensing devices may be divided into two main groups: devices that collect data directly from the patient's body and devices that collect data from the patient's surrounding environment. In the field of internal medicine, commonly used biosensors include pulse oximeters, which measure peripheral oxygen saturation and are useful for monitoring patients with respiratory or cardiac failure. Other frequently used devices include blood pressure monitors, heart rate monitors, body temperature sensors, and electrocardiography (ECG) devices, which record the electrical activity of the patient's heart. Furthermore, in the field of neurology, several biosensing technologies are used to monitor specific physiological signals. These include electromyography (EMG), which records the electrical activity of muscle cells, electroencephalography (EEG), which monitors brain activity, photoplethysmography, and electrooculography (EOG), which records eye movements. In addition, biosensors are also used in other medical specialties. In dermatology, they may be applied for the assessment of galvanic skin response, while in diabetology, CGMs are widely used for real-time glucose monitoring. Special dietary sensors may also be used to estimate or monitor patients' caloric intake. Environmental sensors represent another important component of patient-based monitoring systems. The most used examples include motion sensors, external thermometers, humidity sensors, weight sensors, and gyroscopes. Moreover, more specialized environmental and diagnostic sensors, such as laser-engraved graphene-based immunosensors, have been investigated for the use of saliva in diagnosis and early disease detection. Finally, the data collected by these devices may be transmitted to healthcare information systems and stored in the patient's EHR. Thus, patient-based components of telemedicine systems support continuous monitoring, remote assessment, and more comprehensive integration of patient-related data into digital healthcare infrastructure. [32]

Several biosensor systems, together with short-range communication technologies, form a Local Area Network (LAN) designed to connect networked devices located near the biosensing systems. After data collection and integration, the acquired information is transmitted through long-range communication systems to the Care Seeker Unit and the Care Giver Unit. The previously mentioned long-range communication technologies enable data transmission to the Care Giver Unit, which refers directly

to the healthcare practitioner or medical team. However, the size and nature of the transmitted information may influence the speed and reliability of data transfer. Furthermore, these factors can affect the time elapsed between data detection, transmission, and clinical availability. Thus, effective telemedicine systems require reliable communication infrastructure to ensure timely access to clinically relevant information. [27] The unit through which a medical professional connects remotely is commonly referred to as the Medical Professional Unit. Through this unit, physicians can retrieve data from the database or from the patient's EHR, where information is transferred from the local WBAN through the relevant communication units. However, full access to patient data should be granted only after appropriate authentication. Once authorized access is established, the physician can provide telemedicine services, including teleconsultation with the patient, as well as consultation with other specialists who may also be granted access to the relevant clinical information. Finally, all of these components may function together as parts of a single integrated ecosystem (Fig. 2). Ultimately, one of the major benefits for patients is the possibility of accessing a multidisciplinary team of healthcare specialists in a substantially shorter time than was traditionally required, without the need for physical presence or hospitalization.

3.3 Telemedicine Classification

Telemedicine may be classified according to its mode of operation into asynchronous telemedicine, also known as store-and-forward telemedicine, synchronous telemedicine, also referred to as real-time telemedicine, and remote monitoring.

3.3.1 Asynchronous Telemedicine

In asynchronous telemedicine, clinical data are transmitted to medical experts or other specialists for offline assessment, usually based on a specific request. Although this model is based on delayed evaluation rather than immediate interaction, it still includes online storage and access to medical records. Nevertheless, the main limitation of asynchronous telemedicine is the absence of real-time consultation between the patient and physician, or between physicians themselves. This may increase the risk of misdiagnosis or incorrect interpretation of data. Furthermore, this model requires broader distribution and accessibility of EHR data among specialists, which may increase cybersecurity risks and create additional challenges related to data protection. [33]

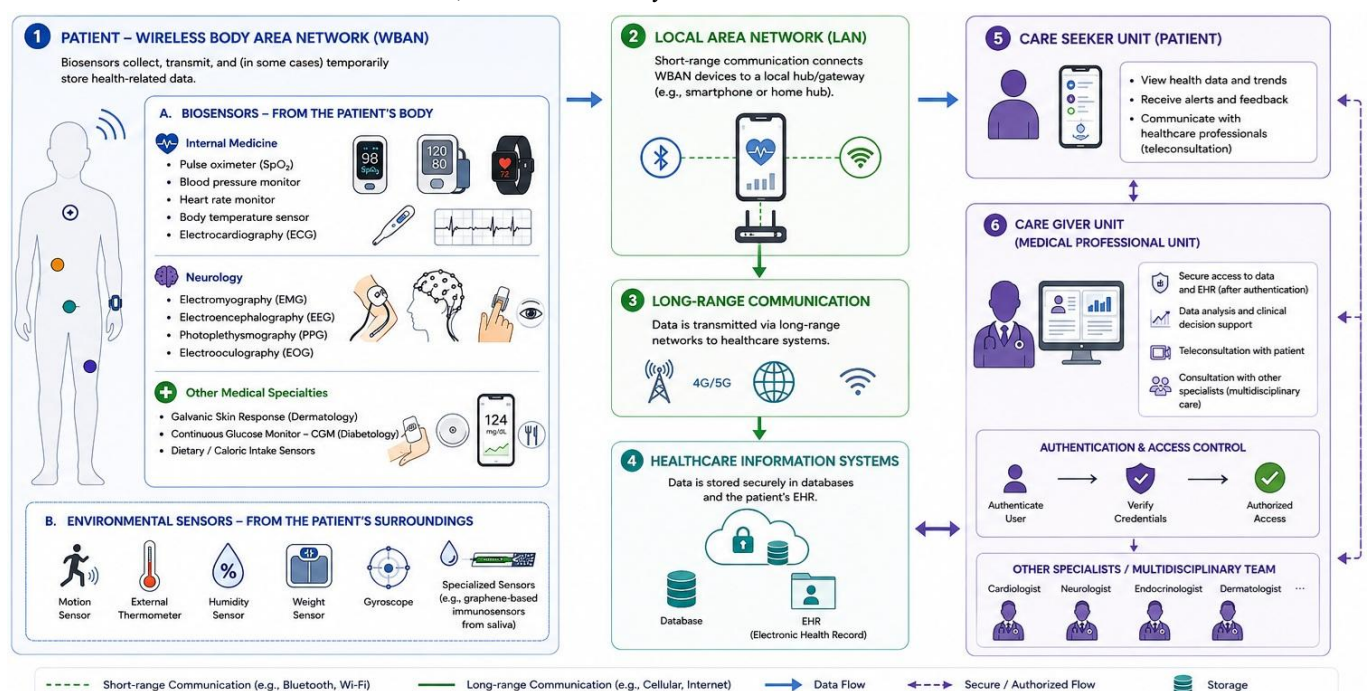


Fig. 2 Operational scheme of patient-based telemedicine systems integrated with the patient's EHR and hospital information systems as a unified ecosystem [27, 32]

3.3.2 Synchronous Telemedicine

Synchronous telemedicine includes various forms of interactive communication between healthcare professionals and patients. The most common examples are telephone calls, online diagnostic communication, and real-time consultations. Furthermore, this mode of telemedicine may also involve the real-time transmission of EHR data. The transmitted information may include not only clinical results and radiographic images, but also physiological parameters reflecting the patient's current clinical status. However, a major limitation of synchronous telemedicine is the requirement for a stable, secure, and reliable communication channel. Therefore, the quality of the network infrastructure plays a critical role in ensuring effective and safe real-time telemedical care. [34]

3.3.3 Remote health monitoring

Remote health monitoring refers to continuous, often real-time, monitoring of a patient's health status. It is widely used in intensive care units (ICUs), where continuous observation of vital parameters is essential. However, its application is not limited to hospital settings, as remote health monitoring is also increasingly used for patients with chronic diseases in their home environment. The spectrum of monitored conditions includes diabetes mellitus (both type 1 and type 2), asthma, chronic obstructive pulmonary disease (COPD), sleep apnea, cardiac arrhythmias, and postoperative states. Furthermore, such systems usually include wearable devices, data transmission technologies, and mobile applications, which together enable continuous data collection and communication between patients and healthcare professionals. While remote health monitoring may significantly reduce hospitalization costs, it can also decrease the stress associated with hospital admission. In addition, it provides physicians with valuable information about how patients manage their usual daily activities and how these activities influence their chronic conditions. Thus, remote health monitoring represents an important component of modern telemedicine and long-term patient care. [33]

3.4 Medical Specialties with the Most Widespread Use of Telemedicine Systems

3.4.1 Radiology

Radiology was one of the first medical specialties to implement telecommunication technologies into routine clinical practice. This approach enables even smaller hospitals, which may not have a sufficient number of radiologists to provide continuous on-site coverage, to maintain radiological services 24/7. Within a functional telemedicine system in radiology, radiology technicians or radiology assistants perform the imaging examination. After the radiographic images are acquired, they are transmitted through a secure communication channel to an on-call radiologist, who may evaluate and report the images remotely, including from home. Furthermore, teleradiology facilitates consultation between departments and enables cooperation with more experienced radiologists in complex or diagnostically challenging cases. By allowing secure image transmission and remote expert interpretation, telemedicine contributes to improved accessibility, continuity, and quality of radiological services. [35]

The characteristics of teleradiology described above represent a typical store-and-forward functionality of asynchronous telemedicine. In this model, radiographic images are acquired, stored, and subsequently transmitted for remote interpretation by a radiologist. Currently, several AI-mediated systems are available for the analysis of radiographic images. However, only a limited number of these systems can directly support or facilitate clinical treatment decisions. For a teleradiology system to function effectively, radiographic images must have adequate resolution and be stored in standardized formats, most commonly DICOM. Less frequently used formats may include JPEG, TIFF, or BMP. After acquisition, these images are usually transmitted to PACS. Furthermore, teleradiology

enables selected radiological procedures, such as X-ray imaging, to be performed in workplaces where a radiologist is not physically present. Nevertheless, the remote interpretation of imaging data requires secure transmission, sufficient image quality, and appropriate integration with hospital information systems. Among modern image-analysis systems, Aidoc, developed in Israel, is designed to rapidly analyze CT or MRI images and may provide potential benefits in the early identification of clinically relevant findings, particularly in emergency situations. Similarly, Qure.ai, developed in India, can analyze X-rays and CT scans and may support clinical decision-making. Yet, AI-supported teleradiology represents a developing field with potential to improve diagnostic workflow, although its implementation remains dependent on technical reliability, clinical validation, and appropriate regulatory oversight. [27, 36]

3.4.2 Dermatology

In the field of dermatology, the main objective is to enable remote assessment and diagnosis of selected dermatological conditions, including skin lesions, nevi, and other cutaneous abnormalities. One of the key technological developments that facilitated the broader use of teledermatology was the availability of high-resolution cameras, which allow clinically relevant images of the skin to be captured and transmitted for specialist evaluation. After image assessment by a qualified dermatologist, the patient may be referred for appropriate treatment or for further diagnostic procedures, such as skin biopsy. Thus, teledermatology is most used as an asynchronous form of telemedicine, based on the store-and-forward transmission of clinical images. Although dermatology is currently one of the medical fields in which telemedicine consultations are well established, in many cases it remains necessary for the patient to undergo an initial evaluation by a general practitioner. This stepwise approach supports the stable role of teledermatology not only as a method of remote consultation, but also as a tool that may accelerate further diagnostic steps and contribute to earlier final diagnosis. While teledermatology represents an important and expanding part of telemedicine, camera-based imaging systems used for skin assessment still require further evaluation, standardization, and certification. [27, 37]

3.4.3 Diabetology and Diabetes Self-Management

In recent years, the use of telemedicine in diabetology and diabetes self-management has become an increasingly important topic, particularly as part of synchronous telemedicine. A major milestone in this medical specialty was the introduction of CGM. This technology is widely used in patients with type 1 diabetes, especially in those treated with insulin pump therapy as part of advanced hybrid closed-loop systems (AHCL), as well as in patients using multiple daily injection therapy (MDI). Furthermore, this modern approach is gradually being integrated into the routine management of type 2 diabetes. Data from CGM and AHCL systems are continuously uploaded to interactive cloud-based platforms, through which physicians can assess glycaemic patterns, adjust insulin therapy, and provide additional recommendations or advice. In addition, these systems may help stratify patients according to their estimated metabolic control, thereby identifying individuals who may require earlier medical intervention. The most advanced cloud-based platforms also include tools for interactive communication between patients and healthcare professionals, as well as real-time glucose data streaming. Several studies have shown that telemedicine represents a promising approach for improving self-management behaviors and reducing fear of hypoglycemia. Moreover, by decreasing the need for frequent in-person visits, this approach may provide a significant cost benefit. According to the recommendations of the American Diabetes Association (ADA), telemedicine may be particularly useful for rural populations. However, several limitations remain. These include potentially higher initial investment costs in developing countries, organizational difficulties, legal issues, loss of connectivity, and cybersecurity risks. Therefore, the successful implementation of telemedicine in diabetology requires reliable

technological infrastructure, appropriate clinical workflows, and adequate protection of patient data. [38, 39]

3.4.4 Ophthalmology

As with artificial intelligence applications, telemedicine has also been implemented in the field of ophthalmology. As described above, modern high-resolution cameras enable the remote monitoring of the progression of chronic ophthalmological conditions over time. This represents a relevant example of synchronous telemedicine, particularly when direct consultation between patients and healthcare professionals is included. Furthermore, AI-evaluated images of retinal diseases, such as diabetic retinopathy and age-related macular degeneration (AMD), can also be assessed remotely. Table 1 shows differences in diabetic retinopathy screening. This may serve as a second-level evaluation after AI-mediated screening, especially in cases where screening identifies positive or suspicious findings. In addition, teleophthalmology may be used for screening other conditions, including retinopathy of prematurity (ROP) in premature infants and glaucoma or uveitis in the adult population. The latest use may be also able in the field of Neuro-ophthalmology [40–41] While its effectiveness depends on appropriate image quality, technical infrastructure, and specialist availability, teleophthalmology can, under optimal conditions, achieve clinical outcomes comparable to those of traditional in-person care. [41]

Table 1: The difference Between Ophthalmoscopy and Teleophthalmology for Diabetic Retinopathy [40]

Ophthalmology	Teleophthalmology
Requires trained ophthalmologist or retina specialist for fundus examination	Requires trained technicians, only the grading requires the trained retina specialist
Dilatation of the pupil is mandatory	Dilatation of the pupil is optional or targeted mydriasis
Less expensive	Higher initial investment for a teleophthalmology setup
Cost to patients is higher	Cost to patients is less
It is less convenient in rural areas as more travel, more time-consuming	It is more convenient and hence requires less travel, less time spent

3.4.5 Cardiology

In the field of cardiology, the recording and interpretation of physiological signals play a crucial role in establishing a diagnosis. Modern telemedicine approaches enable advanced forms of real-time monitoring, allowing diagnostic assessment and treatment optimization without direct physical contact. This is particularly valuable for patients at increased risk of secondary complications related to hospitalization, such as immuno-compromised individuals. The diagnoses with the most extensive application of remote monitoring and telecardiology include cardiac arrhythmias and chronic heart failure. According to the patient's location and the need for medical assistance, telecardiology can be divided into pre-hospital, in-hospital, and post-hospital applications. Pre-hospital telecardiology may be used for the early assessment of acute coronary syndrome and for cardiovascular risk prevention. In-hospital telecardiology includes ECG teletransmission and teleconsultation between healthcare professionals. Finally, post-hospital telecardiology is mainly applied in cardiac rehabilitation, follow-up of patients with chronic heart failure, and remote monitoring or control of implantable cardiac devices. [42–43] Furthermore, telecardiology also enables data collection from implantable cardiac devices, such as pacemakers and implantable cardioverter-defibrillators, thereby supporting more precise device monitoring and adjustment. The most used devices for remote cardiovascular monitoring include blood pressure monitors, thermometers, weight scales, step-counting watches, single-lead ECG devices, 12-lead ECG devices, and pulse oximeters. However,

the use of remote monitoring in patients with myocardial ischemia remains less extensively studied. An essential part of telecardiology is also the use of wearable devices, including small biosensors, smartwatches, smart rings, and other connected technologies. Nevertheless, one important limitation of these devices is that many commercially available wearables lack appropriate certification for routine medical use in remote monitoring. Therefore, their clinical implementation requires careful evaluation of accuracy, reliability, and regulatory status. [43]

3.4.5.1 Pathology

The key principle of telepathology is remote cooperation among specialists from different centers of pathological anatomy. It is particularly useful for consultation of complex cases, assessment of oncological diseases, prognostic evaluation, and support of decision-making in other clinically relevant conditions. Telepathology represents a form of store-and-forward telemedicine, as histopathological images are captured, stored, and subsequently transmitted for specialist evaluation. However, this approach strongly depends on high-resolution imaging to ensure adequate visualization of disease-modified cells and tissue structures. These samples are usually prepared using specific staining methods and then magnified for microscopic assessment. Furthermore, a functional telepathology system must enable rapid and secure transmission of high-quality images between pathology departments, oncology centers, and other specialized medical institutions. Thus, telepathology may support interdisciplinary cooperation, improve access to expert consultation, and contribute to more accurate diagnostic and prognostic evaluation. [44]

3.4.6 Psychiatry

Telemedicine in the field of psychiatry may improve access to medical care for patients with chronic mental disorders, particularly in regions with a shortage of psychiatric specialists. Synchronous telemedicine enables experienced psychiatrists to monitor patients' clinical status and provide online consultations or therapeutic sessions. This approach may support both diagnostic evaluation and long-term therapeutic follow-up. Furthermore, psychiatry is a medical specialty in which complex physical examination is often less central than in many other fields. Therefore, selected psychiatric assessments and interventions may be suitable for remote delivery. In certain psychiatric diagnoses, remotely mediated care may serve not only as supportive follow-up, but also as a direct therapeutic intervention, depending on the nature of the disorder and the patient's clinical condition. Moreover, evidence supporting the use of telepsychiatry is particularly strong in the treatment of post-traumatic stress disorder (PTSD), depression, and attention-deficit/hyperactivity disorder (ADHD). However, a stable and secure internet connection during telephone or videoconferencing sessions is required. [45]

3.4.7 Obstetrics and Gynecology

Telehealthcare technologies in the field of obstetrics and gynecology enable rapid exchange of clinical data and EHR between peripheral hospitals, local outpatient clinics, and highly specialized perinatology centers. This approach may support timely decision-making regarding treatment plans in high-risk pregnancies, while reducing the need for frequent in-person examinations of pregnant women in specialized centers. Consequently, women with high-risk pregnancies may avoid repeated long-distance travel, which can improve comfort and accessibility of care. The most commonly shared clinical data in this field include ultrasound findings and fetal heart rate recordings. However, one of the main limitations is the large volume of transmitted data. Nevertheless, its widespread application in routine clinical practice remains relatively limited. [46]

3.4.8 Telerehabilitation

Across many healthcare specialties, there remains a shortage of specialized physiotherapists with experience in specific clinical conditions, such as post-traumatic states, postoperative

recovery, and stroke rehabilitation. In this context, videoconferencing enables healthcare providers to deliver highly specialized rehabilitation care remotely. One example is remote physical therapy. Apart from increased session frequency and improved time efficiency, one of the greatest advantages of telerehabilitation is that the therapist can monitor the patient performing exercises in real time and assess the progress of rehabilitation. Furthermore, telehealthcare applications in this field may also be considered a form of follow-up telemedicine, as the course of treatment can be continuously monitored and supplemented by data obtained from the patient's WBAN. [47-48] Thus, telerehabilitation may improve patient cooperation and adherence to treatment. However, the major disadvantage is the lack of direct physical contact, particularly when the patient performs exercises incorrectly and requires immediate manual correction. In general, telerehabilitation techniques appear to have a relatively safe profile as an alternative to in-person rehabilitation, with adverse effects reported only rarely. [48]

4 Future Impact and Development of Telemedicine: A Pathway Towards Healthcare 5.0

The further implementation of AI into telemedicine represents an important topic in the future development of healthcare systems and is one of the key attributes of the emerging concept of Healthcare 5.0. AI may play a significant role in enhancing the quality, efficiency, and accessibility of medical and clinical services. However, the specific form of its application may differ according to the type of telemedicine used. In synchronous telemedicine, AI may support models such as virtual triage, where chatbots can help prioritize patients according to their reported symptoms. [49] Furthermore, AI can be used for real-time image analysis or as a virtual assistant capable of reviewing patients' electronic health records and providing clinically relevant suggestions. In asynchronous telemedicine, AI may be particularly useful in medical image analysis, including the routine assessment of radiographic images such as CT, MRI, and other imaging modalities. In addition, natural language processing (NLP) can be applied to clinical texts and electronic health records with the aim of summarizing large volumes of data and supporting clinical decision-making. [50] Clinical Decision Support System (CDSS) may also offer personalized treatment recommendations or predict clinical trends, thereby contributing to the improvement of healthcare quality. Moreover, in remote health monitoring, AI enables continuous, accurate, and intelligent supervision through sensors and wearable devices. Its key applications include continuous analysis of physiological data, such as heart rate, blood pressure, oxygen saturation, and interstitial glucose levels. Figure 3 illustrates the structure of a CDSS and its role in supporting clinical decision-making. However, despite the ability of such systems to process data and provide recommendations, the final clinical decision remains the responsibility of the physician. [36]

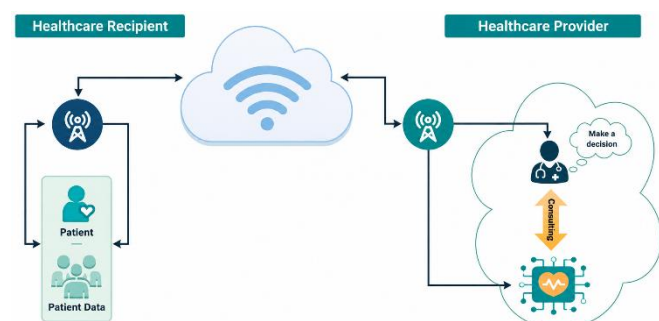


Fig. 3 CDSS using AI and its role in supporting clinical decision-making [36]

Furthermore, AI may support the prediction of disease exacerbation by analyzing temporal data trends and identifying risk signals in chronic diseases such as diabetes, chronic obstructive pulmonary disease, and heart failure. It may also contribute to

medication management, including dosage optimization and the evaluation of potential drug interactions. [50-51] Among modern innovations, the TytoCare system, developed through cooperation between technological companies from the United States and Israel, may support faster clinical evaluation by analyzing patients' clinical data, vital signs, and selected diagnostic information. Nevertheless, the broader implementation of AI-supported telemedicine will require careful validation, appropriate regulation, cybersecurity protection, and integration into existing clinical workflows. [52] Finally, the future evolution of technology towards Healthcare 5.0, corresponding to the fifth industrial revolution, is enabled by the key technological enablers of Healthcare 4.0, with the addition of a stronger patient-centered dimension. The central principle of this concept is a paradigmatic shift from generally applied medical approaches for specific diagnoses towards more personalized and precise healthcare. Currently, many studies focus mainly on potential future system architectures. However, several tested systems and projects already illustrate the practical direction of this development. One example is Babylon Health, a system that integrates artificial intelligence and chatbot-based communication to analyze patients' medical history, symptoms, and clinical signs, while referring the patient to a physician for final decision-making. Furthermore, another example is the integration of Dexcom CGM with the Livongo system, which collects glucose data, analyses historical trends, and may help predict future glucose patterns. Similarly, the concept of a modern tele-intensive care unit, also referred to as TeleICU or eICU, has been developed in the United States. This system enables the remote monitoring of patients' vital signs and clinical data, while continuous AI-mediated analysis may help predict and evaluate dangerous changes in the patient's clinical condition. Thus, such systems may enable a more rapid response to changes in patient status and may contribute to improved outcomes in critically ill patients. Nevertheless, to ensure high-quality care, several general limitations must still be addressed, including system interoperability, data security, and the ability to support early and improved diagnosis. [53]

5 Conclusion

The evolution of Healthcare 4.0 has introduced a modern approach to the delivery of healthcare services. Over recent decades, an increasing number of advanced technologies have been implemented in everyday hospital practice. These innovations have supported the broader use of information technologies in patient monitoring, including mHealth, sensor-based systems, the IoT, the IoMT, and, more recently, the wider application of AI. A modern eHealth system, based on the extensive use of information and communication technologies ICT, integrates data from the patient's environment through internet connectivity and cloud-based systems. Currently, the most used wearable devices include CGMs, smartwatches, smart rings, and other connected technologies. Furthermore, additional medical devices, such as glucometers, spirometers, CGMs, and pulse oximeters, may be connected to the user's smartphone and incorporated into remote monitoring systems. In hospital settings, remote monitoring devices, including point-of-care vital signs monitors, are commonly connected to local CIS, while laboratory devices are integrated into LIS. Thus, both patient-based and hospital-based technologies contribute to the continuous collection, transmission, and integration of clinically relevant data. However, the rapid expansion of AI use in telemedicine has also introduced several challenges and questions for the future. Medical data protection remains one of the key issues that must be addressed to prevent misuse, including identity theft and privacy violations. To reduce these risks, system developers must incorporate appropriate international standards and regulatory frameworks, such as the General Data Protection Regulation (GDPR), to ensure the highest possible level of data security. Nevertheless, even with the integration of modern security mechanisms, adequate education of users and healthcare professionals remains necessary. Another important issue is the potential bias of AI algorithms, particularly when systems are trained on unequal or insufficiently representative datasets. Such bias may contribute to inequalities in diagnosis and treatment, especially

across different patient populations. Therefore, the development of reliable and clinically applicable AI-supported telemedicine systems requires careful validation, transparent training processes, and continuous monitoring of performance. To create a well-functioning telemedicine ecosystem, it is necessary to integrate individual components into a unified system connected with the patient's EHR, allowing relevant data to be accessed when needed. In addition, up-to-date legal frameworks for the routine use of these systems are essential. Finally, the partial inability of AI-based systems to fully comprehend complex clinical contexts, together with the risk of unforeseen errors, remains an important topic for future development. While these limitations must be carefully addressed, advanced technologies such as federated learning may contribute to the development of more accurate, generalizable, and privacy-preserving telemedicine systems.

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The influence of environmental regulations on corporate innovation processes in slovakia

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Abstract: The paper examines the relationship between environmental regulations and innovation processes in Slovak enterprises. The theoretical part is based on concepts of environmental policy, its instruments, environmental management and eco-innovation. The paper assumes that environmental regulations may function not only as constraints but also as stimuli for technological, process, product and ecological innovations. The empirical part is based on a questionnaire survey conducted among 121 enterprises operating in Slovakia. The results indicate that environmental regulations and environmental protection requirements influence business innovation processes, but they are not the only or dominant motive for innovation. Firms innovate more often due to social responsibility, economic efficiency, general legislative requirements and cost reduction. At the same time, the main barriers to innovation are high costs, complicated legislation and insufficient state support. The paper highlights the need for a more comprehensible regulatory framework, wider use of environmental management systems and stronger support for eco-innovation.

Keywords: environmental regulations, innovation, eco-innovation, enterprises, environmental policy, Slovakia

1. Introduction

Growing pressure to protect the environment is changing the operating conditions of enterprises across Europe. Environmental regulations affect emissions, waste management, energy efficiency, resource use and the transparency of business processes. For enterprises, they therefore represent not only a legal framework, but increasingly also a factor influencing technological, process and product innovations.

The literature usually offers two basic perspectives. The first emphasizes rising costs and administrative burdens, while the second, linked to the Porter hypothesis, assumes that appropriately designed regulation can stimulate innovation, improve efficiency and support business competitiveness in the long term [1], [9], [10].

The aim of the paper is to examine how enterprises in Slovakia perceive environmental regulations and whether these requirements motivate them to innovate. The added value of the paper lies in linking the theoretical background with the results of an original questionnaire survey conducted among enterprises of different sizes, ages and ownership structures.

2. Literature Review

Environmental policy is a set of instruments aimed at protecting the environment and achieving the goals of sustainable development. Its normative basis consists of laws, directives and strategies, its economic dimension mainly includes taxes, fees and subsidies, and its voluntary dimension includes education, awareness-raising activities and environmental management [4], [7], [13].

In the European context, Agenda 2030, the European Green Deal and the national strategy Greener Slovakia play a decisive role. These frameworks emphasize emission reduction, higher recycling rates, support for renewable energy sources, green public procurement and pressure for sustainable consumption and production [2], [4], [5], [7].

At the enterprise level, this framework is complemented by the concepts of eco-efficiency and environmental management. Eco-efficiency highlights the creation of higher economic value with a lower environmental impact [11], while EMAS and ISO 14001 enable enterprises to systematically monitor environmental aspects and plan improvements [8], [12].

3. Methodology

The empirical part is based on a questionnaire survey conducted via e-mail among enterprises from various sectors classified according to SK-NACE Rev. 2. Approximately 1500 e-mails were sent, and 121 valid responses were included in the analysis. The response rate was about 8 %. The survey examined the impact of regulations on innovation, the relationship between firm size and

innovation intensity, the importance of ownership structure and the influence of firm age on environmentally motivated innovation.

Table 1. Characteristics of the research sample

Indicator	Value
Number of respondents	121
E-mails sent (estimate)	1500
Response rate	approx. 8%
Largest sector	Construction (>15 %)
Largest region	Bratislava region 31.4 %
Firms founded 2000-2024	52.89 %
Medium-sized firms	32 %
Large firms	17 %

Source: authors' own processing based on the questionnaire survey (2024)

The findings were interpreted through frequency-based and comparative evaluation of responses. The results were compared according to firm size, age, ownership and other characteristics. The intention was to verify whether regulations function more as a modernization stimulus or as an obstacle to the innovation process.

4. Results and Discussion

The results confirmed that environmental regulations and environmental protection requirements have a real impact on enterprise innovation processes. At the same time, however, firms innovate more often in order to reduce environmental burden and improve overall efficiency than merely to comply formally with regulation.

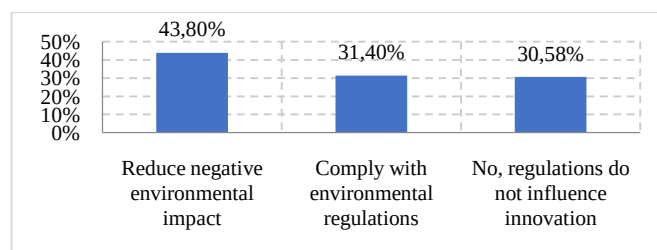


Fig. 1. Impact of environmental regulations and environmental protection on enterprise innovation

As shown in Fig. 1, 43.80 % of respondents stated that their enterprise innovates in order to reduce its negative environmental impact, 31.40 % innovate to comply with environmental regulations, and 30.58 % stated that they do not innovate because of environmental regulations. In practice, environmental protection is therefore a slightly stronger motive than regulation itself.

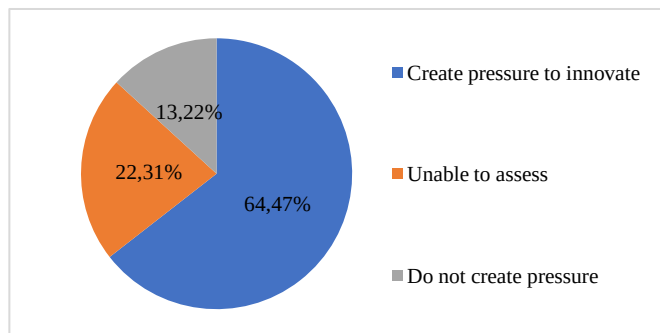


Fig. 2. Perceived pressure of environmental regulations on innovation

The perception of regulation as a pressure to innovate is strong: 64.46 % of respondents agreed that regulations create pressure for innovation, 22.31 % could not take a clear position and only 13.22 % did not perceive such pressure. This supports the conclusion that regulation is an important impulse, but not always the only motive for innovation [1], [9].

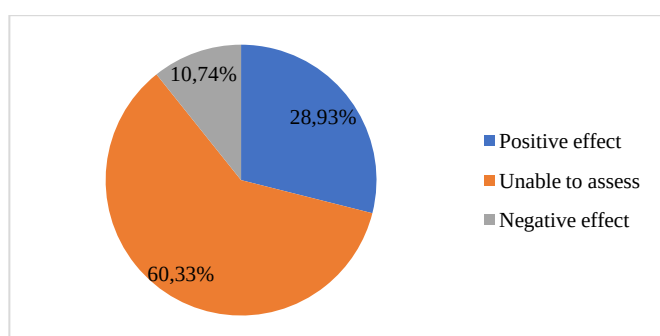


Fig. 3. Impact of regulations on the ability of enterprises to innovate

Approximately 28.93 % of respondents attributed a positive influence to regulations on their ability to innovate, while 10.74 % reported a negative influence. The largest group, however, could not clearly assess this effect. Regulations are therefore perceived ambivalently: at the same time as pressure and as a potential modernization tool.

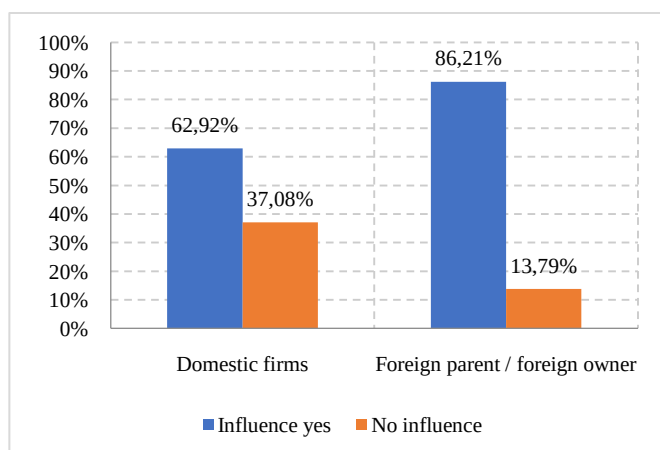


Fig. 4. Impact of environmental regulations by ownership structure

Among Slovak-owned enterprises, 62.92 % reported that regulations and environmental requirements influence innovation, while among enterprises with foreign ownership or a foreign parent company the share reached 86.21 %. This confirms the assumption that international business groups are more sensitive to reputation, ESG standards and formal management systems [8], [9].

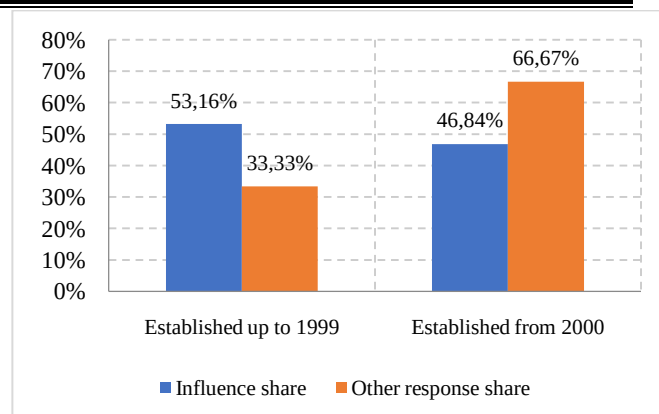


Fig. 5. Impact of environmental regulations by firm age

The assumption that younger firms would be more environmentally oriented was not confirmed. Older firms reacted more strongly: among enterprises established up to 1999, 53.16 % reported the influence of regulations, while among firms founded from 2000 onwards the share was 46.84 %. A likely explanation is the need to modernize older technologies.

Table 2. Selected drivers and barriers of innovation

Indicator	%
Legislation and current environmental standards	63.64
Social responsibility	56.20
Cost reduction	48.76
Environmental regulations and standards	47.93
High innovation costs	70.25
Insufficient state support	57.02
Complicated legislation	52.89

Source: authors' own processing based on the questionnaire survey (2024)

Table 2 summarizes the most important drivers and barriers. The key motives for innovation were legal and normative requirements (63.64 %), followed by social responsibility (56.20 %), cost reduction (48.76 %) and environmental regulations and standards (47.93 %). The most significant barriers were high innovation costs (70.25 %), insufficient state support (57.02 %) and complicated legislation (52.89 %).

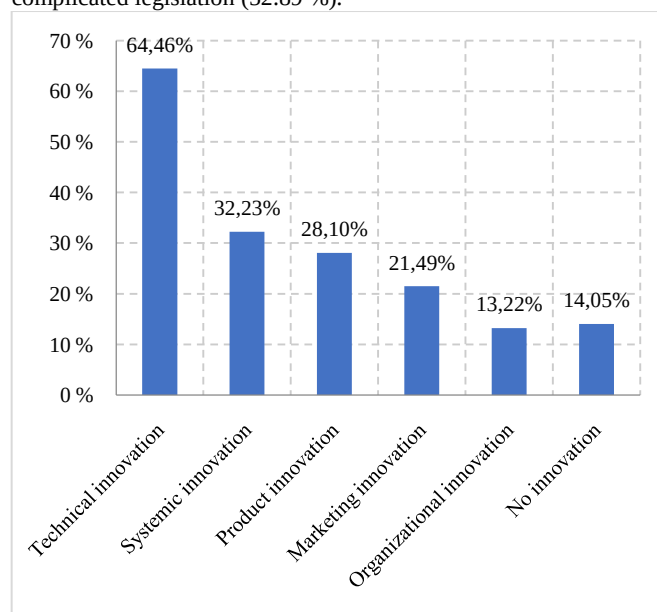


Fig. 6. Types of innovation implemented by enterprises in Slovakia

Technical innovations dominated (64.46 %), followed by systemic innovations (32.23 %), product innovations (28.10 %) and marketing innovations (21.49 %). About 40 % of respondents also declared the development of eco-innovations, which suggests that environmental requirements are most often translated into technical modernization and more efficient operations.

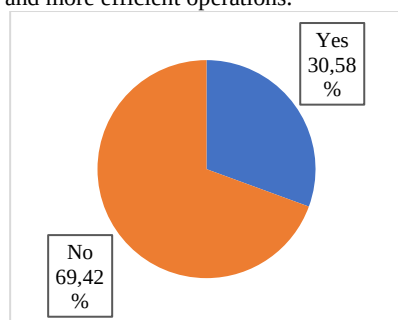


Fig. 7. Use of environmental management systems to monitor environmental regulations

Only 30.58 % of enterprises stated that they use EMAS or a similar system to monitor environmental regulations, while 69.42 % do not use such tools. Firms therefore often lack a systematic mechanism for identifying shortcomings and planning environmental improvements, which reduces their ability to respond to changes in the regulatory environment [8], [12].

A significant share of respondents also does not perceive environmental innovation as a direct competitive advantage in its sector. This may explain why enterprises often pursue compliance indirectly - through cost reduction, better image or technology modernization - rather than through the explicit goal of 'being greener'. From a practical perspective, it is therefore important to simplify orientation in legislation, better connect regulation with financial incentives and expand the use of environmental audits.

The findings also confirm that legislative and economic factors overlap in enterprise decision-making. Firms do not separate environmental requirements from questions of cost, reputation and operational efficiency. The main problem is that regulatory pressure is not always accompanied by sufficient information, financial incentives or methodological support for implementation.

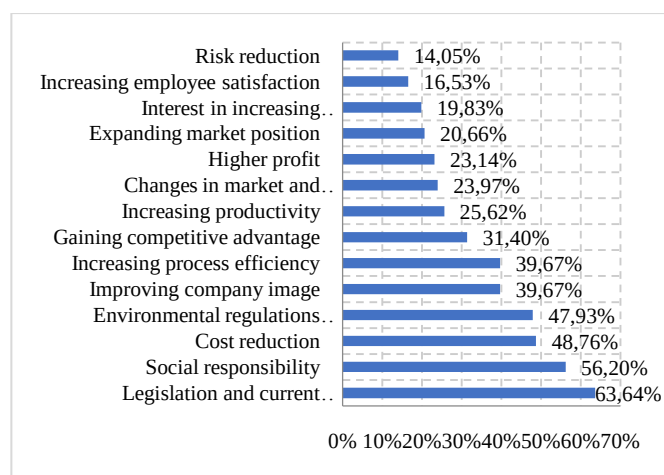


Fig. 8. Reasons for introducing innovations in Slovak enterprises

A more detailed view of the structure of motives shows that, in addition to regulation itself, broader strategic goals also play an important role. The highest share was recorded for legislation and current environmental standards, while strong motives also included social responsibility, cost reduction and improvement of the corporate image. This suggests that environmental innovation in business practice is often closely linked to both marketing and economic considerations.

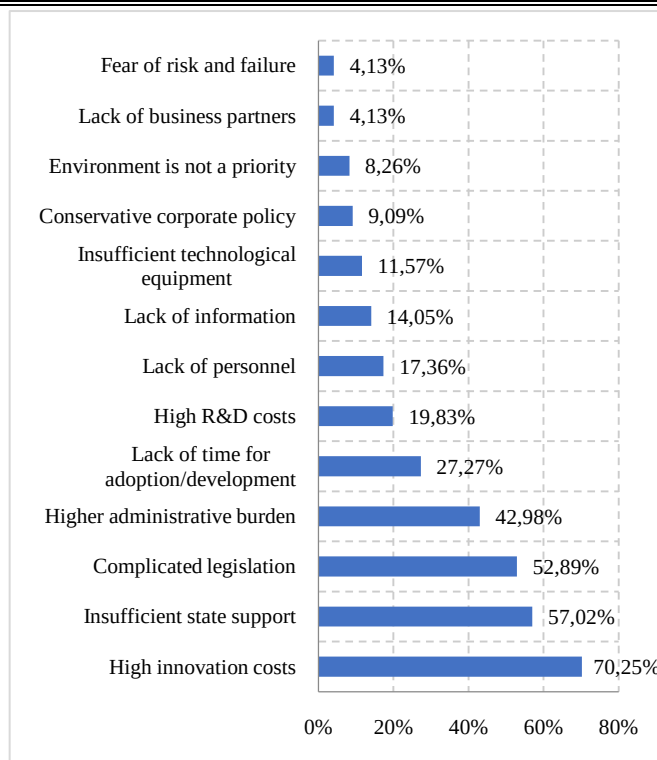


Fig. 9. Barriers to innovation implementation in Slovak enterprises

Figure 9 shows that the implementation of innovation in Slovak enterprises is constrained mainly by high costs, insufficient state support and complicated legislation. These findings confirm that enterprises do not perceive innovation only as a strategic opportunity, but also as a financially and administratively demanding process. This helps explain why environmental regulations are often accepted only when they are linked to clear economic benefits.

4.1 Discussion of findings

Several recommendations for practice follow from these findings. Enterprises should connect innovation decisions with environmental goals already at the investment-planning stage, so that new technologies or process changes bring not only economic savings, but also better environmental performance. The state and supporting institutions should simplify orientation in legislation and strengthen the availability of advisory and financial instruments. If regulatory requirements are linked to clearly communicated business benefits, environmental regulation can become not only an obligation, but also an important modernization impulse.

The low use of environmental management systems should also be considered an important practical problem. If an enterprise does not work with EMAS, ISO 14001 or at least an internal environmental audit, it often cannot systematically identify where the greatest environmental risks arise and where innovation has the highest effect. Instead of planned improvement, it then reacts only to a specific problem or to external pressure. This weakens the firm's ability to perceive regulation as a long-term strategic framework and supports rather short-term, partial solutions.

An equally important finding concerns firm age. Older enterprises showed a stronger innovation response to environmental requirements, probably because they more often face the need to replace outdated equipment, optimize energy intensity and reduce the environmental burden of historically established processes. Younger firms may already have some of these measures built into their operations from the start, and therefore do not perceive them as a separate innovation impulse. This difference shows that when evaluating the relationship between regulation and innovation, it is necessary to consider the individual characteristics of the enterprise and not only its size or turnover.

Particularly interesting is the finding of higher environmentally motivated innovation activity among enterprises with foreign

ownership. This may be interpreted as a consequence of a broader managerial framework in which environmental requirements are linked to ESG reporting, brand reputation and centrally defined internal standards. Slovak enterprises are not necessarily less sensitive to environmental issues, but they often lack a formalized management system that would transfer environmental topics into everyday decision-making and investment planning.

4.2 Implications for practice and policy-making

From the perspective of managerial practice, it is important that enterprises do not separate environmental objectives from investment and innovation decision-making. A practical step is the introduction of at least a basic environmental audit, regular monitoring of energy, material and waste consumption, and linking these indicators with the evaluation of the return on innovation investments. In this way, environmental requirements become a measurable management parameter rather than only a formal obligation.

The results also suggest that environmental policy should not focus only on the repressive or control component. It is equally important to create an environment in which enterprises can identify the concrete benefits of innovation for their operations. This may include advisory support, better availability of information, clearer sector-specific guidelines or more targeted financial instruments for small and medium-sized enterprises. These firms often lack the capacity both to track changing regulatory requirements and to finance technical or process changes on a sufficient scale.

From the viewpoint of public policy, these findings are important because they confirm the difference between the formal adoption of regulation and the real innovation response of the enterprise. A firm may perceive regulatory pressure, but it will invest in innovation only when it can link that investment with economic returns, better image or market expectations. Otherwise, regulation may remain only an administrative obligation without generating a stronger modernization effect. This helps explain why high costs and weak state support emerged as such significant barriers in the survey.

5. Conclusion

The results confirm that environmental regulations are a significant factor in enterprise innovation processes, although their effect is not straightforward. Enterprises in Slovakia innovate more often in order to reduce environmental burden, improve efficiency and meet broader legislative expectations than exclusively because of the formal fulfilment of environmental regulations.

From an applied perspective, simplifying firms' orientation in environmental legislation, wider use of EMAS and similar management systems, and stronger support for partnerships, research and the financing of eco-innovation appear to be particularly important. An environment designed in this way can transform environmental requirements from a perceived burden into a stimulus for modernization and long-term competitiveness.

5.1 Research limitations and future research

It is important to mention the limits of the research carried out. The questionnaire survey was based on the voluntary participation of respondents, which may have influenced the final structure of the sample. Enterprises already interested in environmental issues or with a more positive attitude towards innovation may have been more willing to participate. At the same time, it was not possible to cover all sectors of the economy evenly, and the interpretation of the results should therefore be understood as a picture of the behaviour of an important part of Slovak enterprises rather than as a fully representative picture of the whole business sector.

Another limitation is the nature of the data itself. The answers were based on the subjective assessment of managers or enterprise representatives and therefore may not always capture the real degree of regulatory compliance or the actual scope of innovation. Nevertheless, the survey brought an important insight: enterprises perceive environmental requirements as part of their decision-making framework, but their transformation into specific innovation activity depends on economic possibilities, managerial approach

and on whether the enterprise is able to recognize a strategic opportunity in regulation [9], [10].

For further research, it would therefore be appropriate to complement the quantitative approach with qualitative interviews with managers from different sectors. Such an approach would make it possible to explore in more detail which types of regulation enterprises consider developmental and which they perceive as an administrative obstacle. It would also be useful to examine differences between sectors with a high environmental burden and sectors in which environmental requirements enter business more indirectly, for example through supply chains, public procurement or customer expectations.

A useful follow-up step would also be to assess the real benefits of environmental innovation over a longer period. Future research could focus on whether enterprises, after implementing ecological or technological measures, achieve not only better compliance with regulation, but also measurable cost savings, higher energy efficiency, better reputation and a more stable market position. Such an approach would make it possible to demonstrate more precisely that environmental regulation does not have to be perceived only as an obligation, but can become an impulse for long-term modernization if it is properly designed and supported by suitable public policy instruments.

Acknowledgment

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Trends and risks of industrial innovation development in the republic of belarus

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Abstract: *The study analyzes the impact of growing global economic instability on the innovation activity of Belarusian industry. Despite external pressures, the share of enterprises implementing innovations increased from 20.4% in 2016 to 36% in 2024, with especially rapid growth in the Brest region. However, innovation expenditures remain highly volatile, sharply declining in 2022 and recovering only by 2024, particularly in import- dependent regions. Significant regional disparities persist in innovation performance: the Vitebsk region exceeds 30% of innovative products, while the Grodno region remains at 7%. Innovation services remain low nationwide but show rapid growth in individual regions. The findings indicate that innovation development in Belarus is progressing yet remains vulnerable to currency, logistics, technological, and sanctions-related risks, underscoring the need for integrated risk management models tailored to regional conditions.*

KEYWORDS: INNOVATION, TECHNOLOGICAL RENEWAL, EXTERNAL SHOCKS, DIGITAL TRANSFORMATION, ECONOMETRIC ASSESSMENT, SANCTIONS VULNERABILITY, TECHNOLOGICAL DEPENDENCE

1. Introduction

The innovation- driven development of the industrial sector of the Republic of Belarus in recent years has been shaped by a multifaceted configuration of external and internal determinants. Intensifying global economic instability, escalating trade frictions, shifts in the geopolitical architecture, and the broadening of sanction regimes generate additional challenges for a small open economy, constraining access to advanced technologies, investment resources, and established markets. These dynamics heighten the vulnerability of the industrial sector and necessitate a conceptual reassessment of the mechanisms ensuring its resilience and capacity for sustained innovative growth.

Statistical evidence indicates that, despite external constraints, innovation activity in Belarusian industry has exhibited a generally positive trajectory: the share of enterprises implementing innovations is increasing, the innovation base is expanding, and the volume of innovation- related services is growing in several regions. However, this upward trend is accompanied by pronounced volatility of innovation expenditures, substantial regional disparities, and heightened sensitivity to currency, logistical, and technological risks. Taken together, these factors shape a complex environment in which innovation- driven development becomes both an essential prerequisite for industrial growth and a structurally vulnerable component of it.

Contemporary research underscores that sanction pressure and institutional constraints substantially reshape innovation processes in Belarus. In the works of E. V. Presnyakova [1], sanctions are conceptualized as a form of economic coercion that restricts trade, financial operations, and investment flows, thereby amplifying risks for both innovation and investment activity. The author demonstrates that the state's policy response involves reallocating resources within innovation funds, adjusting tax mechanisms, and adapting the institutional environment, collectively generating new conditions for innovation- driven development.

A substantial contribution to understanding the influence of political and sanction- related factors on innovation ecosystems is provided by the research of A. Khamiankova and T. Marynich [2]. Their studies document the largest peacetime exodus of technological entrepreneurs from Belarus, the dismantling of the local innovation infrastructure, and the high sensitivity of startups to sanction- induced constraints: 64 % of companies report negative effects of sanctions. At the same time, the authors emphasize the pronounced adaptability and “portability” of innovation ecosystems: following relocation, Belarusian startups attracted three times more investment, demonstrating the resilience of human capital and network- based resources. The research further shows that broad economic sanctions may unintentionally hinder the development of sustainable technologies and innovations by amplifying institutional risks.

In a broader context of industrial development, the study by V. Karpovich [3] demonstrates that Belarusian industry between 2015 and 2024 evolved under the influence of successive external

shocks, including the pandemic, sanctions, and persistent structural constraints. The author notes that the sector exhibited substantial resilience, driven by the restructuring of production and logistics chains, an increase in investment activity, and the strengthened role of state- owned holdings. Nevertheless, systemic limitations remain and continue to exert a direct impact on innovation- driven development: high material intensity, declining profitability, shortages of skilled labour, and dependence on imported equipment. The study underscores that the slow pace of technological adoption and the limited scope of modernization continue to generate long- term risks for the industrial sector.

Taken together, existing research demonstrates that the innovation- driven development of Belarusian industry unfolds under the combined influence of external economic shocks, institutional constraints, and structural imbalances. Published empirical and analytical studies highlight the need for adaptive risk- management models, modernization of production systems, strengthening of innovation infrastructure, and enhanced resilience to sanction- related and political pressures. However, comprehensive works that integrate analyses of innovation activity, regional disparities, institutional risks, and the effects of external shocks into a unified analytical framework remain limited – which underscores the relevance of the present study.

2. Materials and Methods

The study draws on data from Belstat, sectoral reports, and analytical materials produced by international organizations (World Bank, OECD, UNECE, UNCTAD, EBRD) for the period 2015-2024. The empirical base includes indicators of innovation activity, innovation expenditures, the structure of industrial production, and regional disparities.

The methodological approach combines descriptive statistics, structural and comparative analysis, as well as trend evaluation of key indicators of innovation development. To identify regional heterogeneity, methods of interregional comparison were applied.

The qualitative analysis was conducted within the framework of the institutional approach, which made it possible to assess the influence of sanctions, regulatory changes, and the role of state- owned holdings on innovation processes. The research sequence included: examining the dynamics of innovation activity; evaluating regional disparities; identifying external and internal risks; determining institutional constraints; and formulating proposals to enhance the resilience of innovation- driven development.

3. Results

The results of the study indicate that the innovation- driven development of the industrial sector of the Republic of Belarus in 2016-2024 unfolded under conditions of unprecedented external pressure, institutional turbulence, and structural constraints, which collectively shaped a new trajectory of technological dynamics [4].

The key external factor was the sanctions imposed by the EU and the United States, which, after 2020, acquired a systemic character and affected virtually all channels of technological renewal—from equipment imports and access to financing to logistics, export operations, and international cooperation. EU sanctions included restrictions on the export and import of high-technology goods, dual-use equipment, petroleum products, and potash fertilizers, as well as flight bans, financial restrictions, and asset freezes [5]. US sanctions intensified the pressure by adding enterprises to SDN lists, prohibiting transactions with American companies, and imposing limitations on the export of technologies [6]. These measures created an institutional environment in which innovation-driven development became simultaneously a strategic necessity and a source of additional risks.

Despite these highly restrictive external conditions, the innovation activity of industrial enterprises demonstrated steady growth. At the national level, the share of organizations engaged in innovation increased from approximately 20 % in 2016 to 36 % in 2024. This indicates that enterprises sought to compensate for external constraints through internal resources, organizational adjustments, and reorientation toward new markets. Particularly high levels were observed in the Brest region and the city of Minsk, where innovation activity exceeded 50 %. These regions became centers of concentration of human capital, competencies, and investment resources, enabling them to adapt more rapidly to sanction-related restrictions. At the same time, the Gomel and Minsk regions maintained comparatively low values, reflecting the structural heterogeneity of industrial development and disparities in access to resources. Sanctions further intensified this differentiation: regions with more advanced infrastructure and stronger international linkages adapted more quickly, whereas peripheral territories faced constraints that hindered modernization.

Table 1. Innovation activity of industrial organizations, %

Region	2016	2020	2024	Change 2016–2024
Republic of Belarus	20,4	26,2	36	15,6
Brest Region	26,3	31,8	54,3	28
Vitebsk Region	18,7	22,4	33,1	14,4
Gomel Region	15,4	19,8	22,2	6,8
Grodno Region	17,9	23,1	29,4	11,5
Minsk Region	19,1	24	28,7	9,6
Mogilev Region	20,2	25,3	31,5	11,3
City of Minsk	29,8	35,1	50,7	20,9

Investment in innovation also exhibited significant volatility, reflecting enterprises' responses to sanction-related constraints. After a sharp decline in 2021–2022, when total innovation expenditures fell by nearly half, a recovery was observed in 2023–2024, and by 2024 investment reached its highest level for the entire observation period. However, the recovery was uneven: Minsk increased innovation spending more than fourfold, whereas the Vitebsk region lost over 75 % of its investment. This indicates that sanctions affect regions asymmetrically: the capital region, with its more diversified economy and access to alternative financing channels, was able to offset external restrictions, while regions highly dependent on traditional industries proved more vulnerable. These findings are consistent with the conclusions of V. Gurski and V. Archakov [7], who emphasize that sanctions exacerbate regional disparities and pose risks to economic security.

The share of innovative products in the total volume of shipped industrial output also demonstrated a positive trajectory, increasing from 16–17 % to more than 22 % in 2024. Particularly high values were recorded in the Vitebsk and Gomel regions, where the share of innovative products reached 35–37 %. This may indicate a reorientation of enterprises toward higher value-added products, which represents one of the key strategies for adapting to sanction-related constraints. At the same time, the Brest and Grodno regions maintained comparatively low levels, reflecting their limited

innovation potential and continued dependence on traditional industries. These trends corroborate the conclusions of V. Karpovich [3], who argues that Belarusian industry exhibits adaptive resilience; however, this resilience is compensatory in nature and is not accompanied by deep technological transformation.

Table 2. Share of innovative products, %

Region	2016	2024	Change
Republic of Belarus	16.3	22.3	+6.0
Brest Region	2.1	10.6	+8.5
Vitebsk Region	32.9	35.0	+2.1
Gomel Region	25.9	36.8	+10.9
Grodno Region	6.2	7.0	+0.8
Minsk Region	14.0	18.2	+4.2
Mogilev Region	17.1	20.4	+3.3
City of Minsk	22.4	28.7	+6.3

The most problematic area proved to be innovation-related services. Their share in the total volume of services nationwide remained extremely low—below 1% throughout the entire period. The only exceptions were several IT clusters, primarily in the Brest and Vitebsk regions, where the share of innovation services reached 9–11 %. However, after 2020 the Brest region experienced a sharp decline, driven by the relocation of IT companies and the erosion of the local innovation ecosystem.

Table 3. Share of innovative services, %

Region	2019	2024	Change
Republic of Belarus	0.6	0.9	+0.3
Brest Region (IT)	36.1	10.2	–25.9
Vitebsk Region (IT)	0.0	9.6	+9.6
Gomel Region	0.3	0.4	+0.1
Grodno Region	0.2	0.3	+0.1
Minsk Region	0.1	0.2	+0.1
Mogilev Region	0.1	0.1	0
City of Minsk	0.6	0.5	–0.1

These trends fully align with the findings of Khamiankova [8], according to which 64 % of Belarusian technology startups report negative effects of sanctions, while many are forced to conceal their Belarusian origin, change jurisdiction, and restructure their business models. The relocation of technology firms led to a reduction in domestic demand for innovation services and weakened regional innovation centers. Moreover, Khamiankova's [2] study shows that sanctions create additional administrative barriers, including enhanced banking oversight, difficulties in opening accounts, and stricter compliance requirements, making it more challenging to conduct innovation-oriented business in the EU and the United Kingdom than in the United States or Latin America. These findings help explain why innovation services in Belarus failed to recover after 2020: a significant share of the country's innovation potential was compelled to move abroad.

Overall, the results of the study show that Belarusian industry demonstrates a capacity for adaptation; however, this adaptation is predominantly compensatory in nature. The growth of innovation activity and the increasing share of innovative products occur against the backdrop of high material intensity, declining profitability, and dependence on imported equipment. Sanctions have amplified existing structural constraints by limiting access to technologies and financing, which is particularly evident in regions with low innovation potential. At the same time, certain regions and sectors were able to use the sanctions-induced crisis as an incentive to restructure production chains, explore new markets, and increase the technological complexity of their output.

Thus, the results of the study reflect a contradictory dynamic: on the one hand, there is evidence of growing innovation activity and partial adaptation to external constraints; on the other, systemic risks persist, reinforced by sanction-related pressures and institutional limitations. These findings confirm the need to shift

from reactive measures to strategic modernization, the strengthening of regional innovation systems, and the development of mechanisms for technological autonomy. Under conditions of continued sanction pressure, innovation-driven development becomes not only a factor of competitiveness but also a key element of the country's economic security.

4. Discussion

The results of the study show that the innovation-driven development of the industrial sector of the Republic of Belarus in 2016-2024 unfolded under conditions of unprecedented external pressure, institutional turbulence, and structural constraints, which collectively shaped a new trajectory of technological dynamics. The key external factor was the sanctions imposed by the EU and the United States, which, after 2020, acquired a systemic character and affected virtually all channels of technological renewal—from equipment imports and access to financing to logistics, export operations, and international cooperation. EU sanctions included restrictions on the export and import of high-technology goods, dual-use equipment, petroleum products, and potash fertilizers, as well as flight bans, financial restrictions, and asset freezes. US sanctions intensified the pressure by adding enterprises to SDN lists, prohibiting transactions with American companies, and imposing limitations on the export of technologies. These measures created an institutional environment in which innovation-driven development became simultaneously a strategic necessity and a source of additional risks.

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Despite these highly restrictive external conditions, the innovation activity of industrial enterprises demonstrated steady growth. At the national level, the share of organizations engaged in innovation increased from approximately 20 % in 2016 to 36 % in 2024. This indicates that enterprises sought to compensate for external constraints through internal reserves, organizational adjustments, and reorientation toward new markets. Particularly high levels were observed in the Brest region and the city of Minsk, where innovation activity exceeded 50 %. These regions became centers of concentration of human capital, competencies, and investment resources, enabling them to adapt more rapidly to sanction-related restrictions. At the same time, the Gomel and Minsk regions maintained comparatively low values, reflecting the structural heterogeneity of industrial development and disparities in access to resources. Sanctions further intensified this differentiation: regions with more advanced infrastructure and stronger international linkages adapted more quickly, whereas peripheral territories faced constraints that hindered modernization.

Investment in innovation also exhibited significant volatility, reflecting enterprises' responses to sanction-related constraints. After a sharp decline in 2021-2022, when total innovation expenditures fell by nearly half, a recovery was observed in 2023-2024, and by 2024 investment reached its highest level for the entire observation period. However, the recovery was uneven: Minsk

increased innovation spending more than fourfold, whereas the Vitebsk region lost over 75 % of its investment. This indicates that sanctions affect regions asymmetrically: the capital region, with its more diversified economy and access to alternative financing channels, was able to offset external restrictions, while regions highly dependent on traditional industries proved more vulnerable. These findings are consistent with the conclusions of V. Gurski and V. Archakov [7], who emphasize that sanctions exacerbate regional disparities and pose risks to economic security.

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The most problematic area proved to be innovation-related services. Their share in the total volume of services nationwide remained extremely low—below 1 % throughout the entire period. The only exceptions were several IT clusters, primarily in the Brest and Vitebsk regions, where the share of innovation services reached 9-11 %. However, after 2020 the Brest region experienced a sharp decline, driven by the relocation of IT companies and the erosion of the local innovation ecosystem. These trends fully align with the findings of Khamiankova [8], according to which 64 % of Belarusian technology startups report negative effects of sanctions, while many are forced to conceal their Belarusian origin, change jurisdiction, and restructure their business models. The relocation of technology firms led to a reduction in domestic demand for innovation services and weakened regional innovation centers. Moreover, Khamiankova's [2] study shows that sanctions create additional administrative barriers, including enhanced banking oversight, difficulties in opening accounts, and stricter compliance requirements, making it more challenging to conduct innovation-oriented business in the EU and the United Kingdom than in the United States or Latin America. These findings help explain why innovation services in Belarus failed to recover after 2020: a significant share of the country's innovation potential was compelled to move abroad.

Overall, the results of the study show that Belarusian industry demonstrates a capacity for adaptation; however, this adaptation is predominantly compensatory in nature [11]. The growth of innovation activity and the increasing share of innovative products occur against the backdrop of high material intensity, declining profitability, and dependence on imported equipment. Sanctions have amplified existing structural constraints by limiting access to technologies and financing, which is particularly evident in regions with low innovation potential [12]. At the same time, certain regions and sectors were able to use the sanctions-induced crisis as an incentive to restructure production chains, explore new markets, and increase the technological complexity of their output.

Thus, the results of the study reflect a contradictory dynamic: on the one hand, there is evidence of growing innovation activity and partial adaptation to external constraints; on the other, systemic risks persist, reinforced by sanction-related pressures and institutional limitations. These findings confirm the need to shift from reactive measures to strategic modernization, the strengthening of regional innovation systems, and the development of mechanisms for technological autonomy. Under conditions of continued sanction pressure, innovation-driven development becomes not only a factor of competitiveness but also a key element of the country's economic security [13].

5. Conclusion

The conducted study made it possible to comprehensively assess the impact of external economic shocks, sanction-related restrictions, and internal structural characteristics on the innovation-driven development of the industrial sector of the Republic of Belarus in 2016-2024. The results obtained demonstrate that innovation dynamics have been shaped by a contradictory combination of enterprises' adaptive capacities and systemic constraints, which have been further reinforced by sanction pressure from the EU and the United States.

The analysis showed that sanctions became the key external factor shaping the institutional environment of industrial development. Restrictions on access to technologies, equipment, financing, and international markets substantially transformed the operating conditions of enterprises, intensified regional differentiation, and increased the risks of technological dependence. At the same time, the industrial sector demonstrated a capacity for partial adaptation: there has been growth in innovation activity, an increase in the share of innovative products, and a recovery of investment activity after the crisis period of 2021-2022. However, this adaptation is predominantly compensatory in nature and is not accompanied by deep structural transformations.

The regional analysis revealed substantial differences in innovation potential: city of Minsk and the Brest region function as centers of concentration of innovation-related resources, whereas the Vitebsk, Gomel, and Minsk regions face limited opportunities for modernization. These disparities are further amplified by the impact of sanctions, reinforcing the conclusion that a differentiated regional policy is required.

Particular attention should be paid to the sphere of innovation-related services, which remains the most vulnerable segment. The relocation of IT companies, the erosion of local innovation ecosystems, and the decline in domestic demand have led to stagnation in the sector despite isolated growth points. These trends fully correspond to the findings of international research, including the study by Khamiankova [8], which documents the large-scale relocation of Belarusian technology startups and their subsequent adaptation within foreign jurisdictions.

Taken together, the results of the study confirm that the innovation-driven development of Belarusian industry is unfolding under conditions of structural vulnerability, limited access to technologies and capital resources, and a high degree of dependence on external factors. At the same time, the identified adaptation mechanisms – reorientation toward higher value-added products, restructuring of production chains, and the growth of innovation activity in selected regions – indicate the presence of potential for further development.

Thus, the innovation trajectory of Belarusian industry under sanction pressure is determined by the balance between external constraints and internal capabilities. Ensuring sustainable development requires a shift from reactive adaptation measures to strategic modernization, including the strengthening of regional innovation systems, the development of technological autonomy, the stimulation of investment, and the creation of conditions for retaining or bringing back high-technology companies. Only a combination of institutional reforms, technological renewal, and an active innovation policy will allow Belarusian industry to secure long-term resilience and enhance its competitiveness amid ongoing external economic turbulence.

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Application of Artificial Intelligence in Mechanical Engineering Mechanics and Fracture Mechanics with an Overview of ANSYS SimAI Platform

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Abstract: Development of artificial intelligence in recent years has opened new possibilities in numerical analysis and engineering design. This paper systemizes the main area of applications of artificial intelligence in engineering with emphasis on computational mechanics. Fundamental approaches of machine learning are described including artificial neural networks, convolutional neural networks (CNN) and physics-informed neural networks and their integration with the finite element method. Additionally, a review is given on the platform ANSYS SimAI platform which combines predictive accuracy of numerical simulations with the speed of generative artificial intelligence in a cloud or local computer environment reducing computational time by one or two orders of magnitude. It is worth noting that artificial intelligence is not a replacement for classical analysis, but a powerful tool which speeds up the innovation process and can expand boundaries of numerical modeling in engineering.

Keywords: ARTIFICIAL INTELLIGENCE, MACHINE LEARNING, ENGINEERING, FINITE ELEMENT METHOD, ANSYS SIMAI, NEURAL NETWORK

1. Introduction

Artificial intelligence (AI), especially methods of machine learning and deep learning, in recent years has become an important tool for solving complex problems in engineering science including numerical mechanics and fracture mechanics, which is confirmed by a significant number of high-impact publications [1-8]. In the field of fracture mechanics and material damage, the application of artificial intelligence provides more precise and computationally efficient modelling of crack propagation, determination of fracture toughness and optimization of design solutions where classical methods based on finite elements are augmented with machine learning models and data [1-4]. For the engineering industry and academic community this development has dual significance. On one hand it shortens the time of product development and lowers time and cost of numerical simulations on from the other side it introduces new approaches like digital and hybrid twins, physics-informed neural networks and machine learning surrogate models which expand the possibilities of classical mechanics and fracture mechanics. This paper gives a concise mechanical engineering-oriented systematization of current literature on the application of artificial intelligence in numerical mechanics, as well as computational fracture mechanics, fatigue mechanics and modern concepts of physics informed machine learning. Accordingly, this paper provides an overview of fundamental machine learning approaches and physics-informed neural networks relevant to mechanical engineering mechanics and shows representative examples of their applications in fracture mechanics and gives a short insight into the emergence of industrial tools of a new generation like, ANSYS SimAI, which integrates artificial intelligence and numerical simulations into a single engineering workflow [1-14].

2. Fundamentals of AI methods in engineering

Development of machine learning and deep learning in engineering and in computational mechanics has led to the forming of a series of models which can approximate nonlinear material behaviors, speed up numerical simulations and serve as surrogates to classical finite element method (FEM) simulations. Recent review papers [1,2,5-14] show that the most common use in engineering applications have is for artificial neural networks (ANN), convolutional neural networks (CNN), physics-informed neural networks (PINN) and a wider set of machine learning (ML) methods (Support Vector Machine - SVM, Gaussian Process Regression - GPR and ensemble models) for optimizing simulation processes and parameter identification. This evolution is schematically illustrated in Fig. 1, which shows the development of AI/ML models for approximation in engineering and fracture mechanics.

Artificial neural networks (ANN)

ANN are currently the most widely used AI models in computational fracture mechanics where they are used for

approximation of nonlinear relations between input (model geometry, material properties, boundary conditions, loads) and output (displacement, deformation, stress distribution, fracture mechanics parameters like stress intensity factor, fracture toughness, fracture energy and crack growth). Recent studies [2,3,6,13] show that ANN trained on experimental and numerically obtained data sets, can replace time and resource high consuming nonlinear finite element method analyses for a wide range of quasi-brittle materials. In the context of mechanical engineering these networks are used as surrogate models for local stresses and strains in critical areas of complex structures [7,14,16].

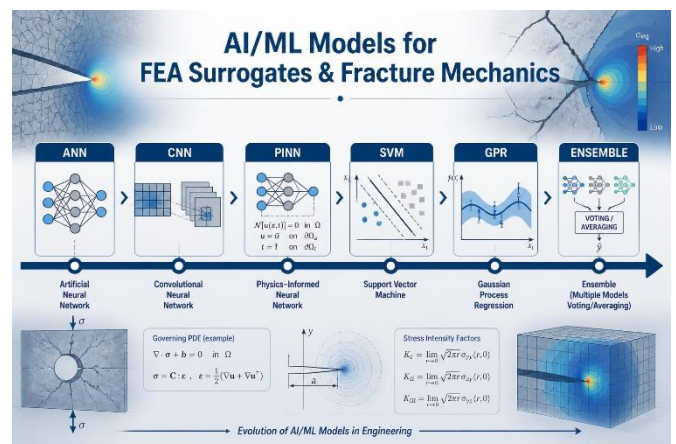


Fig. 1 Development of AI/ML models for approximation in engineering and fracture mechanics

Convolutional neural networks (CNN)

These networks are particularly suitable for processing images and fields and therefore they are used for automatic recognition and segmentation of cracks on steel, concrete and composite constructions as well as for determination of crack geometrical characteristics like length, depth and their planar or spatial orientation. Studies [17,18] show that CNN models trained on large datasets of concrete surface images achieve crack detection accuracy exceeding 95% allowing substitution or enhancement of classical visual inspections and significantly faster assessment of structural conditions. In the field of fracture mechanics, CNN approaches are developed in such a way that they can predict crack pattern and stress distribution and therefore reduce the need to use of highly dense finite element meshes and nonlinear analysis.

Physics-informed neural networks (PINN)

Physics-informed neural networks present a newer approach in which equations of equilibrium, constitutive laws, loads and boundary conditions are directly implemented in the loss function of the neural network. In this way the neural network learns not only from input data sets but also from physical laws. This is particularly

important in computational mechanics where data can be limited but accurate physical behavior of the model is crucial. Recent studies [4,5,10,15,13,19] show that PINNs can be used as alternative mesh-free solvers for problems from solid and mechanics computational mechanics, including plate bending, contact, and discontinuity problems, and have good potential to become a fundamental tool in the development of digital twins for structures.

Machine learning (ML) in the optimization of simulation process

Along with directly predicting stress distribution and the quantity of fracture mechanics parameters, ML methods are increasingly used as surrogate models of classical FEM analysis for systems like for pressure vessels or complex structures where deep networks use connections between input geometry, loads and resulting stresses and deformations. Such surrogate models enable multiple evaluations (for example in optimization and sensitivity analysis) with several orders of magnitude lower computational cost compared to direct nonlinear analysis. Physics-informed ML approaches additionally enable integration of uncertainty in the assessment of reliability. This is especially important for designing safety-critical systems in mechanical engineering [15-19].

3. AI integration with FEM analysis

Integration of methods of machine learning and deep learning with FEM today is considered as one of the key directions of computational mechanics development because it enables reduction of computational costs, automatization of part of modeling processes and increase of the level of automatization in engineering design. Recent literature differentiates AI applications across the preprocessing stage like generation and parametrization of the model, in the solver like surrogate models for partial differential equations and in the process of postprocessing for example faster reconstruction of stress or strain fields. The concept is illustrated in Fig. 2, which shows a workflow diagram of a CNN-based crack detection pipeline applied to images or FEM-based data, integrating AI into the preprocessing and inspection stages of the analysis.

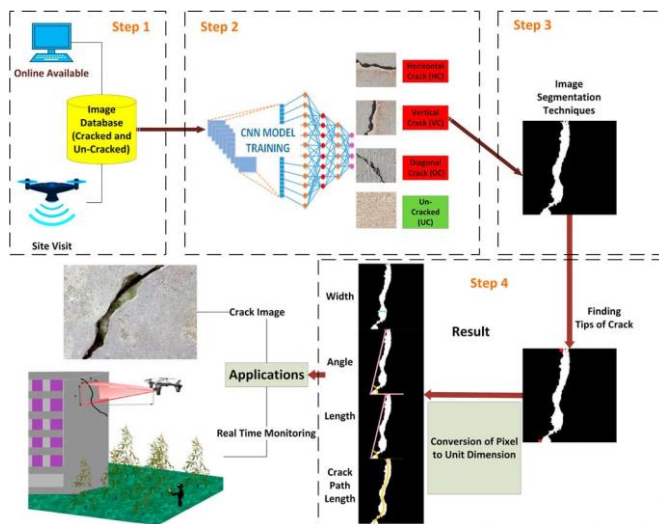


Fig. 2 Workflow diagram of a CNN for crack detection [18]

In the process of preprocessing ML is used for automatic parametrization of geometry, mesh generation and assigning loads and boundary conditions based on history data and rules noted in previous projects. For example, a classical problem of determination of mesh density, type of finite element or distribution of different material zones when heterogeneity is present can be formulated as a problems of classification or regression in which models learn empirical rules which are obtained by experienced engineers through years of practice. In such way AI in preprocessing acts like digital assistant that accelerates model preparation and minimizes the risk of major errors in setting boundary conditions.

The greatest interest is however focused on the use of ML models as surrogate solvers of partial differential equations. Deep neural networks, trained with sets of FEM results, can learn nonlinear relations between simulation inputs (geometry parameters, material models and loads) and output stress or strain field distributions and then in the exploitation phase replace the numerical solver. An example of such a surrogate is shown in Fig. 3, which presents a Finite-PINN mesh-free simulation of solid deformation, including a heat map comparison and accuracy analysis against classical FEM results.

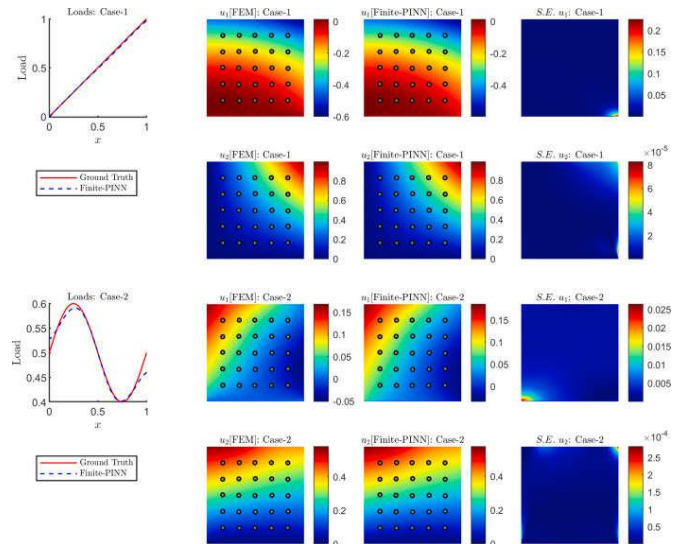


Fig. 3 Finite-PINN mesh-free simulation of solid deformation: heat-map comparison and accuracy analysis [20]

In [14] authors showed that stress distribution in complex constructions can be approximated with a deep model with a difference of obtained results on the order of several percent compared to the referent FEM results while computation time is drastically reduced. Similarly, in [16] the authors developed a deep learning surrogate model for submarine pressure vessel analysis, showing substantial time savings per evaluation. This is particularly valuable for the usually demanding process of optimization and analyses where different scenarios are tested.

In the process of postprocessing, ML models are used for the fast reconstruction of strain, deformation and stress field based on a limited set of measurements or partial FEM analysis results. Instead of rerunning the whole simulation, a trained model can in milliseconds approximate the whole strain, deformation or stress field which is very useful in interactive workflow and where digital twins are used. If the process of fatigue is considered or if weld life prediction is investigated, classical FEM analyses are replaced with a hybrid approach in which an ML model, trained with an extensive number of numerical and experimental scenarios, predicts parameters like local stress, number of cycles to failure and geometric variations in drastically lower computer demands compared to rerunning full nonlinear fatigue or fracture analysis.

Fracture mechanics is one of the most challenging fields of numerical mechanics because of the present strong nonlinearities, discontinuities, path dependence of crack growth and high sensitivity to material and geometric uncertainties present in models. Recent review papers show that exactly in this domain machine learning (ML) can offer the largest potential by learning complex relations between geometry, loading, material behavior and fracture parameters such as stress intensity factors and fracture toughness, and by complementing classical FEM analyses rather than replacing them [1-3,6,16].

4. ANSYS and platform SimAI

Over the past few years commercial simulation software vendors have started to implement AI directly in computer aided engineering

(CAE) in recent years and Ansys SimAI stands out as a leading example [21]. ANSYS SimAI is a cloud-based software-as-a-service (SaaS) application launched in 2024. It combines the predictive accuracy of Ansys numerical solvers with the speed of generative AI to speed up numerical simulations in wide range of physical domains. The platform is physics-agnostic and industry-neutral which means that it can be trained on multiphysics simulation data (solids, fluids, heat transfer and electromagnetics) generated by Ansys tools and third-party solutions. In the last version ANSYS SimAI supports local execution via the PySimAI Python package on Windows and Linux with offline tokens, alongside its primary cloud access. SimAI at its core uses generative deep learning models acting like surrogate ANNs trained on 3D simulation field data where system physics is transferred through existing numerical solutions and not explicit equations as mentioned earlier in the PINN approach. The overall SimAI workflow, illustrated in Fig. 3, consists of three main stages: (i) collection and upload of existing high-fidelity simulation results (CFD, FEM or multiphysics), (ii) cloud-based training of a deep generative model on those results, and (iii) rapid inference for new design variants, delivering full 3D field predictions within minutes.

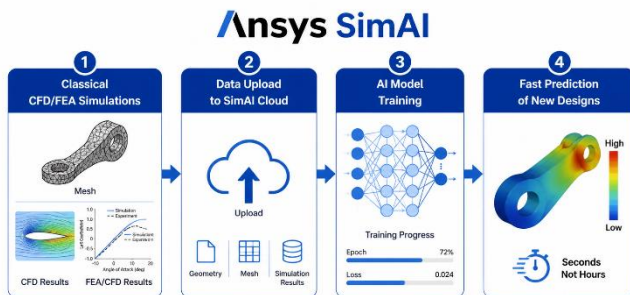


Fig. 3 SimAI workflow diagram

In the typical workflow users first load existing simulation results in the SimAI cloud, where they are separated into training and testing sets and are used to build deep models that connect design geometry with required performance without explicit parametric description. After training a new design which are commonly provided as geometry files can be evaluated within a few minutes and SimAI generates three-dimensional fields and required derived quantities that closely reproduce the reference simulation. According to available benchmark examples sufficiently trained SimAI models achieve speedups of the order of 10-100 times compared to classical high-fidelity simulations for computationally demanding projects, while in some documented CAE workflows in the cloud well trained SimAI models can get effective speedups of 200 times relative to repeatedly running full solver simulations. This significant time reduction enables the evaluation of dozens or hundreds of design candidates in a single session. Figure 4 shows a representative design-space exploration study in which SimAI predictions (such as aerodynamic drag coefficient or peak thermal stress) are mapped across a range of geometric parameters, allowing engineers to identify optimal regions of the design space without running a full solver for each candidate.

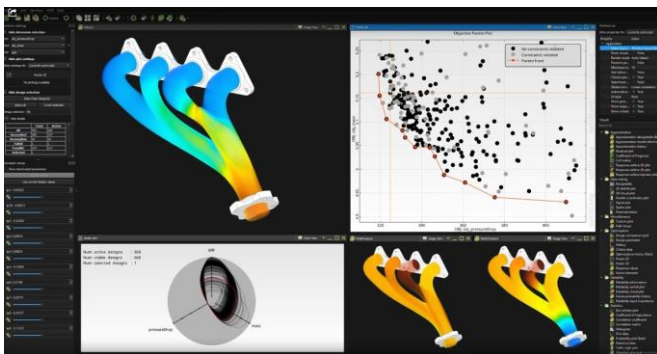


Fig. 4 Example of design-space exploration

Application examples shown by the vendor and independent authors cover a wide spectrum of engineering fields including external and internal aerodynamics (drag assessment of a vehicle), various thermal applications (electronics cooling, heat exchangers) and structural and electrical analyses. In those scenarios SimAI models act as high-level surrogates that enable very fast exploration of large design spaces, rapid multiple scenario analyses and prefiltering of design variants before a smaller subset is selected for expensive and time-consuming high-fidelity simulations. This is especially appealing in mechanically complex systems where a single CFD or nonlinear structural analysis can require hours or days of runtime on high-performance computing infrastructure and substantial license cost.

One of the key goals of the SimAI platform is democratization of simulation. The platform is available via a browser interface which is tailored for designers and non-expert users, users that do not have experience with scripting, high-performance computing configuration, or ML model development. For more advanced users, a Python SDK (PySimAI) is available, which enables integration of the platform into automated workflows and continuous integration and continuous delivery processes, without the need for deep knowledge of machine learning. SimAI is then used as a service that can be called from existing engineering scripts. Since training and running prediction is executed on managed cloud infrastructure, the vendor handles data management, security and scaling, while engineering teams keep control over their simulation sets of data. In this way, SimAI illustrates how AI surrogate models, cloud-based delivery and intuitive user interfaces can be combined in one commercial tool which brings advanced numerical simulation closer to a broader community of mechanical engineers [21-24]. Figure 5 shows the SimAI browser interface, where users can upload geometry files, monitor training progress, inspect predicted field distributions, and review key performance metrics alongside reference simulations - all without any scripting or high-performance computing configuration.

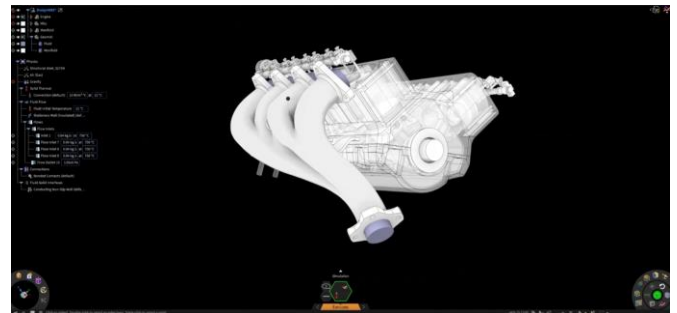


Fig. 5 SimAI user interface display

5. Discussion and conclusion

Despite impressive results the application of AI in numerical mechanics faces important limitations that are not easy to overcome. Most deep models demand large, representative and precisely and qualitatively labeled data sets, while in practice data sets are usually limited, noisy or not uniformly distributed, which can lead to overestimating of accuracy and weak generalization to new geometry, materials or loading conditions.

Additional problem is sensitivity on domain change where models trained on idealized numerical data may not behave reliably on real constructions where there are present tolerances, possible damage and complex exploitation conditions.

Interpretability is also one of the key limitations. Most deep networks act like a black-box and it is difficult for an engineer to explain why a model suggested a particular result like dimension change, fracture toughness value or optimal design. This limits the acceptance of such solutions in critical areas where high safety is required. The development of AI that would be more explainable and more interpretable is still an active research area and there no clear consensus about what level of explainability is enough for strict

engineering norms. Uncertainty quantification in machine learning is not yet standardized in a such way that it can be compared to the classical engineering approach where for the decision of structural integrity of a construction is of key importance to know not just the nominal value of prediction but also its reliability.

Physics-informed neural networks partially address the black-box problem by explicitly embedding equilibrium equations and boundary conditions into the loss function, but they have their own limitations. Recent studies show that PINNs can experience slow convergence, challenging calibration of loss-weight factors, and high computational cost when scaling to 3D geometries and complex nonlinear problems. Moreover, for PINN approaches, the issues of verification and validation remain: PINN solutions must be systematically compared with reference FEM analyses and experiments to quantify discrepancies and define regions of reliable application.

Expected future development is moving toward hybrid models that combine the strengths of classical physics-based analysis and AI. One direction is “physics-guided” ML models, where FEM results generate synthetic data and inform the network architecture, while experimental data are used for fine-tuning and uncertainty quantification. Another direction is digital twins, which integrate real-time measurements, reduced-order physical models, and ML surrogates into a unified framework for structural health monitoring and predictive maintenance. In all these scenarios, the engineer’s role remains central: from selecting the appropriate model and control variables, to monitoring the training process, and finally verifying solutions against codes, safety factors, and engineering judgment.

A review of the available literature shows that artificial intelligence currently serves as an important supplement, but not a replacement, for classical numerical analysis in mechanical engineering, mechanics, and fracture mechanics. Machine and deep learning methods enable the approximation of nonlinear relationships, acceleration of simulation processes, and construction of surrogate models that significantly reduce computational demands, while PINNs and related approaches incorporate physical laws directly into the model architecture, thus extending the classical framework of computational mechanics. Notably, applications are prominent in crack detection and characterization, prediction of fracture parameters and crack growth in quasi-brittle and metallic materials, and in the development of digital twins, where AI enables rapid integration of measurements, simulations, and optimization.

At the same time, commercial tools such as Ansys SimAI show how ML surrogates and generative AI can be implemented in an industrially acceptable form, allowing engineers to evaluate new designs within minutes rather than hours or days, with potential speedups of 10-100 times compared to classical simulations. Such tools contribute to the democratization of simulation – making advanced numerical analyses accessible to a broader user base – while also highlighting the need for clear protocols for verification, validation, and uncertainty quantification [21-24].

In conclusion, AI is not a substitute for the engineer or for established methods such as FEM, but rather a tool that dramatically accelerates the innovation cycle and enables exploration of a much wider design space than was previously possible with classical approaches alone. Future development will likely move toward even tighter integration of AI and physical models, the emergence of hybrid digital twins, and the standardization of V&V procedures for AI-enhanced simulations, while expert engineering judgment will remain the core of the entire design and structural safety assessment process.

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НИЗКОНИКЕЛЕВЫЕ МЕТАСТАБИЛЬНЫЕ ТРИП СТАЛИ: АКТУАЛЬНОСТЬ ИСПОЛЬЗОВАНИЯ, ПЕРСПЕКТИВНЫЕ СПОСОБЫ ДЕФОРМАЦИОННОЙ ОБРАБОТКИ

LOW-NICKEL METASTABLE TRIP STEELS: RELEVANCE OF USE, PROMISING METHODS OF DEFORMATION TREATMENT

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Abstract. Currently, in the production of various metal products for critical applications, the problem of using materials with both high strength and plastic properties has been partially solved by using residual austenitic steel, known as TRIP steel in international practice. This steel has a multi-phase structure consisting of ferrite, bainite, residual austenite, and martensite. This work focuses on the relevance of the production and use of low-nickel metastable TRIP steels in various industries. Additionally, the paper explores two promising methods for the deformation treatment of TRIP steel, including asymmetric rolling for producing sheet billets and radial-shear rolling for producing round bars. These methods allow for the implementation of severe plastic deformations during the deformation process, which can enhance the processes occurring in TRIP steel during deformation treatment.

Keywords: TRIP STEEL, AUSTENITE, MARTENSITE, LOW-NICKEL METASTABLE TRIP STEELS, DEFORMATION TREATMENT, SEVERE PLASTIC DEFORMATION, ASYMMETRIC ROLLING, RADIAL-SHEAR ROLLING

1. Введение

Уже не одно десятилетие в различных отраслях промышленности, особенно в авиа- и автомобилестроении, в связи с растущими требованиями к безопасности, надежности и уменьшению веса элементов конструкции и деталей машин, наблюдается устойчивая тенденция к применению материалов, обладающих высокими показателями не только по прочности, но и одновременно по пластичности. Конструкционные элементы из обычных сталей повсеместно заменяются на пластики и композиты, а облегченные силовые элементы конструкций на высокопрочные стали с требованием повышенной пластичности, чтобы при аварии происходило не хрупкое разрушение, а управляемое смятие прочного силового каркаса с адсорбированием большей энергии удара за счет повышенной прочности и достаточной пластичности материала.

Как известно большинство традиционных способов повышения прочностных характеристик металлоизделий, такие как термообработка; деформационное упрочнение, и в частности способами обработки давлением, реализующими в процессе деформирования интенсивные пластические деформации; термомеханическая обработка, в большинстве случаев приводят к снижению пластических свойств материалов данных металлоизделий. При производстве различных металлоизделий ответственного назначения данная проблема в настоящее время частично решена применением стали с остаточным аустенитом, известная в международной практике как ТРИП (Transformation Induced Plasticity) сталь. Эта сталь имеет многофазную структуру, состоящую из феррита, бейнита, остаточного аустенита и мартенсита [1]. Главной особенностью данного материала является присутствие в микроструктуре данного материала метастабильного аустенита и наличие так называемого ТРИП-эффекта, который проявляется в трансформации кубической гранецентрированной решетки аустенита в объемно-центрированную решетку мартенсита в результате коллективного сдвига плоскостей при приложении нагрузки. Именно данная особенность ТРИП сталей существенно влияет на комплекс их механических свойств и позволяет добиться, как повышения прочностных, так и пластических свойств.

2. Актуальность использования низконикелевых метастабильных ТРИП сталей

Одной из основных причин отсутствия широкого промышленного применения данных сталей является высокая стоимость их производства, так как они все высоколегированные. Поэтому в настоящее время перед учеными и производителями ТРИП сталей стоит задача по разработке новых низколегированных марок сталей, в том числе и ТРИП сталей, обладающих все тем же повышенным уровнем механических свойств. В частности этой проблемой занимаются ученые Института черной металлургии (The Institute of Iron and Steel Technology) Технического университета - Фрайбергская горная академия (TUBAF). Начиная с 2020 года по настоящее время в академии реализуется проект №44797210 «Alloy and structure design of austenitic cast Cr-Ni-Cu-N steel exhibiting TRIP/TWIP properties for cold massive forming», который финансируется Немецкой исследовательской ассоциацией (DFG). Так же в академии проводятся и инициативные исследования в области выплавки, обработки и исследования структуры и свойств экономнолегированных аустенитных сталей различного химического состава. По полученным в рамках проводимых исследований результатам ими опубликован целый ряд научных работ в данном направлении, в том числе работы [2-16]. Одно из направлений, проводимых в Институте черной металлургии Технического университета - Фрайбергская горная академия исследований, связано с выплавкой и исследованием новых никельсберегающих метастабильных ТРИП сталей. В первую очередь это связано с тем, что высокое содержание никеля значительно повышает стоимость стали [17, 18]. Также надо отметить, что по данным ВОЗ, никель - один из наиболее опасных загрязнителей окружающей среды. Повышенное содержание никеля в окружающей среде (согласно классификации Международного агентства исследований рака (IARC) металлический никель (пыль) и гипосульфит никеля являются канцерогенами и опасны в концентрациях 0,0004–0,4 и 0,0001–0,1 мг/м³, соответственно [19]) приводит к появлению эндемических заболеваний, бронхального рака.

Другой немаловажной нишей применения безникелевых высокопрочных сталей является ядерная энергетика и перспективные термоядерные энергетические установки [20]. Никель при облучении нейтронами распадется очень

токсичные и долгоживущие изотопы [21]. При среднем содержании никеля в 10% в типичных сталях применяемых для конструкций самого корпуса реактора и трубопроводов близких к активной зоне, проблема наведенной радиоактивности этих деталей, составляющих основу реактора, очень велика [22-24]. И если, с более известной проблемой утилизации и переработки самого ядерного топлива (например в МОХ-топливо [23]) все относительно просто, то что делать с многотонными массивными корпусами реакторов не вполне ясно. Эта, ранее незаметная проблема, будет только нарастать с растущей декомиссией старых энергоблоков массово построенных в 70-е и 80-е годы. Получение нового класса безникелевых реакторных сталей позволит приблизиться к решению утилизации корпусов реакторов. Особенную локальную актуальность этот вопрос приобрел после Национального референдума о строительстве АЭС в Казахстане [25].

На основе выше сказанного можно сделать вывод, что исследования в области выплавки и последующей деформационной обработки низконикелевых метастабильных ТРИП сталей до сих пор являются актуальными исследованиями. Так как данные (никельсберегающие метастабильные) ТРИП стали с каждым годом будут находить все более широкое применение в различных отраслях промышленности, в том числе они могут найти свое применение и при производстве беспилотных аппаратов.

3. Перспективные способы деформационной обработки ТРИП-сталей

Актуальность исследований в области деформационной обработки низконикелевых метастабильных ТРИП, как и ТРИП сталей любого химического состава, связана с тем, что благоприятный комплекс физико-механических свойств формируется в них непосредственно в ходе деформирования за счет реализации, наряду с дислокационным скольжением, таких процессов, как двойникование, образование дефектов упаковки и деформационного мартенсита [26]. Интенсифицировать выше названные процессы, протекающие при деформировании ТРИП сталей, на наш взгляд возможно за счет реализации в процессе деформирования интенсивных пластических деформаций. При этом, в случае получения листовой заготовки, интенсивные пластические деформации в деформируемом металле могут быть реализованы за счет применения такого способа деформирования, как асимметричная прокатка [27] (рис. 1).

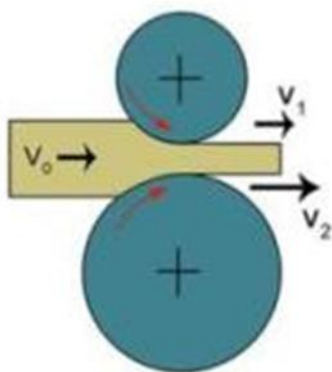


Рис. 1. Асимметричная прокатка

При получении же металлоизделий в виде прутков круглого поперечного сечения, наиболее перспективным способом деформационной обработки является радиально-сдвиговая прокатка (РСП) [28] (рис. 2).

Данный способ деформирования обеспечивает интенсивную проработку исходной структуры металла деформируемого прутка и формирование градиентной ультрамелкозернистой структуры при минимальном количестве проходов. Связано это с тем, что увеличенный при

радиально-сдвиговой прокатке (в отличие от обычной поперечно-винтовой прокатки по трехвалковой схеме) угол подачи до значения $\alpha = 18^\circ - 20^\circ$ (при обычном угле раскатки $\beta = 5^\circ$) способствует развитию сильнейшей вихревой деформации от поверхности к центру деформируемого прутка [29]. При этом в очаге деформации реализуется схема напряженного состояния близкая к всестороннему сжатию с большими деформациями сдвига [28-30]. А геликоидальное истечение металла по заданным траекториям с замедлением внешних слоев заготовки и ускорением внутренних создает интенсивные сдвиговые перемещения в очаге деформации труднодостижимые другими способами. При РСП происходит глубокое уплотнение и проработка структуры металла по всем уровням металлофизического строения. По своему морфологическому строению металл после РСП становится материалом нового качества. При этом достигается комплексное повышение и стабилизация физико-механических и служебных свойств металла. Наибольший прирост создается в пластических и вязких, а также корреляционно связанных с ними эксплуатационных свойствах [29].

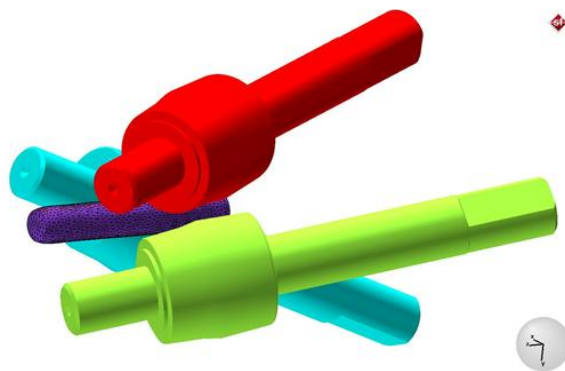


Рис. 2. Радиально-сдвиговая прокатка

Данный способ деформирования обеспечивает интенсивную проработку исходной структуры металла деформируемого прутка и формирование градиентной ультрамелкозернистой структуры при минимальном количестве проходов. Связано это с тем, что увеличенный при радиально-сдвиговой прокатке (в отличие от обычной поперечно-винтовой прокатки по трехвалковой схеме) угол подачи до значения $\alpha = 18^\circ - 20^\circ$ (при обычном угле раскатки $\beta = 5^\circ$) способствует развитию сильнейшей вихревой деформации от поверхности к центру деформируемого прутка [29]. При этом в очаге деформации реализуется схема напряженного состояния близкая к всестороннему сжатию с большими деформациями сдвига [28-30]. А геликоидальное истечение металла по заданным траекториям с замедлением внешних слоев заготовки и ускорением внутренних создает интенсивные сдвиговые перемещения в очаге деформации труднодостижимые другими способами. При РСП происходит глубокое уплотнение и проработка структуры металла по всем уровням металлофизического строения. По своему морфологическому строению металл после РСП становится материалом нового качества. При этом достигается комплексное повышение и стабилизация физико-механических и служебных свойств металла. Наибольший прирост создается в пластических и вязких, а также корреляционно связанных с ними эксплуатационных свойствах [29]. Данный способ обработки давлением был отработан на целом ряде черных (в том числе и на близких по составу и свойствам аустенитных марках стали) и цветных металлов и сплавов, а также на различных композиционных материалах и преимущества его использования приведены в большом количестве научных работ, в том числе в работах [31-42]. Обзор научно-технической литературы показал, что изучением вопроса влияния асимметричной и радиально-сдвиговой прокатки на эволюцию микроструктуры и изменение механических свойств

ТРИП сталей пока еще ни кто не занимался. То есть до сих пор не изучены вопросы влияния различных параметров данных (асимметричной и РСП) способов прокатки, таких как температура, обжатие, скорость деформирования и других на возможность получения высококачественных заготовок из низконикелевых метастабильных ТРИП сталей. Поэтому исследования в данном направлении являются актуальными и требуют тщательного изучения.

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ИЗУЧЕНИЕ ИЗНОСОСТОЙКОСТИ ОБРАЗЦОВ, ДИСПЕРСНО-УПРОЧНЕННЫХ С ПОМОЩЬЮ ЦЕНТРОБЕЖНОГО ЛИТЬЯ КАРБИДАМИ ТИТАНА, ВОЛЬФРАМА И ЦИРКОНИЯ

STUDY OF THE WEAR RESISTANCE OF SAMPLES DISPERSELY HARDENED WITH TITANIUM, TUNGSTEN, AND ZIRCONIUM CARBIDES BY CENTRIFUGAL CASTING

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Abstract. One of the promising methods for producing dispersed-reinforced steels with an undifferentiated layer interface is centrifugal casting. This work focuses on studying the effect of dispersed strengthening of steel with titanium, tungsten, and zirconium carbides using centrifugal casting on the wear resistance of 12X18H10T corrosion-resistant steel. A physical experiment was conducted using a high-frequency induction melting unit and a horizontal centrifugal casting machine to produce a batch of cylindrical castings with a diameter of 120 mm, a height of 90 mm, and a wall thickness of 20 mm, which were dispersed-strengthened with titanium, tungsten, and zirconium carbides. The results of the study showed that castings made from 12X18H10T corrosion-resistant steel that were strengthened with tungsten carbide using centrifugal casting were the most resistant to abrasive wear. On the other hand, castings made from 12X18H10T corrosion-resistant steel that were complexly strengthened with three carbides (titanium, tungsten, and zirconium) in equal proportions were the least resistant to abrasive wear. This can be explained by the uneven distribution and clustering of the carbide inclusions, which can lead to localized wear during abrasion.

Keywords: DISPERSED HARDENING, DISPERSED REINFORCED STEEL, CENTRIFUGAL CASTING, WEAR RESISTANCE, MICROHARDNESS, TITANIUM, TUNGSTEN, AND ZIRCONIUM CARBIDES

1. Введение

В чёрной металлургии традиционным и, наверное, самым простым способом повышения механических свойств выплавляемых сталей и сплавов является легирование, при котором различные свойства данных материалов достигаются за счёт увеличения содержания легирующих элементов в металлической матрице. В тоже время с экономической точки зрения устойчивый рост стоимости ферросплавов и легирующих добавок делает данный способ всё менее привлекательным. Поэтому уже не одно десятилетие более перспективным подходом к повышению механических свойств выплавляемых сталей и сплавов считается способ обогащения микроструктуры металла дисперсными частицами микронных (или мельче) размеров [1, 2]. Такой метод обеспечивает создание композиционных материалов с особыми характеристиками благодаря равномерному или целенаправленно неравномерному распределению частиц [3, 4].

При этом одним из перспективных направлений получения сталей и сплавов со структурой, обогащенной дисперсными частицами, является определенное (заданное) сочетание в объёме выплавляемого материала дисперсных выделений и градиентной структуры. Ранее проводимые исследования показывают, что совместное действие наноразмерных выделений и неоднородной структуры по толщине материала может обеспечить прочность более 3 ГПа при сохранении высокой пластичности [5, 6].

Одним из перспективных способов направленной кристаллизации и получения заготовок, в которых содержание упрочняющих фаз изменяется от поверхности к центру, является центробежное литье. Именно данный способ позволяет получать дисперсно-армированные стали с невыраженной границей раздела слоев [7].

Целью данной работы является исследовать влияние дисперсного упрочнения стали карбидами титана, вольфрама и циркония, осуществленного с помощью центробежного литья, на износостойкость данной стали.

2. Методика

Для достижения поставленной цели был проведен физический эксперимент по получению с помощью центробежного литья опытной партии дисперсно-упрочненных отливок. Для проведения физического эксперимента использовали установку высокочастотного индукционного плавления металла СЭЛТ-001-15/44-Т и машину горизонтального центробежного литья. В качестве шихты была взята марка стали 12X18H10T ($C \leq 0.12\%$, $Cr = 17-19\%$, $Ni = 9-11\%$, $Ti \leq 0.7\%$, $Mn \leq 2\%$, $Si \leq 0.8\%$, $S \leq 0.02\%$, $P \leq 0.035\%$, Fe – остальное), раскисление производилось первичным порошковым алюминием. В экспериментах использовались карбид титана (TiC), карбид вольфрама (WC), и карбид циркония (ZrC), состав и масса добавляемых частиц представлены в таблице 1. Каждая плавка дублировалась 3 раза. В результате проведения плавки были получены отливки цилиндрической формы диаметром 120 мм, высотой 90 мм, с толщиной стенок 20 мм.

Таблица 1. Масса добавленных карбидов в исследуемые образцы

Маркировка образца	Состав вводимых частиц	Масса добавки, г
Etalon	-	-
TW	TiC + WC	50 + 50
TWZ	TiC + WC + ZrC	33 + 33 + 33
TZ	TiC + ZrC	33 + 33 + 33
T	TiC	100
Z	ZrC	100
W	WC	100

Для проведения испытаний на износ с внешней и внутренней стороны отливки были подготовлены образцы размерами 10×10×50мм.

Износ полученных образцов определялся методом абразивного истирания. В соответствии с данным методом исследования износостойкость полученного материала исследуется путем вычисления потери массы образца в

результате прохождения определенного расстояния с определенной нагрузкой по абразивной бумаге. Исследования на износ проводили на лабораторной установке, представленной на рисунке 1.

Установка для измерения износостойкости материала состоит из станины, двигателя, цилиндрического и конического редуктора с червячными парами, вращающегося стола, держателя, пускового механизма. Двигатель передаёт вращающий момент через систему шестерен рабочей поверхности, так называемому столику, с закрепленной на ней абразивной бумагой. Так же вращение передается на редуктор, работа которого обеспечивает передвижение держателя с образцом над поверхностью рабочего столика. Под действием сил тяжести, нагрузка, которая приложена сверху на держатель, передается образцу, который начинает контактировать с абразивной поверхностью. В результате вращения абразивной поверхности и перемещения держателя происходит изнашивание закрепленного образца со стороны контактируемой поверхности. Для каждой области измерения дублировались по три раза (т.е. осуществлялось по три прохода). Массу исследуемых образцов взвешивали до и после испытания на аналитических лабораторных весах.

Параллельно все образцы также были исследованы на микротвердость (от внешней стороны отливок к внутренней). Отступ от краёв составлял 2 мм.



Рис. 1. Внешний вид лабораторной установки для измерения износостойкости материала

3. Результаты и обсуждение

Результаты (усредненные) исследования износостойкости полученных дисперсно-упрочненных карбидами титана, вольфрама и циркония (в различной вариации) отливок представлены в таблице 2, а результаты (средние значения) измерения микротвердости в таблице 3.

По результатам измерения износостойкости можно сделать вывод, что износостойкость образцов при абразивном истирании определяется главным образом: уровнем и градиентом микротвёрдости по сечению; наличием и характером распределения твёрдых дисперсных фаз/оксикарбидных включений; степенью кластеризации включений.

Так, образец W показывает максимальную износостойкость (минимальные потери массы) как на внутренней, так и на внешней стороне. Это связано с наиболее высокой микротвёрдостью по всему сечению и выраженным поверхностным упрочнением. Предварительные металлографические исследования показали, что отдельные частицы WC не наблюдались, а вольфрам присутствует в матрице, что соответствует механизму твердорастворного

упрочнения и повышению сопротивления микрорезанию абразивом.

Таблица 2. Результаты измерения износостойкости образцов

Образец	Зона	m_0 , гр.	m_1 , гр.	m_2 , гр.	Δm_1 , гр.	Δm_2 , гр.	Δm_{cp} , гр.
Etalon	внут.	2,420	2,300	2,180	0,120	0,120	0,120
Etalon	внеш.	2,480	2,385	2,291	0,095	0,094	0,095
T	внут.	2,510	2,410	2,310	0,100	0,100	0,100
T	внеш.	2,540	2,446	2,352	0,094	0,094	0,094
TW	внут.	2,560	2,472	2,382	0,088	0,090	0,089
TW	внеш.	2,590	2,490	2,390	0,100	0,100	0,100
TZ	внут.	2,505	2,395	2,285	0,110	0,110	0,110
TZ	внеш.	2,545	2,440	2,336	0,105	0,104	0,105
Z	внут.	2,530	2,425	2,319	0,105	0,106	0,106
Z	внеш.	2,570	2,480	2,390	0,090	0,090	0,090
TWZ	внут.	2,480	2,350	2,220	0,130	0,130	0,130
TWZ	внеш.	2,530	2,420	2,310	0,110	0,110	0,110
W	внут.	2,600	2,530	2,460	0,070	0,070	0,070
W	внеш.	2,620	2,565	2,510	0,055	0,055	0,055

Таблица 3 - Микротвердость в различных сечениях

Образец	Микротвердость, HV				
	Внутренняя сторона	1/3R	2/3 R	Внешняя сторона	Среднее
Etalon	106.9	140.2	141.4	140.3	132.2
T	129.7	133.1	154.6	138.9	139.1
TW	156.3	136.8	133.4	149.5	144.0
TZ	129.5	135.6	133.0	135.6	133.4
Z	127.7	140.0	144.0	145.0	139.2
TWZ	107.4	127.9	127.5	128.2	122.8
W	170.0	190.0	186.4	194.6	185.0

Образец Z имеет более высокие результаты на внешней стороне, чем на внутренней. Это объясняется тем, что для этого образца характерно наличие в структуре внешней зоны повышенной доли Zr-содержащих оксидно-карбидных включений и более выраженный градиент упрочнения к наружной поверхности. Это повышает сопротивление абразивному износу именно со стороны наружной поверхности.

Структура образца T ожидаемо обеспечивает умеренное повышение износостойкости и относительно небольшую разницу между внутренней и внешней сторонами. В данном образце частицы TiC/Ti(C,N) распределяются более равномерно (без резкого градиента микротвёрдости), поэтому потери массы близки для обеих зон, с небольшим преимуществом наружной стороны.

Образец WT по совокупности данных проявляет анизотропию по сечению образца: внутренняя часть изнашивается меньше, чем внешняя, то есть имеет более высокую износостойкость. Исследования микротвёрдости для WT показали обратный градиент (внутренняя зона твёрже наружной). При этом общий уровень износостойкости - выше, чем у эталона.

Износостойкость образца TZ показывает слабое улучшение относительно эталона. Это также подтверждается данными микротвердости: данные по микротвердости близки к эталону, а распределение включений местами неоднородно (кластеры), что при абразивном истирании может приводить к локальному выкрашиванию и не давать выраженного прибавления износостойкости.

Многокомпонентная подача карбидов показала наименьшее влияние на износостойкость: в образце TWZ на внутренней стороне показатели даже ниже эталона, что объясняется выраженной неравномерностью распределения большого количества частиц и кластеризация, а также минимальными показателями средней микротвердости. Для абразивного износа это неблагоприятно, так как кластеры и границы раздела «матрица-включение» в данном случае могут работать как зоны облегчённого микровыкрашивания, повышая суммарную потерю массы.

Вывод: Абразивная износостойкость, оцененная по потере массы при истирании, закономерно зависит от уровня/градиента микротвёрдости и характера распределения твёрдых фаз. Минимальные потери массы демонстрирует образец W (особенно на внешней стороне: $\Delta m_{cp} \approx 0,055$ г), что соответствует наиболее выраженному упрочнению. Образец Z также показывает улучшение прежде всего во внешней зоне ($\Delta m_{cp} \approx 0,090$ г), что связано с повышенной концентрацией Zr-содержащих оксидно-карбидных включений у наружной поверхности. Для образца T улучшение умеренное и более равномерное по сечению (внутренняя $\Delta m_{cp} \approx 0,100$ г; внешняя $\approx 0,095$ г), тогда как образец WT проявляет обратную анизотропию (внутренняя износостойкость выше внешней). Наименее устойчивым к абразивному износу оказался образец TWZ (внутренняя $\Delta m_{cp} \approx 0,130$ г), что объясняется неравномерностью распределения и кластеризацией включений, создающих зоны локального выкрашивания при истирании.

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New technology for producing a screw reinforcement profile from bar scrap of ferrous metals

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Abstract: This work is devoted to the development and research of a new technology for processing bar scrap from 40X steel to obtain high-quality finished metal products in the form of a screw reinforcement profile. The developed technology included two stages. At the first stage, the round-section bar scrap is formed on a radial-shear rolling mill to obtain conventional bars of the desired diameter and create initial conditions for the formation of an ultrafine grained gradient structure in the resulting screw profile. The second stage is the direct production of a screw profile with a gradient ultrafine-grained structure on a combined installation. Metallographic studies have shown that after the implementation of the second stage of obtaining a screw reinforcement profile, a gradient structure is observed in 40X steel, with equiaxed grains, the size of which lies within 1.2-1.4 μm in the peripheral region and to a greater extent with elongated, directional-oriented grains in the central region of the resulting reinforcement.

Keywords: RADIAL-SHEAR ROLLING, COMBINED INSTALLATION, BAR SCRAP, RECYCLING, SCREW REINFORCEMENT PROFILE, MICROSTRUCTURE.

1. Introduction

At the moment, almost 2 billion tons of steel are produced in the world, which is used for the manufacture of various metal products used in various industries. At the same time, it must be recognized that metallurgy is most often a "dirty" industry, since in this case there is quite a lot of environmental pollution. Therefore, metallurgical companies have been facing the task of "greening" metallurgy for more than a decade. And currently there are achievements in this direction. At the same time, the metal products turn into waste, which have served their service life (scrap), which also needs to be disposed of. One of the simplest and most frequently used methods of recycling ferrous scrap and alloys, as well as non-ferrous ones, is its remelting and further reuse.

If we talk about ferrous scrap metal, then in some countries of the world another method of its processing has long been put into practice, namely, recycling of some metal products that have served their service life by various methods of hot pressure treatment to obtain a finished commercial product. In our opinion, this method of processing ferrous scrap and alloys can be attributed to "green" technologies, as it allows to make a small contribution to improving the environmental situation in the world.

At the moment, in many countries of the world, a number of different technological processes have been developed for the processing of some metal products that have served their service life using hot pressure treatment into a ready-made commercial product. The founder of this direction of processing metal products that have served their service life by hot pressure treatment is the American scientist E.E. Slick, who at the beginning of the last century developed a technology for processing railway rails by hot rolling in calibers in order to obtain flange profiles [1]. But then the technology he proposed was not widely used in practice. It was only at the end of the 20th century that the world scientific community and manufacturers of metal products became interested in this direction. Here are just some works [2-5] devoted to the development and study of technologies for processing railway rails by hot rolling to produce various finished metal products. For example, one of these technologies, namely the technology of rolling railway rails into construction fittings, has found application at a metal rolling plant in Tula (Russia).

In addition to rolling railway rails into various finished metal products, technologies for recycling non-dimensional pipe segments are also being developed to produce marketable products in the form of a thin ribbon. Thus, in [6-8], two options for processing pipe segments into a cold-state tape were considered: the first option is flattening – rolling – separation, and the second option is flattening – separation – rolling. According to both proposed options, a high-quality thin steel strip with a length of 1.5 m was obtained.

The authors of the work [9] proposed a technology for using man-made waste from metallurgical production of non-ferrous trimming of copper pipes made by pressing to obtain a composite

tape of the copper-steel-copper system. This technology includes the following stages of deformation: the draft of a pipe segment between the strikers, inside which a steel plate is placed; subsequent longitudinal rolling of the resulting billet.

Another promising way of recycling some metal products that have served their service life is their rolling on radial-shear rolling mills [10]. But most often this method is applicable only for recycling cylindrical metal products, for example, pumping rods [11] and used railway axles [12], as well as bar scrap of ferrous metals and alloys [13], including in the form of fittings [14]. In all cases, this method is based on the principle of hot radial shear rolling of a used so-called bar to a smaller diameter and subsequent use of the resulting bar of a smaller cross-section for its intended purpose. It should be noted that radial-shear rolling makes it possible to obtain long-length products from various materials with a gradient ultrafine-grained structure [15] and in addition, this method is the most technologically advanced and easy to implement compared to many other methods of metal forming, which realize severe plastic deformation.

As already noted above, radial-shear rolling makes it possible to process bar scrap of ferrous metals to obtain a marketable product in the form of bars for various purposes. In the future, these rods can be used, among other things, to produce various high-quality metal products, for example, hardware products or a coupling screw for formwork, but this will require the use of additional technological solutions.

Developing the direction of recycling of bar scrap using radial-shear rolling, a new technological process for processing bar scrap metal was proposed, combining radial-shear rolling and pressing through a screw matrix (Fig. 1). This technology will make it possible to obtain a high-quality commercial product from round-cross-section bar scrap in the form of a screw reinforcement profile with a gradient ultrafine-grained structure and with a given level of mechanical properties.

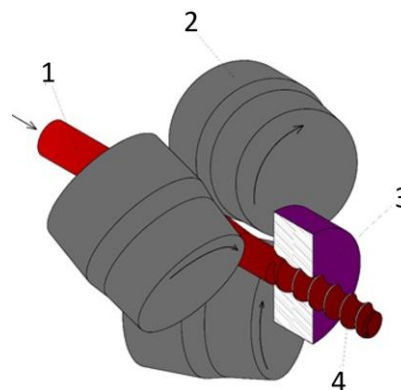


Fig. 1. Combined method for obtaining a screw reinforcement profile from bar scrap of ferrous metals: 1 – bar scrap; 2 – rolling rolls; 3 – screw matrix; 4 – screw profile

Earlier in [16-17], using computer modeling in the DEFORM software, it have been already proved the possibility of implementing this combined process and determined the most rational geometric and technological parameters for its implementation. The purpose of this work is to confirm in practice the possibility of obtaining a screw profile with a gradient ultrafine-grained structure during the implementation of a new combined method shown in Fig. 1.

2. Materials and Methods

A laboratory combined installation for the production of a reinforcing profile was assembled on the basis of the radial shear rolling mill RSR 10-30 (Fig. 2a), on which a screw matrix was installed (Fig. 2b) with a maximum diameter of the working screw channel of 20 mm. Bar scrap, namely studs (GOST 9066-75, type-A1), was used as the initial blanks for the physical experiment with size of M36 x 150 mm made of 40X steel, which have served their service life. Before deformation, these studs were subjected to homogenizing annealing.

The proposed technology for recycling bar scrap in the form of studs includes two stages. At the first stage, the pins with a diameter of 36 mm, previously subjected to homogenizing annealing, were heated to a temperature of 1150 ± 10 °C and kept at this temperature. Further, these studs were deformed on the RSR 10-30 radial-shear rolling mill according to the reversible scheme [13] to a diameter of 24 mm, that is, 4 passes were carried out according to the scheme $\varnothing 36 \rightarrow \varnothing 33 \rightarrow \varnothing 30 \rightarrow \varnothing 27 \rightarrow \varnothing 24$ mm.

Before the implementation of the second stage, the rods with a diameter of 24 mm obtained at the first stage were heated to a temperature of 1000 ± 10 °C. The second stage of the stud recycling technology was implemented on a combined installation assembled at the RSR 10-30 radial-shear rolling mill (Fig. 2c). The deformation process of preheated rods on the assembled combined installation was as follows: first, the rod was rolled in the working cage of the RSR 10-30 mill with an absolute compression in diameter of 5 mm, at the outlet of which it entered the screw matrix and due to the pushing force created by the rolls, and pushed through the screw channel. As a result, a screw profile was obtained on the deformed bars (Fig. 2d).



a)



b)



c)



d)

Fig. 2. Radial-shear rolling mill RSR 10-30 and the installation assembled on it to produce a reinforcing screw profile: a - mill RSR 10-30; b - screw matrix; c - working cage of the mill and the installed screw matrix; d - resulting screw profile

3. Results and discussion

Metallographic studies of the resulting screw reinforcement profile, as well as those obtained on the SVP 14-40 radial-shear rolling mill, were carried out using a Quanta 200i 3D scanning electron microscope. The microstructure was studied in the center and on the periphery of the section of the obtained rods with a diameter of 24 mm and a screw profile. The results of metallographic studies are shown in Fig. 3.

An analysis of the microstructure evolution showed that the initial structure of the studs subjected to homogenizing annealing has a typical coarse-grained ferrite-pearlite structure with an average grain size lying in the range of 45-60 μm . The microstructure of the peripheral region of a 24 mm diameter bar obtained by radial-shear rolling has a predominantly equiaxed ultrafine-grained character with an average grain size in the range of 1.6-1.8 μm (Fig. 3a). Structural striation is observed in the central zone of these bars, i.e. grains elongated in the direction of rolling are observed with dimensions lying in the range of 6-10.5x1.1-17 μm (Fig. 3b). That is, a gradient structure was obtained in a 40X steel bar after radial shear rolling, as expected.

Analysis of the microstructure of 40X steel after the implementation of the second stage of deformation, i.e. after obtaining a screw profile, showed that by installing a screw matrix on a radial-shear rolling mill, we not only obtain a screw reinforcement profile, but also additionally modify the previously obtained gradient structure of 40X steel. At the same time, in the central and peripheral regions of the resulting screw reinforcement profile, the grain size has further decreased. In the peripheral region, the grain size decreased to an average size of 1.2-1.4 μm (Fig. 3c). In the central region of the resulting screw profile, grains elongated in the direction of rolling are also observed to a greater extent, due to the preliminary deformation of the initial studs according to the standard reversible radial-shear rolling scheme, but due to additional twisting of the rod and back pressure arising from the side of the screw matrix, a partial change in the structure previously obtained at the first stage occurred. In particular, in the central zone, a partial restructuring of the existing striped texture began to occur: most of the grains in this area also remained elongated, but their disorientation in directions appeared, and equiaxed grains were also observed in this area (Fig. 3d).

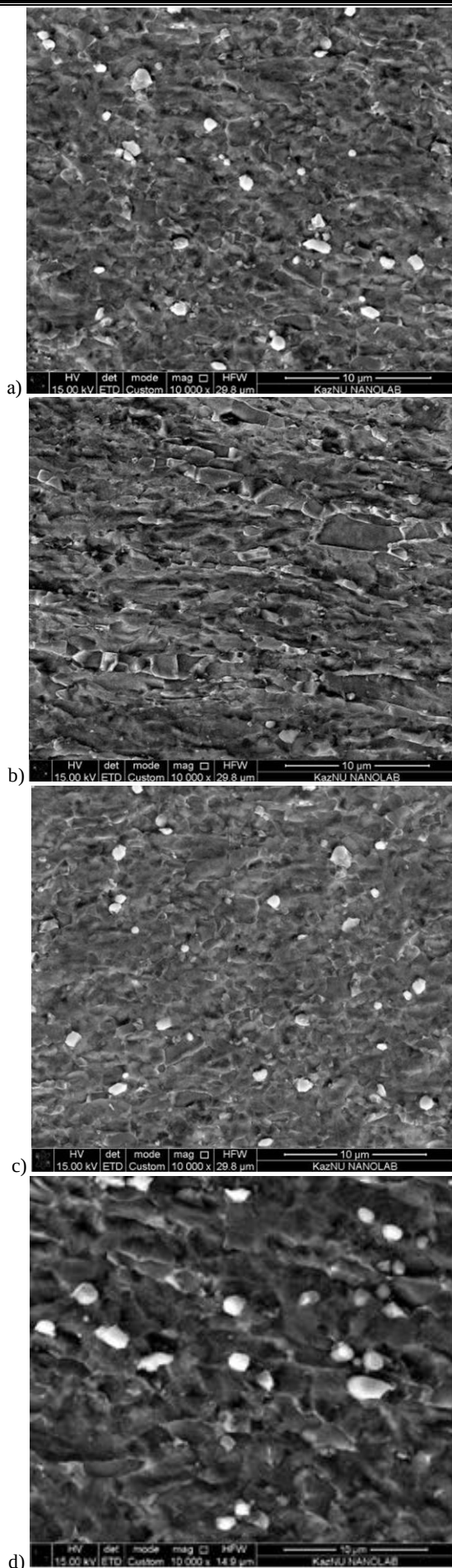


Fig. 3. Microstructure of 40X steel: a, b – periphery (a) and center (b) of the bar after radial-shear rolling to a diameter of 24 mm; c, d - periphery (c) and center (d) of the resulting screw reinforcement profile

Conclusion

The conducted research has proved in practice that the proposed combined technological process for obtaining a screw profile is feasible. This process can be used for recycling bar scrap of ferrous metals to obtain a finished commercial product in the form of a screw profile and, accordingly, it can be attributed to "green" technologies.

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A new Signal Panel with Led Edge lighting and uniform luminescence on both sides

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Abstract: The paper refers to an edge-lit LED signage panel able to provide uniform luminance on both sides of the visible surface. The panel structure is of a sandwich type, consisting of PMMA sheets, backlit films and printed self-adhesive film, all mounted within a slim aluminium frame. Illumination is achieved by means of a continuous rope-type LED strip positioned on the upper edge, while light uniformity is obtained through light transmission across the mass of the Plexiglas Edge Lighting material and through reflection from aluminium metallic films applied to the lateral sides. The panel ensures low energy consumption, has a very small thickness (10–15 mm), Wi-Fi connectivity, and modular cascade installation capability. It is intended for heavily trafficked indoor spaces, offering a modern, reliable and aesthetic solution for signage and advertising. The integrated configuration using Shelly Plus RGBW PM modules establishes a smart, energy-efficient, and remotely monitored signage system for interior spaces. This configuration is fully compatible with existing BMS infrastructure and scalable for future expansion across additional zones.

Keywords: LED SIGNAGE PANEL, UNIFORM LUMINANCE, MODULAR CONNECTIVITY, LOW ENERGY CONSUMPTION

1. Introduction

In airport or other crowded indoor spaces, the signage panels play an essential role in guiding and informing passengers. This article aims to present the advantages of an innovative signage panel product. Compared to classic systems in which lighting is achieved using bulbs arranged inside the panel, the proposed panels have a light source consisting of an LED light strip arranged on the inner surface of the upper side of the panel frame, the light being transferred to the entire surface of the panel, through acrylic materials. These panels are equipped with LED strips powered at 24V direct current (DC) and operate continuously 24/7 (Fig. 1).

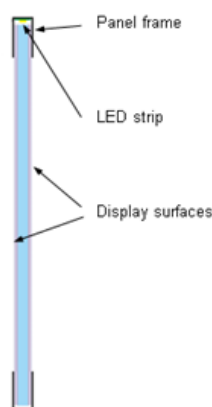


Fig. 1. Main parts of signage panel

The advantage of these panels is given by the advantages offered by the LED strip, namely: the lifespan of the LED strip is superior to classic bulbs, the possibility of implementing solutions for automatic adjustment of the light intensity depending on the ambient light level, without affecting the visibility of the displayed information, with the effect of optimizing energy consumption.

All solutions and patents encountered in the international literature propose different approaches, yet none manage to achieve uniform luminance on both sides due to interference in light transmission.

There are many solutions and technologies for obtaining signage panels, but these are based on multiple light sources or on transmission by reflection, without achieving uniform light transmission through the PMMA material mass with illumination from only one side of the panel, between the aluminum protective frame and the edge of the Plexiglas® material [1, 2, 3].

Advantages of the new signage panel:

- Low energy consumption through illumination with an LED strip positioned on the edge of the panel, on its upper side;
- Uniform illumination across the entire panel surface;

- Connectivity through a Wi-Fi module for easy operation management (on/off) and collection of electrical consumption data;
- Bidirectional visibility and dual display;
- High reliability and reduced maintenance;
- Slim assembly for the double-sided panel with acrylic front surfaces and a resistant aluminium frame (10–12 mm active/lighted section and 13–15 mm aluminium frame).

2. Energy consumption and laboratory tests

Modern airport terminal architecture uses solutions for ambient lighting in passenger access areas using both natural light by using generous glass wall surfaces and ceiling skylights but also artificial light. In this way, the ambient lighting of passenger access areas is variable during the day [4].

The objective is to ensure optimal visibility under varying ambient lighting conditions while achieving energy efficiency, operational reliability, and remote-control capability.

All signage panels operate using 24 V DC LED illumination systems, continuously powered for 24 hours a day.

During daylight hours or in well-lit areas, panel brightness can be reduced automatically, while it increases at night or in low-light conditions. To minimize power usage without compromising visibility and safety, the system includes a light intensity control strategy based on ambient lighting conditions.

Laboratory tests for the Chip-On-Board LED Panel [5, 6, ...,9]:

- Thermal testing – IR/thermocouple monitoring after 4h operation.
- Optical testing – luminance uniformity and photometric efficiency.
- Electrical testing – voltage/current stability and protection.
- Mechanical testing – vibration and protection (IP/IK).
- Field operation – install in a real setting such as an airport, mall, or other spaces with intense traffic.

In the Fig. 2 is presented the power supply testing: SELV power supply (e.g. BERGMEN Eco LED Compact power supply or LiFUD 24V, 30-100 W).



Fig. 2. Testing the panel power supply

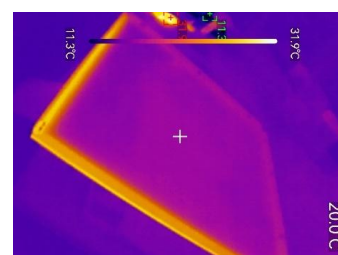


Fig. 3. Measuring the temperature of the illuminated panel

Measuring the temperature of the illuminated panel (Fig. 3) was another important test, based on power/meter of the LED strip lighting [10].

The temperature increasing due to LED strip lighting is calculated with the relation (1):

$$\Delta T = P_{\text{tot}} \times R_{\text{th}} \quad (1)$$

where:

P_{tot} = total dissipated power (W) = 10 W × length (m) (approx. — from Arelux data).

R_{th} = effective thermal resistance of the construction to air transfer (°C/W).

Quick calculations (ambient temperature 25 °C): 10 W/m.

The calculation of ΔT and the approximate surface temperature = 25°C + ΔT .

1 m ($P = 10$ W)

On aluminum ($R_{\text{th}} = 0.5$ °C/W): $\Delta T \approx 10 \times 0.5 = 5$ °C → surface temperature ≈ 30 °C.

On acrylic in the box ($R_{\text{th}} = 2$ °C/W): $\Delta T \approx 10 \times 2 = 20$ °C → surface temperature ≈ 45 °C.

3. System Architecture Overview

The use of lighting signage systems using LED strips is a solution that offers a reduction in energy consumption compared to classic systems with bulbs, and the management of the light intensity of these strips depending on the ambient lighting in the location where they are located can further reduce energy consumption, without affecting the visibility of the information they display.

The Table 1 shows the system components available with or without energy management.

Table 1: Panel characteristics according the 2 variants

	System without energy management	System with energy management
Power Supply Unit (PSU) 230 V AC / 24 V DC regulated converter	✓	✓
Illumination Source 24 V DC LED strips	✓	✓
Control and dimmer box installed on the low-voltage (24 V DC) circuit.		✓
Wireless Communication: Integrated 2.4 GHz Wi-Fi connectivity for remote management and data exchange		✓

Fig. 4 shows the power connections for both solutions, with and without energy management

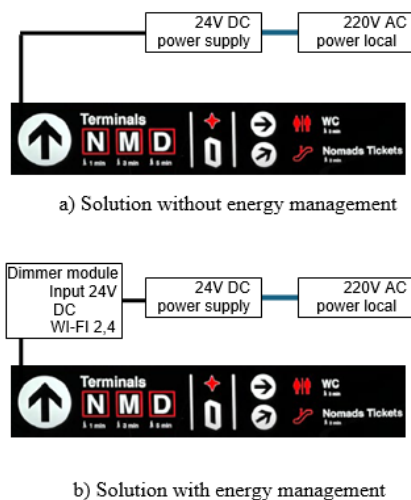


Fig. 4. Panel connections, with or without energy/brightness adjustment

The control and dimmer box is a smart module provide several key functions:

- Dimming Control – Allows fine adjustment of LED brightness levels via PWM (Pulse Width Modulation).
- Power Monitoring – Measures real-time voltage, current, and power consumption per signage panel.
- Remote Control – Enables remote adjustment of illumination parameters via a centralized management platform.

Currently there is a wide range of such modules and we used Shelly Plus RGBW PM. This is a controller for LED strips, operated manually via on/off inputs or remotely via Wi-Fi or Bluetooth, with 4 independent channel control capabilities of 4 white LED strips or one RGB strip.

Flexibility in operation is given by an integrated ESP32 processor which together with RAM and ROM memories supports loading and running of scripts, webhooks, MQTT, WebSocket, HTTPS, UDP, TLS and custom certificates. The custom operating logic is stored at the module level so that once loaded, the module operates without operator intervention according to the scripts.

It has functionalities that recommend it for controlling the brightness of airport signage panels, such as:

- Fine voltage control on the 4 outputs that can achieve a very sensitive dimmer of LED strips
- Real-time consumption measurement
- Internal temperature monitoring, overtemperature protection
- Overcurrent protection
- Connection to Wi-Fi routers without a dedicated hub
- Easy integration with open-source platforms

The module allows connection to Wi-Fi networks only in the 2.4 GHz band. It has an RF power < 4 dBm, which limits its distance from the router to 10m indoors and 30m outdoors.

The communication protocol used by the Shelley device is 4.2 (802.11n), a protocol that offers a higher data transfer speed and has improved cyber protection that protects against scanning the device's MAC address.

4. Control and Communication System

4.1 Network Topology

All modules connect to the airport's dedicated internal Wi-Fi network, segregated from public access networks and aligned with cybersecurity protocols.

Data from multiple devices is aggregated using one of the following methods:

- MQTT (Message Queuing Telemetry Transport) protocol with a central broker
- HTTP / REST API for direct data exchange with BMS servers

The communication interface allows two-way operation:

- Remote command transmission for brightness adjustment or reboot
- Data acquisition for performance analysis and trend visualization

4.2 Centralized Monitoring Dashboard

The remote interface consolidates operational data from all signage panels within a central dashboard. Core interface features include:

- Panel Identification: Unique ID, location, and associated area
- Real-Time Status: Operating mode, brightness percentage, current consumption
- Energy Analytics: Hourly/daily/weekly consumption graphs
- Remote Controls: Brightness adjustment, on/off switching, module restart

Access control is configured according to airport IT security standards with user authentication and role-based permission layers.

Module Setup and Integration Steps

1. Power Connection:

- Connect the 24 V DC output from the PSU to the Shelly module's input terminals.
 - Wire each LED strip channel (W or RGBW) through the module's output terminals.
2. Network Configuration:
 - Connect each module to the airport's Wi-Fi network using predefined SSID and encryption credentials.
 - Assign a static IP address or DHCP reservation for tracking.
 3. Control Calibration:
 - Set default brightness levels and dimming profiles via the web interface or Shelly Cloud App.
 - Integrate module endpoints into the central BMS using HTTP or MQTT configuration scripts.
 4. Testing and Validation:
 - Verify communication between the module and central dashboard.
 - Test light intensity variations over different ambient light scenarios.
 - Record baseline energy consumption profiles.

5. Operation and Maintenance

a) Routine Monitoring

Operators can view the system dashboard remotely to ensure all panels function within specified parameters. Automatic alerts are generated for:

- Excessive power consumption
- Disconnected modules
- Unexpected light intensity deviations
- Excessive overheating

b) Control Functionality

- Manual Control: Set brightness levels locally via web interface or mobile application.
- Automatic Control: Dimming schedules initiated via software based on time of day or sensor input.
- BMS Integration: The building management platform (e.g., via MQTT or HTTP REST) can dynamically adjust brightness zones according to real-time light sensor feedback.

c) Preventive Maintenance

The energy data trends can be used to identify aging LED strips or deteriorating power supplies that draw higher currents, enabling predictive maintenance scheduling.

d) Cascading and Group Control Options

The Shelly Plus RGBW PM modules allow flexible *cascade* (group or hierarchical) control modes to simplify the management of large panel systems. This enables centralized or zone-based adjustments without needing individual manual control of each unit.

The cascading (group control) function can be implemented in the following ways:

✓ Cloud / Platform-Based Cascading

- All modules connect to the Shelly Cloud or local MQTT broker.
- Zones (e.g., *Departures, Arrivals, Corridors*) are defined within the management interface.
- A single brightness command to the group automatically updates all assigned Shelly modules.
- Advantage: No local wiring between modules — uses Wi-Fi synchronization.
- Use Case: Ideal for large airports with multiple terminals and subzones.
- ✓ *Local Master-Slave Logic (LAN Cascading)*
- One Shelly module in a zone acts as a “local master.”

- Other modules receive instructions through the same network via direct API calls or MQTT subscription topics (e.g., *zone/Bright_A/set/#*).
- Advantage: Reduces cloud dependency and improves response speed.
- Use Case: For safety-critical areas requiring low-latency control, such as gate displays or emergency signage.
- ✓ *Hybrid Control*
- Combines both approaches:
 - Local master controls all panels in the zone.
 - Central BMS still monitors energy and overrides schedules when necessary.

Usual Case: Airport concourses with flexible configuration, seasonal layouts, or partial shutdown procedures.

The electrical and control architecture is presented in the Fig.5:

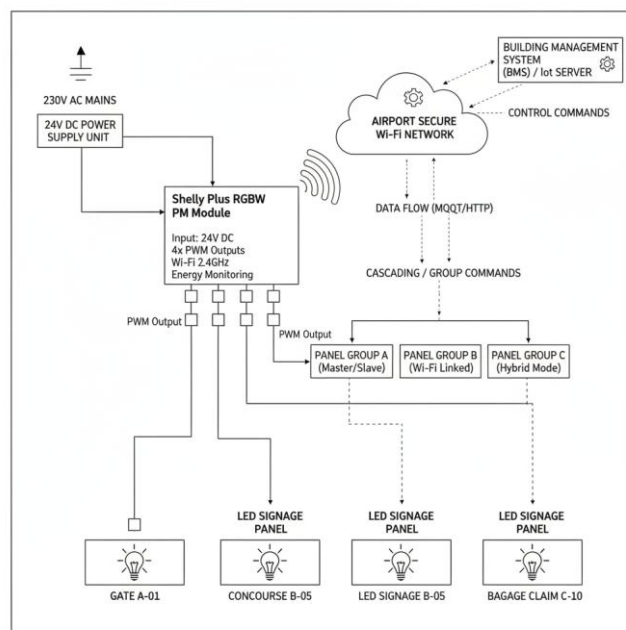


Fig. 5. Control network architecture in BMS

System Performance and Benefits are presented in the Table 2

Table 2. Description of the benefits of panels using WiFi and BMS integration

Benefit	Description
Energy Reduction	Up to 40 % load reduction via adaptive dimming
Centralized Control	Unified management of all zones via BMS or IoT platform
Scalable Infrastructure	Add new panels through Wi-Fi provisioning only
Predictive Maintenance	Early detection of LED degradation and PSU wear
Operational Resilience	Local cascading ensures function even during cloud outages

6. Case study

In a regional airport in Romania, with a traffic of 600,000 passengers in 2023, a new terminal was built with an area of 12,791 sq m. The organization of passenger flows at the new terminal required a number of 122 signage panels with lighting using COB LED light strips.

The signage panels are sized depending on the information displayed, the length and number of pieces being described in the Table 3.

As can be seen from the table above, 205.01 m of LED strip were integrated to illuminate the signage panels. At an average consumption of 12W per linear meter, the total energy consumption is 2.46 KW per operating hour, respectively 21550 KW per year.

Table 3. Case study for total length of the panels

No	Length (mm)	No of pieces	Total length (m)
1	1000	46	46
2	1500	13	19.5
3	1800	1	1.8
4	1850	3	5.55
5	2000	41	82
6	2520	8	20.16
7	3000	10	30
Total length (m)			205.01

At an average electricity cost of 0.3 EUR/KW, the annual cost of electricity consumed by the signage panels in the version without consumption management is approximately 6465 EUR.

In the energy consumption management variant using Shelly modules, considering that each module controls one panel on each of the 4 outputs (although the Shelly module can control 96W on each output, the equivalent of 8 ml LED strip), the required number of Shelly modules is 31 pieces. At an average cost of 27 EUR/piece, the total cost of the modules is 837 EUR.

Through this investment and a program adapted to the ambient lighting conditions inside the passenger terminal, a consumption reduction of about 35% could be achieved by reducing the light intensity of the LED strips. This consumption reduction represents 7500 KW/year, respectively 2250 EUR/year. As can be seen, an investment of 837 EUR, and minimal labor costs can achieve savings of 2250 EUR/year [11, 12].

7. Conclusion

By integrating Shelly Plus RGBW PM modules with cascading and hierarchical control logic, the airport achieves a fully smart, energy-efficient interior signage system. Each panel can be independently or group-controlled, synchronizing brightness and operating modes remotely through Wi-Fi and the BMS interface.

This approach ensures:

- Reliable signage illumination
- Measurable energy efficiency
- Scalable architecture ready for future smart-building integration.

The integrated configuration using Shelly Plus RGBW PM modules establishes a smart, energy-efficient, and remotely monitored signage system for interior spaces. By implementing PWM-based dimming control, automatic brightness adjustment, and real-time telemetry through Wi-Fi protocols, the airport achieves substantial energy optimization and enhanced maintenance oversight.

This configuration is fully compatible with existing BMS infrastructure and scalable for future expansion across additional zones.

Examples of applications:

- Signboards for airport terminals and public parking lots.
- Fixed light indicators for public spaces.

Limitation: Signboards cannot be placed outside buildings, in conditions of excessive humidity.

The panel is adapted for use in relevant environments (environment with intense human traffic, minimum temperatures 18°C-maximum 25°C, and relative humidity 30%-60%).

Advantages of the final prototype which is able to meet the TRL7 technological maturity conditions:

- Slim assembly, 10-15 mm thick for the 2-sided panel.
- Uniform lighting due to the way the LED strip is placed and the light transmission through the white layers of the materials used (white backlit film, white sticker, white ink or any white material) which makes the light uniform on the panel surfaces.
- Reduced energy consumption by using the COB LED strip.
- Smart connectivity via Wi-Fi module.
- Possibility of mounting multiple panels in cascade.
- Modern signaling panel, designed for heavily trafficked indoor spaces.



Fig. 6. Final prototypes with custom sizes, graphics and colors

The final prototypes with encapsulated graphics and example of colors are presented in the Fig. 6.

Acknowledgments

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Comparative tests of sprayed concrete, intended for repair and restoration works by dry and wet spraying

Part I: Physical and mechanical characteristics

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Abstract: The basic principles of sprayed concrete mix design are reviewed. The technological options for use of the material for repairs and restoration works, executed by “wet” and “dry” spraying methods, are analysed.

Widespread research program is developed and implemented for assessment of the main physical-mechanical and structural characteristics of sprayed concrete for repairs and restoration works. New (author's) compositions are prepared for this purpose, which are subjected to series of tests, together with factory made products, in form of dry mixes, by leading producer. Two compositions of sprayed concrete are chosen after preliminary selection – conventional for “dry” spraying and specially designed hybrid fiber-reinforced high-tech sprayed concrete for “wet” application method. The numerous additional components are included in the composition of the latter – high range water-reducing admixture based on polycarboxylate ether, polymeric modifier for enhancing of fresh mix compactness and rebound decreasing and new generation internal deep capillary-crystalline admixture.

Original scientific results are obtained concerning the basic physical-mechanical and stress-strain characteristics of both compositions of sprayed concrete. The critical comparative analysis of the results is presented and the right options for the application of the compositions are suggested.

Keywords: SPRAYED CONCRETE, DRY SPRAYING, WET SPRAYING, FIBER REINFORCEMENT, CAPILLARY CRYSTALLINE ADMIXTURE, STRENGTH AND MODULUS OF ELASTICITY, WATER IMPERMEABILITY AND FROST RESISTANCE

1. Introduction

The use of sprayed concrete is effective for restoring the cross-section, respectively to increase stiffness and load-bearing capacity of concrete and reinforced concrete structures [1,2]. With a properly designed composition and compliance with technological discipline during execution, sprayed concrete is characterized by high strength, density and impermeability, which is of paramount importance in ensuring the durability of the treated structures or individual structural elements.

In modern construction practice, two spraying methods are used - dry and wet once.

In the dry method, the constituent materials of the sprayed concrete are supplied separately - on the one hand, the dry components (cement, additives, fillers, fibers, etc.), and on the other - the water. The mixing of the components occurs in the air, during movement - between the spraying nozzle and the surface on which the concrete is layered. This technology allows for a low water-cement ratio, high strength and hence a reduced amount of cement required to guarantee the properties of hardened concrete. The main disadvantage is the influence of the human factor - the operator manually determines the amount of water, which is a prerequisite for unevenness of the composition of the concrete.

In the wet method, the concrete mix is prepared centrally at a concrete batching plant with the possibility of strict control of the composition of the concrete, plus the possibility of using many different components related to achieving certain characteristics of the concrete mix and hardened concrete.

2. Concrete mix design

The particle size composition of the aggregates in sprayed concrete is influenced by two main factors – physical and technological.

In order to achieve maximum volumetric concentration of the aggregates, minimal volumetric changes, high modulus of elasticity, durability, etc., it is necessary to use aggregates with a continuous particle size composition (**Fig. 1**). The above is also valid for ordinary concretes. To guarantee high adhesion to the base substrate (old concrete) and minimal rebound, it is necessary to ensure a

minimum of fine particles, up to 0,25 mm in size, in the range from 11 to 26%. This content of fine particles is significantly higher than in ordinary concretes, even those intended for placement with a concrete pump. The increased content of fine particles leads to a significant increase in the specific surface area of the aggregates and to increased cohesion of the concrete mix.

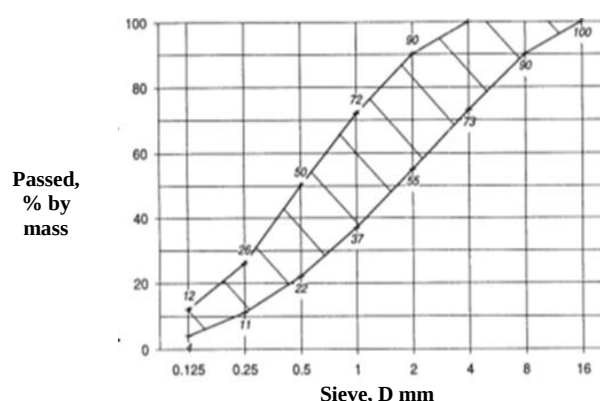


Fig.1 Recommended granulometric curve of aggregate for shotcrete, according to [3]

The coarse aggregate is in an amount of 0 to 25% of the total amount of aggregates, and its size should not exceed 16 mm. Most often, if coarse aggregate is used, a fraction of 4-8 mm is used and in a limited amount, due to the risk of increasing rebound (ricochet).

In the present case, after preliminary selection of the constituent materials, a design composition for **wet concrete (WS)** was prepared, i.e. in the form of a ready-mix fresh concrete mix.

Sulphate-resistant Portland cement CEM I 52,5R SR-5 was used, in an amount of 500 kg/m³. The amount of setting water is significantly reduced by using a highly water-reducing chemical admixture (HRWRA) based on polycarboxylate ester, which in this case acts extremely effectively, due to the high content of fine fractions in the mix. Additionally, a polymer modifier is introduced into the composition to increase the cohesiveness and compactness of the fresh concrete and reduce ricochet. By adding a new generation internal capillary crystallizer, absolute water impermeability of the hardened concrete is obtained. The addition

of fibers allows to improve the ductility, impact toughness, crack resistance and other important properties of the hardened concrete.

Parallel tests were also conducted on **sprayed concrete DS (commercial product)**, which is available as a ready-mix in bags.

3. Old concrete substrate preparing and spraying

The conditions that must be met when performing sprayed concrete in order to guarantee a satisfactory level of quality of the sprayed concrete are described in detail in **the EFNARC European Specification for Sprayed Concrete and BDS EN14487-2:2007 [4]**.

The sprayed concrete must be applied to a completely clean, rough, undisturbed and water-saturated surface. High-pressure water (hydro-blasting) or sandblasting are recommended for cleaning and roughening the base.

The location of spraying was selected and a pilot area was prepared by agreement between the interested parties for experimental application of the two shotcrete compositions - the one based on dry shotcrete **DS** and the one defined as a new technical proposal **WS** - for shotcrete by the "wet" method.

The applicators prepare the base for application - ensuring the parameters of the surface for shotcrete, including preliminary positioning and anchoring of a welded steel mesh, as well as its anti-corrosion protection. In this way, the necessary prerequisites for experimental application are created under the same conditions for both methods (**Photos 1 and 2**).

After all preliminary works 2 sprayed compositions are placed and smoothed out to the old concrete surface (**Photos 3-6**).



Photo 1



Photo 2



Photo 3 DS spraying



Photo 4 WS spraying



Photo 5



Photo 6

4. Concrete sampling

For the purposes of standardized sampling, in accordance with the requirements of **BDS EN 14488-1**, to prove the technical characteristics of the two compositions compared, the necessary formwork was provided in advance - wooden crates for forming the so-called "pies", on which spraying was performed, and from them the necessary test-cores were later cut by drilling to prove the technical characteristics of the two compositions. From the obtained "pies" were cut drilling cores with a diameter of 100 mm and a height equal to the laid layer of shotcrete - respectively 150 and 200 mm (**Photos 7 and 8**).

From the drilling cores, by cutting and aligning, cylindrical test bodies with a base diameter of 100 mm and a height of 100 mm and 200 mm were obtained. The test specimens are stored under laboratory conditions and tested at two, previously agreed ages - 7 days and 28 days.



Photo 7



Photo 8

The indicators of the main mechanical characteristics of the hardened concrete - compressive strength, stabilized modulus of elasticity under compression, ultrasonic pulse propagation velocity, etc., are determined, which allow predicting the behavior and durability of the restored structure.

5. Test results

All tests were conducted at the **University Construction Testing Laboratory (UCTL), University of Architecture, Construction and Geodesy, Sofia**, which holds a valid accreditation certificate for the relevant standardized methods.

5.1. Compressive strength

Since the compressive strength is determined by testing cores of different sizes, the procedure provides for the use of correction factors for the size of the cores taken according to **Table NA.4 of BDS EN 206/NA:2021 (Table 1)**. The volume density was calculated after measuring the exact dimensions of the test specimens.

The results obtained are presented in **Table 1**.

Table 1 Compressive strength

Compositions	Volume density, (kg/m ³) at		Compressive strength, (MPa) at	
	7 days	28 days	7 days	28 days
DS	2236	2225	36,10	43,80
	2212	2220	32,20	45,90
	2237	2233	33,90	43,00
	mean: 2230	mean: 2230	mean: 34,00	mean: 44,20
WS	2322	2292	49,50	57,40
	2305	2306	55,30	60,60
	2316	2290	51,10	62,40
	mean: 2320	mean: 2300	mean: 51,90	mean: 60,10

5.2. Determination of ultrasonic pulse velocity

The determination is carried out in accordance with the requirements of **BDS EN 12504-4:2005 (Photo 9)**. The test methodology is mainly related to determining the time for the passage of the ultrasonic pulse through the concrete cross-section and determining the speed of its propagation. The speed of sound propagation is directly dependent on the so-called dynamic modulus of elasticity and the density of the concrete, which is a determining factor for its compressive strength.

$$v = \sqrt{\frac{K.E_d}{\rho}}$$

v - ultrasonic pulse velocity, km/s;
 E_d - dynamic module of elasticity of the concrete, MPa;
 P - concrete density, kg/m³;
 K - correction coefficient

$$K = \frac{1 - \mu}{(1 + \mu)(1 - 2\mu)},$$

μ - concrete Poisson's coefficient, equal to 0,2 (in accordance of Eurocode 2)



Photo 7



Photo 8

Table 2 Concrete ultrasonic speed velocity

Compositions	Concrete ultrasonic speed velocity, (km/s), at	
	7 days	28 days
DS	4,184	4,292
	4,237	4,405
	4,184	4,301
	mean: 4,202	mean: 4,333
WS	4,619	4,684
	4,484	4,515
	4,246	4,329
	mean: 4,450	mean: 4,509

5.3. Stabilized static modulus of elasticity in compression

The determination of the stabilized static modulus of elasticity under compression is carried out according to the requirements of **BDS EN 12390-13 - method "B"**, which in this part is practically identical to **ISO 1920-10 (Photo 10)**.

Cylindrical test specimens were used, cut from the structure with a base diameter to height ratio equal to 1:2.

Test results are presented in **Table 3**.

Table 3 Static modulus of elasticity

Compositions	Stabilized static modulus of elasticity in compression (GPa), at	
	7 days	28 days
DS	24,20	29,60
	23,70	29,10
	24,10	27,60
	mean: 24,00	mean: 28,80
WS	36,40	37,60
	35,00	37,30
	35,90	36,80
	mean: 35,80	mean: 37,20

5.4. Depth of penetration of water under pressure

The test was conducted according to **BDS EN 12390-8 (Photo 11)**.

The test specimens used were cylinders, with a diameter and height of 150 mm. The measured water penetration depths are shown in **Table 4**.



Photo 9



Photo 10

Table 4 Depth of penetration of water under pressure

Composition	Depth of penetration of water under pressure, mm, at	
	7 days	28 days
DS	48	36
	38	32
	46	38
	mean: 44	mean: 35
WS	38	22
	38	16
	25	21
	mean: 34	mean: 20

5.5. Splitting tensile strength

The test was conducted according to **BDS EN 12390-6** and the results obtained are shown in **Table 5**.

Table 5 Splitting tensile strength

Composition	Splitting tensile strength, (MPa), at	
	7 days	28 days
DS	2,09	3,51
	1,81	3,20
	2,15	2,83
	mean: 2,02	mean: 3,18
WS	2,82	3,43
	2,21	3,40
	2,15	3,34
	mean: 2,39	mean: 3,39

5.6. Frost-resistance by accelerated method

Frost resistance is determined in accordance with the requirements of **BDS EN 206:2013 +A2:2021/NA:2021 NA.O.2** Accelerated method for determining the frost resistance of hardened concrete by freezing and thawing in a sodium chloride solution.

The test specimens are saturated, frozen and thawed in an aqueous sodium chloride solution in a refrigeration chamber capable of maintaining a temperature lower than minus 35°C (-35°C), preferably down to minus 50°C. The mass of the test specimens is measured with a balance with an accuracy of ± 0,1g and a range of not less than 50% more than the mass of the test specimens;

The test specimens are dried to a constant mass, then saturated with a 5% sodium chloride solution. At least one freezing and thawing cycle is performed within one day. The test is performed continuously. In case of forced interruption, the test bodies are stored in a 5% sodium chloride solution.

Test results are shown in **Table 6 and Photos 13 and 14**.



Photo 13 WS sample's general view after 5 cycles, zero mass lost



Photo 14 DS sample's general view after 5 cycles, mass lost

Table 6 Frost-resistance by accelerated method

Composition	Mass lost, %, after	
	4 cycles (equivalent frost resistance class $C_{fr} 150$)	5 cycles (equivalent frost resistance class $C_{fr} 200$)
DS	1,00	3,10
	1,70	3,00
	0,80	3,20
	mean: 1,20<2,00 (approved for $C_{fr} 150$)	mean: 3,10>2,00 (not approved for $C_{fr} 200$)
WS	0,00	0,30
	0,00	0,30
	0,00	0,40
	mean: 0,00<2,00 (approved for $C_{fr} 150$)	mean: 0,30<2,00 (approved for $C_{fr} 200$)

6. Conclusions

The results obtained from the standardized tests conducted on the two sprayed concrete compositions allow the following important findings and comments to be made:

- compared to the composition for "dry" spraying **DS**, the proposed composition **WS** has a higher volume density at 7 and 28 days of age, and also demonstrates higher compressive strength and tensile strength at splitting at the studied ages;

- the proposed composition for "wet" spraying **WS** shows a higher ultrasound propagation speed at 7 and 28 days of age, which is directly related to its higher strength indicators at the studied ages;

- the proposed composition **WS** shows significantly higher values of the studied stabilized modulus of elastic deformations under compressive loading at the two studied ages;

- the proposed composition for **WS** shows significantly lower permeability, which is expected to decrease further (to 0) after periodic treatment with water under pressure, due to the presence of a capillary crystallizer;

- compared to the composition for "dry" spraying **DS**, the proposed composition **WS** demonstrates the highest frost resistance class $C_{fr}200$ with proven insignificant mass loss. at the same time, the composition **DS** meets the lower requirements for frost resistance class $C_{fr}150$.

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МКЭ МОДЕЛИРОВАНИЕ ЭВОЛЮЦИИ МИКРОСТРУКТУРЫ В ХОДЕ ОДНОПРИВОДНОЙ АСИММЕТРИЧНОЙ ПРОКАТКИ ТОЛСТОГО ЛИСТА В РЕЛЬЕФНЫХ ВАЛКАХ

FEM MODELING OF MICROSTRUCTURE EVOLUTION DURING SINGLE-DRIVE ASYMMETRIC ROLLING OF THICK SHEET IN RELIEF ROLLS

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Abstract: The paper presented the results of microstructure evolution obtained by finite-element modeling in the DEFORM program for a new concept of asymmetric rolling in relief rolls - single-drive rolling, in which one of the rolls is driven and the other roll is idled. After rolling in relief rolls, the billet undergoes two-stage leveling in smooth rolls. The presence of a single driven roll with the ability to adjust its rotational speed allows for a higher asymmetry coefficient. The microstructure evolution was evaluated using the Cellular Automata method, which allows for the assessment of changes in both grain size and shape. It was found that using a billet with a heating temperature of 700°C is the most preferable option, as it eliminates the negative effect of static recrystallization.

Keywords: ASYMMETRIC ROLLING, RELIEF ROLLS, FEM, MICROSTRUCTURE EVOLUTION.

1. Введение

Одним из перспективных высокотехнологичным способом получения высококачественных металлоизделий в виде горячекатаного листа и толстых плит уже не одно десятилетие является асимметричная прокатка, в процессе которой в деформируемом материале реализуются дополнительные потоки деформации сдвига [1]. Наиболее распространенными видами асимметричной прокатки являются кинематическая (разные скорости вращения валков), геометрическая (разные диаметры валков) и использования валка без привода (холостого хода), как показано на рис. 1 [2, 3]. Во время асимметричной тонколистовой прокатки возникают дополнительные деформации сдвига, которые в сочетании с деформациями сжатия могут обеспечить эффективное структурное измельчение зерен.

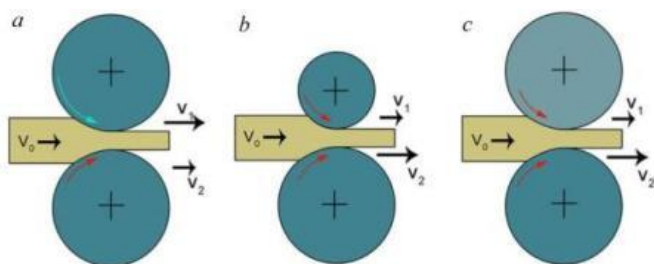


Рис. 1. Варианты асимметричной прокатки: а – в валках с разными окружными скоростями; б – в валках разного диаметра; в – с одним валком без привода

При этом необходимо отметить, что оба наиболее распространенных способа реализации асимметричной прокатки (геометрический и кинематический) имеют свои технологические недостатки. Реализация геометрической асимметрии при прокатке широкого сортамента толстолистового проката требует изготовления целого парка валков различного диаметра. Также хочется отметить, что при геометрической асимметрии чаще всего невозможно добиться высокого значения коэффициента асимметрии по причине ограничения диапазона диаметров валков конструктивными габаритами станины. Реализация кинематической асимметрии не имеет явных ограничений коэффициента асимметрии и зависит от возможности регулирования скоростей электродвигателей. Однако для данного варианта асимметрии необходима кардинальная реконструкция прокатного стана путем обеспечения индивидуального привода валков с

возможностью регулировки окружных скоростей каждого рабочего валка по отдельности.

Альтернативным решением данных недостатков может стать вариант прокатки с одним приводным валком [4], который позволит еще больше повысить технологичность процесса получения высококачественных металлоизделий в виде горячекатаного листа и толстых плит. В этом случае достаточно физически отсоединить один валок от системы привода, что не потребует существенной модернизации прокатного стана.

Поэтому предлагается следующая концепция нового способа асимметричной прокатки. Первый проход осуществляется в рельефных валках с фактором асимметрии (геометрическим или кинематическим). При этом лишь один из валков является приводным, второй валок является холостым и приводится во вращение за счет сил трения при контакте с движущейся заготовкой.

Целью данной работы было моделирование эволюции микроструктуры стальной заготовки при реализации одноприводной асимметричной прокатки толстого листа в рельефных валках для оценки измельчения зерна.

2. Методика моделирования

В данной работе было решено проводить все теоретические исследования в программе DEFORM, как наиболее активно развивающемся продукте в области моделирования процессов ОМД. Заготовку решено деформировать на стане в Карагандинском индустриальном университете, где ранее были успешно проведены эксперименты по деформированию алюминиевых и медных заготовок аналогичной толщины [5]. При этом на лабораторном стане имеется возможность прокатки как в симметричном режиме (оба валка диаметром 200 мм), так и в асимметричном режиме с коэффициентом асимметрии 1,5 (диаметр верхнего валка 200, диаметр нижнего валка 300 мм).

В качестве варьируемого технологического параметра была выбрана температура заготовки, которая оказывает существенное влияние как на напряженное состояние при деформировании, так и на процесс рекристаллизации. Поскольку в данном исследовании используется обычная сталь марки AISI 1015, то были выбраны следующие значения температуры: 1100°C (горячая прокатка с протеканием статической рекристаллизации) и 700°C (горячая прокатка без активации механизма статической рекристаллизации).

Конструкция рельефной поверхности валков представлена на рис. 2. Длина бочки валков равна 400 мм. Диаметр гладких

валков для выравнивания заготовки равен 200 мм. Заготовка представляет собой лист прямоугольной формы сечением 10 х 300 мм и длиной 350 мм.

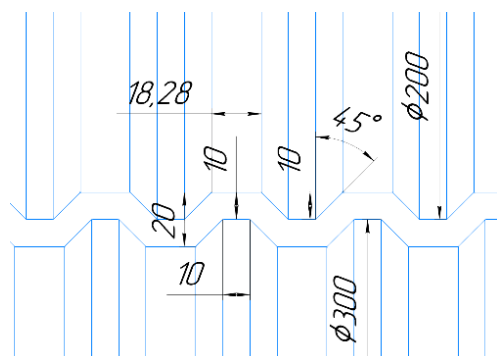


Рис. 2. Конструкция рельефных валков для прокатки заготовки толщиной 10 мм

В качестве материала для заготовки была выбрана сталь марки AISI 1015. При компьютерном моделировании процесса использовались следующие технологические параметры:

- материал заготовки был полностью изотропным;
- прокатка проводилась при температуре окружающей среды 20°C;
- коэффициент теплообмена заготовки с инструментом составлял $5000 \text{ Вт} \cdot \text{м}^{-2} \cdot \text{°C}^{-1}$;
- коэффициент теплообмена заготовки с окружающей средой составлял $0,002 \text{ Вт} \cdot \text{м}^{-2} \cdot \text{°C}^{-1}$;
- для создания максимально жестких условий захвата коэффициент трения на контакте металла с валками был принят 0,7 (что соответствует закругленной поверхности с насечкой и высоким уровнем шероховатости).

Для создания сетки конечных элементов были задействованы адаптивные настройки решателя. Вместо фиксированного числа конечных элементов было указана минимальная величина грани тетрагонального элемента, равная 1,5 мм. Таким образом, при любом перестроении сетки по толщине заготовки всегда будут минимум 6 элементов. Этого количества элементов по толщине вполне достаточно для адекватного отображения формоизменения. Поскольку конструкция зазора в рельефных валках подразумевает максимальное значение амплитуды заготовки, равное двойной толщине, то зазоры для выравнивания на втором и третьем проходе были установлены в 25% и 50% соответственно, т.е. для заготовки толщиной 10 мм во втором проходе зазор был равен 15 мм, а в третьем проходе – 10 мм.

3. Результаты и обсуждение

Для отображения результатов моделирования были заданы установки окна: формат – квадратное, размерами 150 на 150 мкм. В качестве исходной структуры металла в отожженном состоянии было задано равноосное расположение зерен со средним размером 40 мкм (Рис. 3).

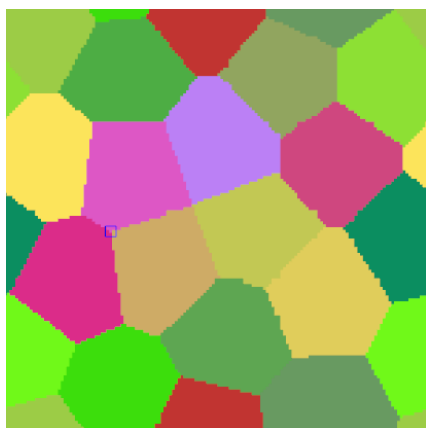


Рис. 3. Исходная микроструктура

На рис. 4 представлены результаты изменения размера зерна после одноприводной асимметричной прокатки при двух температурах. Численные значения среднего размера зерен при одноприводной прокатке для заготовки толщиной 10 мм представлены в таблице 3.

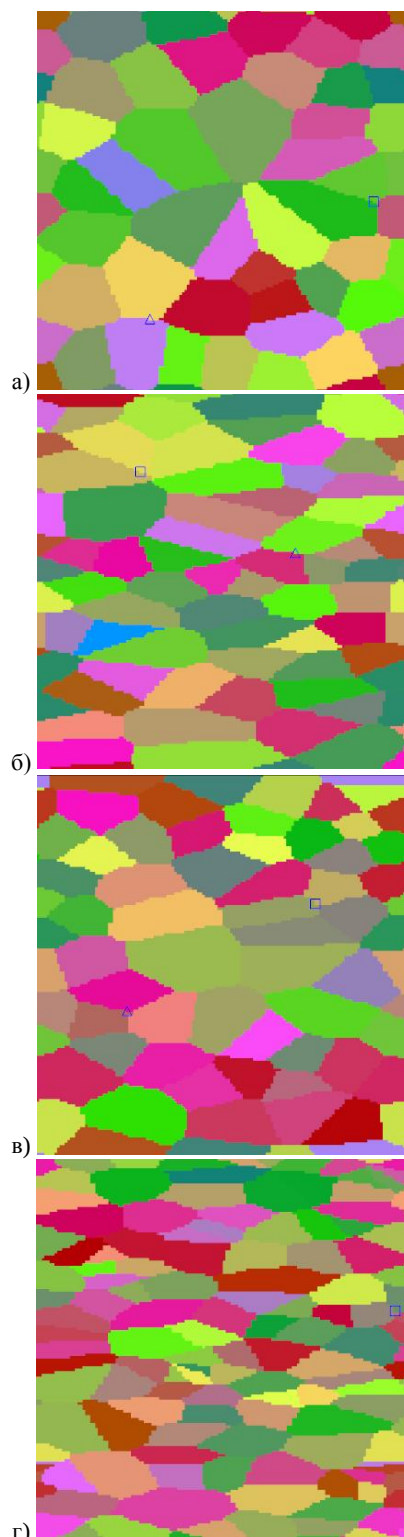


Рис. 4. Микроструктура в продольном сечении заготовки толщиной 10 мм при одноприводной прокатке: а – центр при 1100°C; б – поверхность при 1100°C; в – центр при 700°C; г – поверхность при 700°C

Таблица 1. Средний размер зерен для заготовки толщиной 10 мм при одноприводной прокатке, мкм.

Модель прокатки	Центр	Поверхность
Одноприводная, 1100°C	25	21
Одноприводная, 700°C	22	16

При рассмотрении результатов по одноприводной прокатке можно отметить следующие нюансы:

1) при пониженной температуре общий уровень измельчения зерна является более интенсивным по причине отсутствия эффекта статической рекристаллизации;

2) вытянутость зерен наблюдается при обеих температурах, однако в модели при 700°C вытянутость зерен более выражена за счет отсутствия статической рекристаллизации;

3) в модели при 700°C поверхностные слои получают уровень измельчения 55-60 % от начального размера зерна, тогда как в центральных слоях измельчение значительно ниже. Это является результатом воздействия высокого уровня асимметрии и отсутствия статической рекристаллизации.

Оценка эволюции микроструктуры показало, что использование заготовки с температурой нагрева 700°C является наиболее предпочтительным вариантом, так как в этом случае отсутствует негативный эффект статической рекристаллизации. Также при данной температуре реализация одноприводного варианта деформирования позволяет в наивысшей степени измельчить исходное зерно.

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Optimization of natural gas reforming parameters in the midrex process to increase hydrogen yield and reduce fuel consumption

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Abstract. In this paper, a comprehensive analysis of the process of natural gas reform in MIDREX technology was carried out, which was aimed at optimizing this process in order to increase hydrogen yield, reduce the specific consumption of natural gas and minimize the risks of soot formation. The paper also calculates the thermal balance, combined steam-carbon dioxide reforming (SMR + DRM). Based on the conducted studies, optimal reforming modes were determined: gas outlet temperature $\sim 915\text{--}920^\circ\text{C}$; $\text{H}_2\text{O}/\text{C} \sim 1.8$; increased CO_2 fraction. Switching to an optimized reforming mode reduces natural gas consumption by 5.5%, increases H_2 output by 6.4%, and reduces CO_2 emissions due to better energy efficiency and H_2 addition potential. The results obtained in this work are useful for upgrading existing Midrex installations in the direction of decarbonization, including the transition to MIDREX Flex/ H_2 technologies.

Keywords: DIRECT REDUCTION OF IRON, MIDREX PROCESS, CATALYTIC REFORMING, HYDROGEN, ENERGY EFFICIENCY, THERMODYNAMICS, CARBON FOOTPRINT.

1. Introduction

In the context of global decarbonization of metallurgy (Paris Agreement, IEA Iron and Steel Technology Roadmap), the global metallurgical industry is undergoing a profound transformation due to the simultaneous increase in energy costs, stricter environmental requirements, and the need to reduce greenhouse gas emissions. In this context, direct reduction of iron (Direct Reduced Iron, (DRI)) technologies are considered as one of the key alternatives to traditional blast furnace processing [1, 2]. Among these technologies, MIDREX technology holds a dominant position, providing more than 60% of the global production of DRI and HBI (Hot Briquetted Iron) using natural gas as a source of reducing agents ($\text{H}_2 + \text{CO}$), as evidenced by statistical data and analytical reviews from recent years [1-3].

The key feature of the MIDREX process (Fig. 1) is the use of reducing gas generated directly at the plant through catalytic reforming of natural gas using the recycled gas from the blast furnace. Unlike the classic steam reforming schemes used in the chemical industry for producing hydrogen, the MIDREX reformer operates under complex multi-component raw material conditions, including significant concentrations of CO_2 and H_2O [3, 4]. This fundamentally changes the nature of the reactions and the thermal balance of the unit. The reformer is a key component that determines the quality of the gas ($\text{H}_2/\text{CO} \sim 1.6\text{--}1.8$), energy consumption (30–40% of the cost), and CO_2 emissions. Current trends include the addition of hydrogen (MIDREX NG with H_2 up to 30–100%, MIDREX H_2) [5-8] to reduce CO_2 by 35–95% compared to (Blast Furnace / Basic Oxygen Furnace, (BF/BOF)).

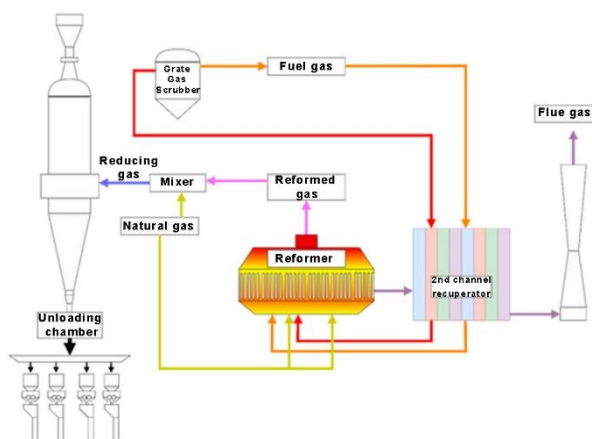


Fig. 1. Schematic representation of combined steam-carbon dioxide reforming in the MIDREX process

An analysis of the scientific and technical literature shows that the fundamental principles of catalytic steam reforming of methane were established in the works of Rostrup-Nielsen, Froment, and

Trimme, which provided detailed studies of the kinetics and thermodynamics of the SMR (Steam Methane Reforming) and WGS (Water–Gas Shift) reactions on nickel catalysts [9–13]. These studies continue to serve as the basis for calculations and modeling of industrial reformers. However, more recent publications have shown that the presence of carbon dioxide in the feedstock activates the DRM (Dry Reforming of Methane) reactions, leading to the formation of the so-called combined reforming of methane [13–17].

Several authors have emphasized that DRM, on the one hand, contributes to the utilization of CO_2 and the formation of carbon monoxide, which is necessary for the carbonization of DRI, while on the other hand, it reduces the H_2/CO ratio and increases the risk of soot formation [15]. The authors of [16–19] have demonstrated that the stability of nickel catalysts under combined reforming conditions is determined not only by the average ratio of oxidants to carbon, but also by the local conditions of heat and mass transfer in the reaction tubes. The industrial aspects of MIDREX reformers are well documented in numerous technical reports and publications by technology developers, including those related to the modeling and optimization of existing installations [20]. These studies have highlighted that operators often use elevated steam ratios as a protective measure against soot formation and catalyst degradation. However, this approach leads to increased fuel consumption, increased heat load on the furnace, and reduced energy efficiency of the entire system [21]. An analysis of the current state of the art reveals that a significant portion of existing research is either fundamental in nature and does not take into account the specific gas composition of MIDREX, or focuses on specific operational aspects without comprehensive thermodynamic analysis. The literature lacks systematic data on the combined effects of temperature, pressure, and $\text{H}_2\text{O}/\text{C}$ and CO_2/C ratios on hydrogen yield, H_2/CO ratio, and natural gas consumption specifically in the context of MIDREX industrial reformers [27, 28, 32, 33].

Thus, the relevance of this study is due to the need for a comprehensive analysis of the process of combined steam-carbon dioxide reforming of natural gas, taking into account the actual operating conditions of MIDREX units. The results of such an analysis will not only clarify the theoretical understanding of the processes involved, but also provide practical recommendations aimed at improving energy efficiency, reducing fuel consumption, and minimizing the carbon footprint of DRI production. The goal of this work is to determine the optimal parameters for reforming natural gas in the MIDREX process, which will increase the yield of hydrogen and reduce the specific fuel consumption.

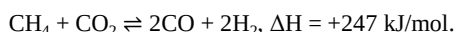
2. Theoretical foundations of the process

The process of producing reducing gas in the MIDREX technology is based on the catalytic conversion of natural gas in the presence of the oxidizing components of the shaft furnace recycle gas. Unlike classical steam reforming, where the initial raw material is a binary system of methane and water vapor, the MIDREX

reformer uses a multi-component reaction medium that includes CH_4 , H_2O , CO_2 , H_2 , and CO . This allows for the simultaneous occurrence of several interconnected chemical reactions that form a complex thermodynamic and kinetic equilibrium of the process. Steam Methane Reforming (SMR) plays a crucial role in determining the composition of the reducing gas:



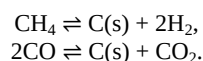
This reaction is highly endothermic and is accompanied by an increase in the number of gas moles, which, according to Le Chatelier's principle, requires high temperatures and relatively low pressure to shift the equilibrium towards the formation of hydrogen. SMR provides the main contribution to the generation of H_2 in the reformed gas. In addition to SMR, dry reforming of methane (DRM) becomes significant in the MIDREX process:



The increased endothermicity of DRM compared to SMR makes it highly sensitive to temperature. This reaction leads to an increase in CO content and a decrease in the H_2/CO ratio, which is important for achieving the desired conditions for direct reduction carbonization of iron. The Water Gas Shift (WGS) reaction also has an impact on the gas composition:



At temperatures typical for the MIDREX reformer outlet zone (850–920°C), the WGS equilibrium is shifted towards the formation of CO . However, at elevated vapor ratios, this reaction can contribute to additional hydrogen generation and simultaneously affect the partial pressures of CO and CO_2 . The combination of these reactions forms the so-called combined steam-carbon dioxide reforming, where SMR and DRM occur in parallel, and WGS acts as a balancing mechanism for redistributing the components of the reducing gas. One of the key limitations of the reforming process is the formation of solid carbon on the surface of nickel catalysts, which leads to their deactivation and increases the hydraulic resistance of the reaction tubes. Thermodynamically, soot formation is possible through the cracking of methane and the Budau reaction [27, 28, 39]:



The probability of these reactions increases at lower values of the oxidizer-to-carbon ratio (O/C) and local temperature inhomogeneities in the gas inlet zone of the reaction tubes [13–15]. As can be seen from the thermodynamic carbon stability diagram (Fig. 2), reducing the O/C ratio at the operating temperatures of the reformer leads to the process entering the region of thermodynamically possible soot formation. Modern studies show that the stability of nickel catalysts is determined not only by the average values of process parameters, but also by the local conditions of heat and mass transfer, as well as the uniformity of flow distribution in the tube bundle [16,18]. An additional risk factor is the presence of sulfur compounds, even in trace concentrations, which can lead to rapid passivation of nickel active sites. Therefore, the theoretical analysis of the MIDREX reforming process should take into account the combined effects of the thermodynamics of the main reactions, kinetic limitations, and catalyst deactivation factors, which is essential for subsequent optimization of process parameters.

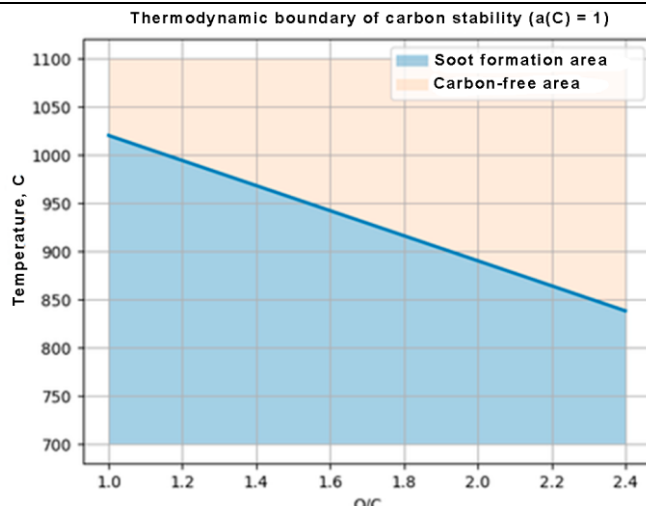


Fig. 2. Thermodynamic boundary of soot formation

Although thermodynamics determines the maximum possible concentrations, the actual composition of the gas at the reformer outlet depends on the kinetics (catalyst activity and contact time). In industrial conditions, the Midrex process is carried out at gas outlet temperatures of 850–920°C. This results in a residual methane (CH_4) content in the reformed gas of 0.5–1%. A decrease in catalyst activity or a drop in flue gas temperature leads to an increase in methane slip, which is equivalent to a loss of fuel and a decrease in H_2 yield.

3. Impact of technological parameters on the reforming efficiency

The effectiveness of the reform process in MIDREX technology is determined by the cumulative effect of temperature, pressure, and molar ratios of the components of the gas mixture. Unlike isolated chemical and technological processes, the MIDREX reformer functions as part of a single thermochemical system that is tightly coupled to the operating mode of the shaft furnace, which imposes additional restrictions on the choice of optimal parameters.

The influence of temperature. Temperature is a determining factor affecting the degree of methane conversion and the equilibrium composition of the reducing gas. The endothermic nature of steam and carbon dioxide reforming reactions causes a shift in equilibrium towards the formation of hydrogen and carbon monoxide with increasing temperature. According to thermodynamic calculations and industrial observations, an increase in the temperature of the gas outlet from the reformer to 900–920°C reduces the residual methane content to 0.5–1.0% vol., which corresponds to the rational use of chemical energy of the fuel [20, 22]. An increase in temperature leads to a shift in the equilibrium of the endothermic reactions of SMR and DRM towards the formation of H_2 and CO , which is accompanied by a decrease in the residual methane content (Fig. 3).

At the same time, an excessive increase in temperature leads to an increase in thermal stresses in the reformer pipes and accelerated degradation of the catalyst, which limits the upper limit of the operating range. Thus, the temperature regime of the reforming should be considered as a compromise between maximum methane conversion and the durability of the equipment. The influence of pressure. From a thermodynamic point of view, an increase in pressure has a negative effect on the SMR and DRM reactions, accompanied by an increase in the number of moles of gas. However, under MIDREX conditions, the choice of pressure is determined not only by chemical equilibrium, but also by the requirements of the gas dynamics of the shaft furnace, ensuring stable counterflow and preventing air intake.

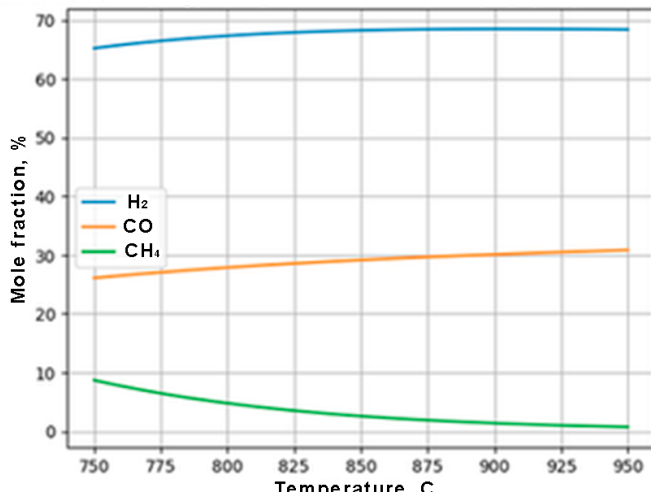


Fig. 3. Influence of temperature on the equilibrium composition of the reformed gas

Operational practice shows that the optimal reforming pressure range is formed based on minimizing conversion losses while maintaining stable operation of the entire gas circuit. In this context, the effectiveness of reforming should be assessed not by the absolute degree of methane conversion, but by the integral energy effect for the entire conversion [22, 25, 28]. The effect of the H_2O/C and CO_2/C ratios. The steam/carbon and CO_2 /carbon ratios have a complex effect on the synthesis gas composition, the risk of soot formation, and the stability of the catalyst. An increase in H_2O/C helps to suppress methane cracking and the Boudoir reaction, reducing the likelihood of carbonaceous deposits. However, an excessive steam ratio leads to an increase in the thermal costs of water evaporation and a decrease in the concentration of reducing components in the gas.

The presence of CO_2 activates DRM reactions, which promotes the utilization of carbon dioxide and the formation of CO necessary for the carburization of DRI [14, 15]. At the same time, an excessive increase in CO_2/C reduces the H_2/CO ratio and may worsen the reduction potential of the gas [18]. Studies show that the optimal range for MIDREX industrial installations is $H_2O/C=1.6$ – 1.8 with a controlled CO_2 content providing an H_2/CO ratio of the order of 1.6 – 1.8 [21–23]. From the calculated thermodynamic map (Fig. 4) it follows that an increase in the vapor ratio leads to an increase in H_2/CO , while an increase in the proportion of CO_2 in the gas mixture has the opposite effect, reducing the reduction potential of the gas. Thus, the efficiency of reforming is determined not by the extreme values of individual parameters, but by their consistent combination, ensuring the thermodynamic stability of the process, minimal risk of deactivation of the catalyst and the required quality of the reducing gas.

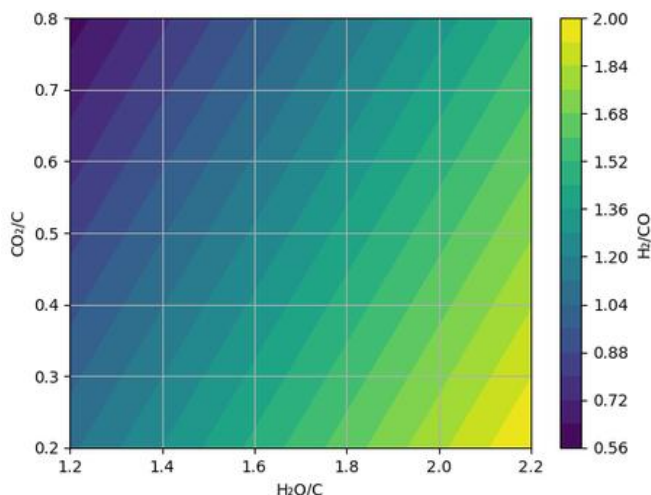


Fig. 4. Thermodynamic map of the ratio H_2/CO

4. Calculation of thermal balance and parameters optimization

To evaluate the effectiveness of the proposed approaches, the thermal balance of a standard Midrex reformer pipe (diameter 280 mm, core length 10 m) was calculated at a module capacity of 257 t/h DRI. The heat balance was calculated using the equation:

$$Q_{\text{total}} = Q_{\text{reaction}} + Q_{\text{sensible}} + Q_{\text{loss}}$$

where Q_{reaction} – the sum of the enthalpies of SMR (+206 kJ/mol) and DRM (+247 kJ/mol) reactions multiplied by the degree of conversion;

Q_{sensible} – the heat spent on heating the gas mixture from the inlet temperature ($T_{\text{in}} \approx 450^\circ\text{C}$) to the outlet temperature (T_{out});

Q_{loss} – heat losses (assumed 2% of the supplied power).

Two operating modes were modeled:

- basic mode (conservative): $T_{\text{out}} = 880^\circ\text{C}$, high steam ratio ($H_2O/C = 2.5$) to guarantee against soot;

- optimized mode (suggested): $T_{\text{out}} = 920^\circ\text{C}$, reduced vapor ratio ($H_2O/C = 1.8$), increased CO_2 content in the power supply.

The calculated thermodynamic estimates given for 1000 Nm^3 of natural gas are presented in Table 1.

Table 1. Simulation results

Parameter	Unit	Basic mode	Optimized mode	Change
Outlet temperature (T_{out})	$^\circ\text{C}$	880	920	+40
Steam ratio (H_2O/C)	-	2,5	1,8	-28%
Conversion CH_4	%	92,5	96,8	+4,3
Product composition (H_2)	%	54,0	60,5	+6,4
Product composition (CO)	%	32,5	35,2	+2,7
Ratio H_2/CO	-	1,66	1,72	Optimum for DRI
Residual methane	%	1,9	0,9	-50%
Specific energy consumption	GJ/t	10,8	10,2	-5,5%

Switching to an optimized mode demonstrates a reduction in energy consumption, despite an increase in operating temperature. This is due to a sharp decrease in energy costs for heating ballast water vapor (a decrease in Q_{sensible} overrides an increase in Q_{reaction}). In addition, the reduction of H_2/CO from 1.85 to 1.62 improves the conditions of DRI carburization in the shaft furnace, allowing a product with a carbon content of 1.5–2.0% to be obtained, which reduces energy consumption during subsequent electric melting. Based on our experimental studies, we have formulated the following recommendations for the engineering and technical staff of Midrex installations [30, 31, 34, 35] (Table 2). These parameters are indicative for catalysts based on $\alpha - Al_2O_3$ with a Ni content of 12–15%.

The recommendations given in table 2 allow us to use the main parameters of the reform process as diagnostic and control indicators. The deviation of these parameters from the optimal ranges directly affects the degree of metallization of DRI and the modulus of reducing gas ($H_2 + CO$), which determines the sequence of corrective actions discussed below.

Table 2. Recommendations for optimizing the reform parameters

Control parameter	Optimal range	Consequences of rejection	Recommendations
Outlet gas temperature	905 – 920 °C	<900°C – an increase in CH ₄ overshoot, a decrease in the reduction potential of the gas; 930°C – increased heat load, accelerated degradation of pipes and increased fuel consumption.	Maintain the maximum possible temperature T, limited by the pipe wall temperature t° (usually T _{max} =1050°C)
Pressure (at the inlet and outlet of the reformer)	2.5 – 2.3 bar	Pressure increase - decrease in equilibrium methane conversion (Le Chatelier principle); A decrease in pressure below the calculated pressure is a risk of disruption of the gas dynamics of the shaft furnace.	Keep it as low as possible, ensuring a pressure drop in the shaft furnace
Steam ratio (H ₂ O/C)	1,6 – 1,8	1.8–2.0 – increase in heat losses and specific fuel consumption; < 1.5 – approximation to the region of thermodynamically possible soot formation.	Decrease smoothly (0.05 step) with pressure drop control (ΔP) on pipes
CH ₄ content at the output	0.9 – 1.0 %	1.0 % – incomplete conversion and inefficient use of natural gas; < 0.8% – increase in heat load without significant gain in gas quality.	Use as an indicator of catalyst activity
Sulfur content (S)	<5 ppm	5-10 ppm – gradual decrease in the activity of the nickel catalyst; 10 ppm is a rapid and practically irreversible poisoning of the catalyst.	Strict control of the desulfurizer operation (ZnO)

Conclusions

The paper provides a comprehensive analysis of the process of natural gas reforming in MIDREX technology from the standpoint of thermodynamics, reaction chemistry and energy efficiency, which made it possible to consider the reformer not as an isolated apparatus, but as an integral element of a single gas-thermal system for direct iron reduction. It is shown that in the conditions of the real gas composition of MIDREX, the reforming process has a combined character and is determined by the combined reactions of steam and carbon dioxide reforming of methane, as well as the

reaction of water gas shear. It has been established that the presence of CO₂ in the recycled gas fundamentally changes the equilibrium composition of the reducing gas and should be taken into account when choosing optimal operating parameters. Based on the analysis of the influence of technological parameters, it was found that temperature is a key factor determining the degree of methane conversion and the quality of the reducing gas, while the pressure and composition of the gas mixture impose system limitations related to the requirements of the gas dynamics of the shaft furnace. It is shown that it is advisable to evaluate the effectiveness of reforming by the integral energy indicators of the entire gas circuit, rather than by local conversion rates. The calculation of the heat balance showed that an excessive increase in the steam ratio leads to an unjustified increase in heat costs without significantly increasing the stability of the process. It is proved that optimization of the H₂O/C and CO₂/C ratios makes it possible to reduce the specific consumption of natural gas, maintain the required H₂/CO ratio and at the same time minimize the risk of soot formation and degradation of the catalyst. Practical recommendations are formulated for optimizing the parameters of reforming for MIDREX industrial installations, the implementation of which ensures a reduction in specific fuel consumption by 5-7%, a reduction in the heat load on the reformer and an increase in the overall energy efficiency of the direct iron reduction process. The results obtained expand the existing understanding of the process of combined reforming in DRI technologies and can be used in the design, modernization and optimization of operating modes of existing and prospective MIDREX installations [36-38].

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Innovative AI Modelling for Wettability Control in Laser- Structured Functional Surfaces

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Abstract: Controlling wettability is increasingly essential for innovative applications in advanced manufacturing, energy systems, and biomedical engineering. This study presents an AI-driven modelling framework that predicts the wettability of laser-textured microstructured surfaces using height-map-based geometric analysis. Both synthetic and experimentally derived textures were converted into true 8-bit height maps, allowing for the extraction of important topographical descriptors such as Sa , Sq , Sz , Sdr , solid fraction (ϕ), and dominant spatial period. These parameters were integrated into a hybrid predictive approach that combines machine-learning techniques with physics-based wetting models (Wenzel and Cassie-Baxter). Young's intrinsic contact angle was optimized using real experimental data, enabling accurate predictions across two regimes for a set of ten engineered test surfaces.

Keywords: SURFACE TOPOGRAPHY, AI- DRIVEN MODELLING, CONTACT ANGLE PREDICTION, WENZEL AND CASSIE-BAXTER, HEIGHT- MAP ANALYSIS

1. Introduction

Surface wettability, defined as the ability of a liquid to spread or repel on a solid surface, plays a critical role in a wide range of engineering and scientific applications, including self- cleaning coatings, anti- icing systems, biomedical devices, and heat transfer technologies [1–4]. The wetting behavior of a surface is commonly characterized by the contact angle (CA), which depends on both the chemical composition and the micro- and nano- scale topography of the surface. While ideal smooth surfaces can be described by Young's equation, real engineered surfaces are inherently rough and heterogeneous, requiring more advanced models to accurately describe wetting phenomena.

Two classical models are widely used to describe wettability on rough surfaces: the Wenzel model and the Cassie-Baxter model [5]. The Wenzel model assumes that the liquid fully penetrates surface asperities, leading to an apparent contact angle dependent on the surface roughness factor. In contrast, the Cassie-Baxter model describes a composite interface in which the liquid rests partially on trapped air pockets, resulting in higher apparent contact angles and often superhydrophobic behavior. These models form the theoretical basis for understanding wetting transitions and for designing surfaces with tailored hydrophilic or hydrophobic properties. However, the transition between these regimes is complex and depends strongly on geometric features such as feature size, spacing, and hierarchical structure [6].

In recent years, laser surface texturing (LST) has emerged as a versatile and precise method for designing functional surfaces with controlled wettability [7,8]. LST enables the fabrication of micro- and nano- scale patterns such as grooves, dimples, and hierarchical structures on a wide range of materials, providing a powerful tool for tuning surface interactions with liquids. Numerous studies have demonstrated that the wettability of laser- textured surfaces can be significantly modified by altering process parameters such as scanning speed, pulse duration, and pattern geometry. Furthermore, bio- inspired designs, such as lotus- leaf or shark- skin- like structures, have been successfully implemented to achieve extreme wetting states, including superhydrophobicity [9].

To quantitatively characterize surface topography, modern surface metrology relies on standardized areal parameters defined in ISO 25178, such as Sa (arithmetical mean height), Sq (root mean square height), and Sdr (developed interfacial area ratio). These three- dimensional parameters provide a comprehensive description of surface geometry and are essential for correlating microstructure with functional properties such as wettability. Despite these advances, establishing a direct and reliable relationship between topographical descriptors and contact angle remains a challenging task due to the complex interplay between geometric and physicochemical factors [10].

Recently, artificial intelligence (AI) and machine learning (ML) techniques have been increasingly applied to model and predict wettability from surface characteristics [11,12]. Neural networks

and other ML approaches have demonstrated high predictive accuracy by capturing nonlinear relationships between surface parameters and contact angle. Additionally, emerging studies combining ML with experimental data from laser- textured surfaces have shown promising results in predicting wettability across a wide range of materials and structures. Nevertheless, the performance of purely data- driven models is often limited by the scarcity of high- quality experimental datasets, highlighting the need for hybrid approaches that integrate physical models with AI- based techniques.

In this context, the present study aims to develop an integrated framework for predicting the wettability of laser- textured surfaces using a combination of synthetic height- map generation, image- based topographical analysis, and physics- guided modelling supported by AI concepts. Specifically, the work focuses on extracting key surface parameters from engineered textures, calibrating wettability models using experimental data, and applying hybrid predictive methods to estimate contact angles for newly designed surface geometries. This approach seeks to provide a reproducible and scalable methodology for the design and optimization of functional surfaces with tailored wetting behavior.

2. Materials and Methods

2.1 Surface Data Preparation and Height- Map Generation

The study was based on a combined dataset consisting of both synthetic surface structures and experimentally measured laser- textured surfaces. The real pictures of laser-textured surfaces are shown in Fig. 1 [13]. A set of ten synthetic surface geometries was generated to represent a wide wettability spectrum ranging from superhydrophilic to hydrophobic regimes. Each structure was initially provided as a grayscale PNG image and subsequently converted into a true height- map representation, in which pixel intensity values (0–255) correspond directly to normalized surface heights.

The conversion process involved transforming each image into a grayscale format and applying linear normalization to ensure uniform scaling across all samples. The normalized pixel values were then interpreted as relative height distributions and mapped to physical surface heights using assigned maximum amplitudes (Z_{max}). The Z_{max} values were selected within the range of 200 – 800 μm , depending on the intended structural complexity of each surface. This approach enabled the creation of a consistent and physically interpretable dataset suitable for both computational analysis and potential laser surface processing.

2.2 Real Surface Dataset and Experimental Data

In addition to synthetic datasets, experimentally derived height- maps of real laser- textured surfaces were used for model calibration. These datasets were obtained from the Excel file, containing multiple texture types (e.g., dimple, pyramid, fish- scale, and bio- inspired structures) along with their corresponding measured contact angles and surface depths.

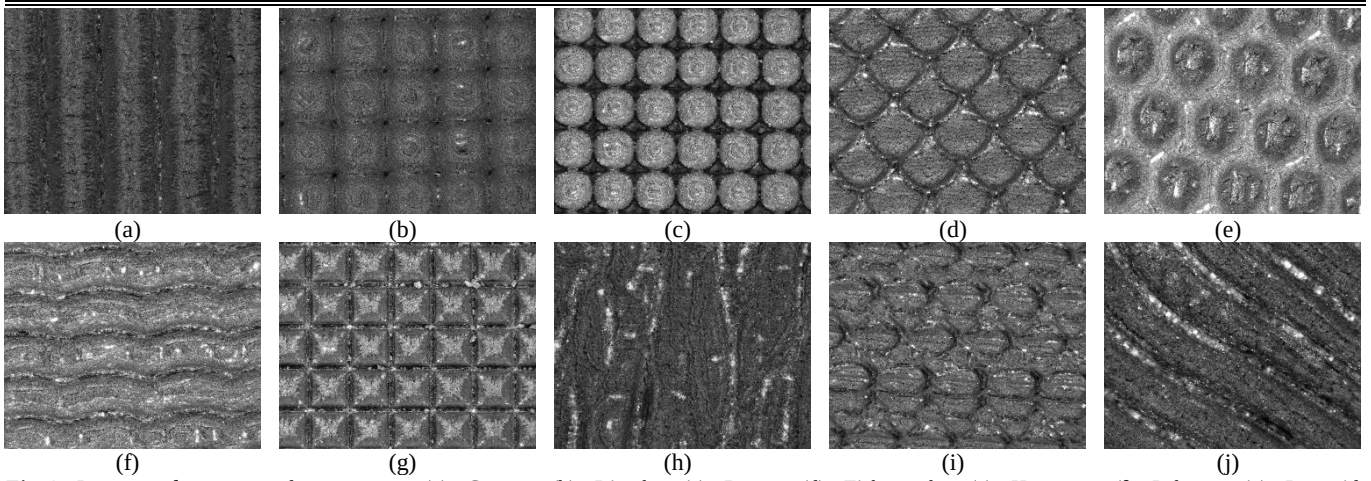


Fig. 1 Laser surface textured structures: (a) Cactus; (b) Dimple; (c) Dome; (d) Fish scale; (e) Hexagon; (f) Lobster; (g) Pyramid; (h) Salamander; (i) Shark; (j) Whale.

The experimental height- maps were processed using the same normalization and scaling procedures as the synthetic data to ensure methodological consistency. Surface heights were converted into physical units (μm) based on measured mean texture depths. These real datasets served as the ground truth for calibrating wettability models and evaluating predictive performance.

2.3 Surface Topography Characterization

Quantitative characterization of surface geometry was performed using areal surface texture parameters defined in ISO 25178 standard. These parameters were selected as they provide a comprehensive three- dimensional representation of surface topography. The primary parameters extracted in this study include:

Sa (arithmetical mean height) – average deviation from the mean plane

Sq (root mean square height) – standard deviation of height distribution

Sz (maximum height) – peak- to- valley height difference

Ssk (skewness) – asymmetry of surface height distribution

Sku (kurtosis) – peakedness of height distribution

Sdr (developed interfacial area ratio) – percentage increase in surface area relative to a flat plane

The Sdr parameter was calculated using discrete gradient estimation derived from Sobel- type convolution kernels applied in both x and y directions. The local slopes obtained from these gradients were used to compute the true surface area, enabling evaluation of the surface roughness factor.

In addition to ISO parameters, several functional geometric descriptors were extracted:

Solid fraction (ϕ) – calculated using Otsu thresholding to separate solid peaks from void regions;

Dominant spatial period – obtained via two- dimensional Fast Fourier Transform (FFT) analysis;

Autocorrelation length (Sal) and *texture isotropy* (Str) – derived from normalized spatial autocorrelation functions;

Approximate feature diameter – estimated from solid fraction and periodicity.

These descriptors were used to capture both the statistical and structural characteristics of the surface, enabling a more complete understanding of their influence on wettability behavior.

2.4 Wettability Modelling

The wetting behavior of each surface was evaluated using two classical theoretical models: the Wenzel model and the Cassie-Baxter model, which describe wetting on rough surfaces under different physical conditions [14].

The Wenzel model (Fig. 2) assumes complete wetting of surface asperities and is expressed as:

$$\cos\theta_W = r \cos\theta_Y, \text{ where } r = 1 + Sdr / 100 \quad (1)$$

where r is the roughness ratio (related to Sdr) and θ_Y is the intrinsic Young's contact angle.

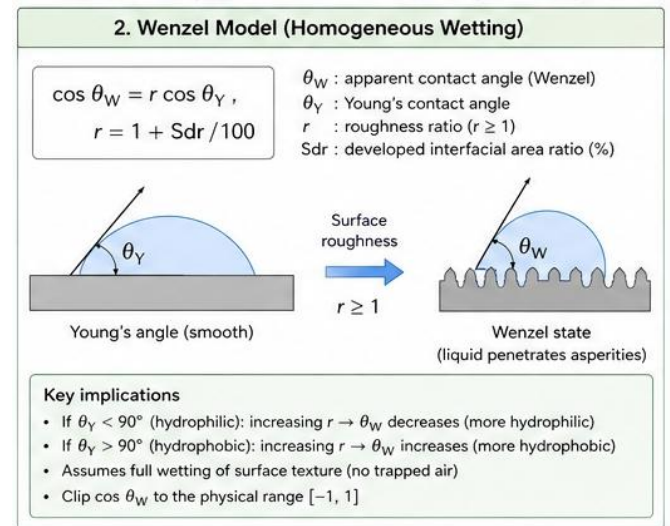


Fig. 2 Illustration of the Wenzel model

The Cassie-Baxter model (Fig. 3) assumes a composite solid–air interface and is defined as:

$$\cos\theta_{CB} = \phi \cos\theta_Y - (1 - \phi), \quad (2)$$

where ϕ represents the solid fraction of the surface.

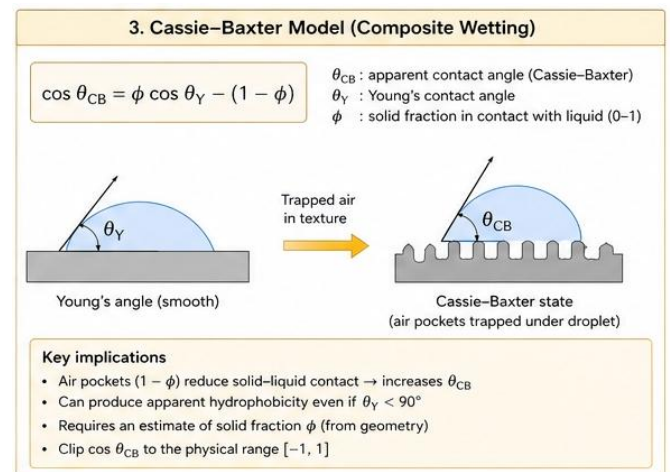


Fig. 3 Illustration of the Cassie-Baxter model.

In this study, both models were applied to each surface to evaluate possible wetting regimes and transitions. The roughness factor r was approximated as:

$$r = 1 + Sdr / 100 \quad (3)$$

linking ISO parameters directly to physical wetting behavior.

2.5 AI Assisted Model Calibration

To improve predictive accuracy, an AI- assisted calibration approach was implemented. A dataset of real surface measurements (including contact angle values) was used to optimize the intrinsic Young's contact angle θ_Y . A grid search optimization method was employed over a range of plausible values ($30^\circ - 120^\circ$), minimizing the root- mean- square error (RMSE) between predicted and experimentally observed contact angles.

In addition, a Random Forest regression model was evaluated as a purely data- driven alternative. The model utilized the extracted topographical features (Sa , Sq , Sz , Sdr , ϕ , and others) as input variables. Due to the limited size of the experimental dataset, the regression model showed restricted generalization capability, and therefore its role was primarily supportive rather than definitive.

The final predictive approach was based on a hybrid framework, combining physics based equations with AI- assisted parameter calibration. This methodology allowed the incorporation of both theoretical understanding and data- driven optimization.

2.6 Data Processing and Implementation

All computations were performed using Python based tools, including NumPy for numerical processing, SciPy for signal analysis, and Pandas for data handling. Image processing was carried out using the Pillow library, while FFT and autocorrelation analyses were implemented using standard numerical routines.

The final results, including all surface parameters and predicted contact angles, were compiled into structured Excel files for further analysis and visualization.

3. Results and Discussion

3.1 Surface Topography Characteristics

The quantitative analysis of the ten synthetic height- map structures revealed a wide variation in surface topography parameters, reflecting the intended transition from hydrophilic to hydrophobic regimes. The extracted ISO- based parameters (Sa , Sq , Sz) exhibited a gradual increase with assigned surface complexity and height scaling (Z_{max}), indicating greater deviations from the mean plane and higher peak- to- valley amplitudes. This trend is consistent with expectations for engineered textures, where increased feature height and spacing contribute to enhanced surface roughness.

The developed interfacial area ratio (Sdr) showed a particularly significant variation across the dataset, ranging from approximately 2% for smoother structures to over 100% for highly rough, complex surfaces. This increase in Sdr indicates a substantial rise in the true surface area relative to the projected area, which has a direct influence on wettability behavior through the roughness factor r . Notably, structures classified as hydrophobic or highly structured exhibited markedly higher Sdr values, suggesting a strong amplification of roughness effects.

The solid fraction (ϕ) varied within a relatively narrow range (approximately 0.38–0.49), yet its influence on wetting behavior proved to be critical. Even small variations in ϕ significantly affected the predicted contact angle values under the Cassie-Baxter model. This highlights the sensitivity of wetting behavior to the distribution of solid-liquid contact areas and the presence of air pockets within the structured surface.

Spectral and spatial analyses further revealed that most synthetic surfaces exhibited quasi- periodic patterns, as confirmed

by FFT derived dominant spatial periods. Autocorrelation analysis indicated that the majority of structures were relatively isotropic ($Str \approx 0.8 - 1.0$), implying uniform distribution of features in all directions. Such isotropic surfaces are generally less prone to anisotropic wetting behavior, which is beneficial for consistent droplet interaction in practical applications.

3.2 Wettability Predictions Using Physical Models

The application of the Wenzel and Cassie-Baxter models to the synthetic surfaces revealed two distinct wetting regimes, strongly dependent on surface roughness and solid fraction.

Wenzel Model Behavior

The Wenzel model predictions demonstrated a clear trend: as surface roughness increased (higher Sdr and roughness factor r), the predicted contact angle decreased significantly. For low- roughness surfaces, Wenzel contact angles ranged between approximately 23° and 28° , indicating moderately hydrophilic behavior. However, for highly rough surfaces, the model predicted near- zero contact angles, suggesting complete wetting.

This behavior is consistent with the theoretical formulation of the Wenzel model, where surface roughness amplifies the intrinsic wetting characteristics. Given the optimized Young's angle ($\sim 30^\circ$), the increase in roughness strongly favors wetting, leading to the transition toward a fully wetted state. This indicates that, under Wenzel conditions, highly textured surfaces enhance hydrophilicity rather than hydrophobicity, particularly when the intrinsic material is already moderately wettable.

Cassie-Baxter Model Behavior

In contrast, the Cassie-Baxter model predicted consistently higher contact angles across all surfaces, with values ranging from approximately 95° to 106° . These results indicate hydrophobic behavior and, in some cases, approach the threshold for superhydrophobicity.

The relatively stable predictions across different structures suggest that the Cassie-Baxter regime is primarily governed by solid fraction rather than roughness magnitude. Since ϕ remained within a moderate range ($\sim 0.4 - 0.45$), the resulting contact angles showed limited variation. This emphasizes that achieving significantly higher hydrophobicity would require either lower ϕ values (i.e., more air fraction) or hierarchical surface design.

3.3 Wettability Predictions Using Physical Models

A direct comparison between the two models highlights a fundamental divergence in predicted wetting behavior. While the Wenzel model predicts increasing hydrophilicity with surface roughness, the Cassie-Baxter model predicts sustained hydrophobicity. This discrepancy reflects the different physical assumptions behind the models.

The Wenzel regime assumes complete liquid penetration into the surface texture, resulting in increased solid-liquid contact area. In contrast, the Cassie-Baxter regime assumes partial contact, with air pockets reducing the effective contact area. The observed differences in predicted contact angles suggest that the actual wetting behavior of the surface will depend on whether the liquid penetrates the texture or remains suspended above it.

For intermediate surfaces, the predictions of both models diverge significantly, indicating that these structures lie within the wetting transition region. Such surfaces are highly sensitive to external conditions, including droplet size, impact velocity, and environmental pressure. This highlights the importance of considering both models when designing functional surfaces, as real systems often exhibit mixed or metastable wetting states.

3.4 Role of Surface Parameters in Wettability

The results demonstrate that not all surface parameters contribute equally to wettability prediction. Among the extracted features, Sdr and ϕ emerged as the most influential parameters.

The parameter Sdr directly controls the roughness factor in the Wenzel model, making it a critical determinant of wetting behavior in fully wetted conditions. High Sdr values significantly amplify the intrinsic wettability of the material, which explains the rapid decrease in contact angle observed in the Wenzel predictions.

The solid fraction ϕ plays a dominant role in the Cassie-Baxter model by determining the relative contributions of solid and air interfaces. A lower ϕ results in higher contact angles due to increased air entrapment. Although ϕ variation was limited in this study, its impact on contact angle prediction remained substantial.

Other parameters, such as Sa , Sq , and Sz , provide useful descriptors of surface morphology but do not directly enter the theoretical wetting equations. However, they are indirectly related to wettability through their influence on Sdr and feature geometry. Similarly, autocorrelation and spectral parameters (Sal , Str , dominant period) help characterize structural organization but play a secondary role in direct wettability prediction.

3.5 Evaluation of AI- Assisted Modelling

The AI- assisted component of this study was primarily used to optimize the intrinsic Young's angle based on experimental data. The grid- search optimization resulted in a value of approximately 30° , which provided the best agreement between predicted and measured contact angles for the available dataset.

The attempt to use a Random Forest regression model demonstrated the limitations of purely data- driven approaches

when the dataset is small. Although the model was able to capture general trends, its predictive accuracy was limited due to insufficient training data. This confirms that, in the context of surface wettability, hybrid approaches combining physics and AI are more robust than purely machine- learning methods, particularly in early- stage research or when experimental data is scarce.

3.6 Implications for Surface Design

The proposed workflow provides valuable insights for the design of functional surfaces. The results indicate that achieving hydrophobic or superhydrophobic behavior is not solely dependent on increasing surface roughness. Instead, the interplay between roughness, solid fraction, and structural geometry must be carefully considered.

To promote Wenzel behavior (e.g., for applications requiring strong liquid adhesion), surfaces should be designed with high roughness (high Sdr) and continuous contact pathways. Conversely, for hydrophobic or self- cleaning applications, surfaces should be engineered to favor the Cassie-Baxter regime by reducing ϕ and introducing features that trap air, such as re- entrant or hierarchical structures.

The use of synthetic height- maps allows for rapid prototyping of such designs, enabling systematic exploration of parameter space before experimental fabrication. This significantly reduces development time and cost, especially in laser surface engineering applications. AI generated surfaces for laser-texturing are shown in Fig. 4.

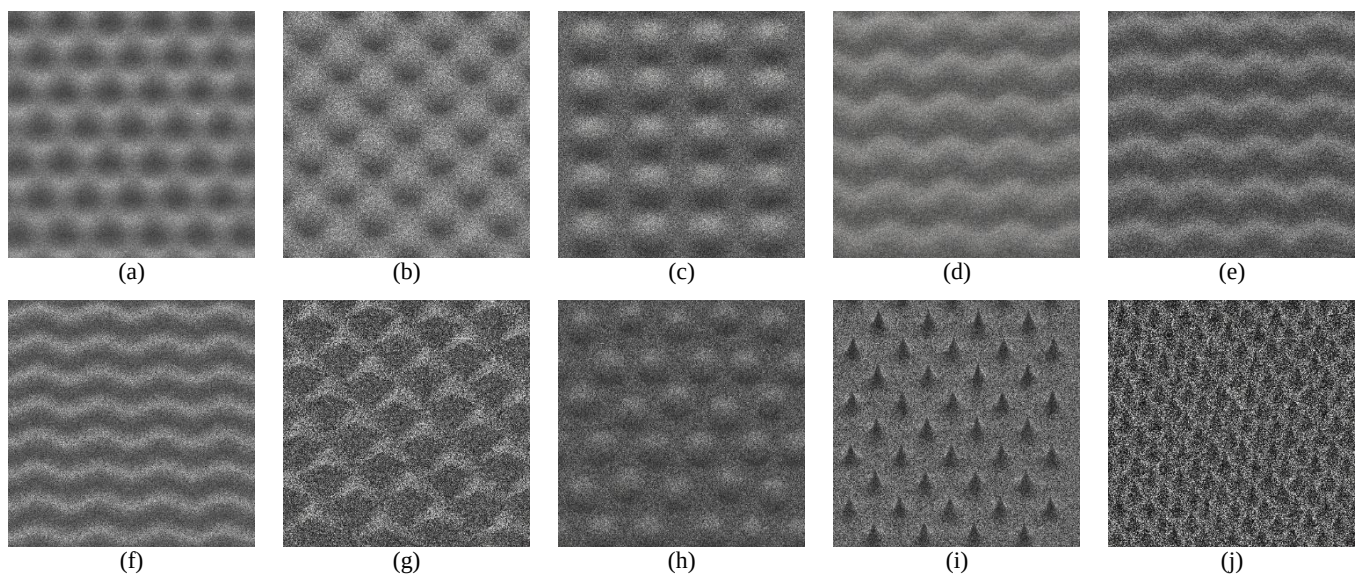


Fig. 4 AI-generated structures: (a) Superhydrophilic; (b) Very hydrophilic; (c) Hydrophilic; (d) Mild hydrophilic; (e) Neutral; (f) Transition; (g) Mild hydrophobic; (h) Hydrophobic; (i) Very hydrophobic; (j) Superhydrophobic.

3.7 Implications for Surface Design

Despite the promising results, several limitations should be noted. The primary limitation is the relatively small dataset of experimentally measured contact angles, which restricts the accuracy of model calibration. Additionally, the current approach does not account for surface chemistry effects, which can have a significant impact on wettability.

Future work should focus on expanding the dataset, incorporating chemical surface properties, and exploring more advanced AI models capable of handling complex nonlinear interactions. Experimental validation of the predicted contact angles will also be essential to confirm the applicability of the proposed methodology.

Overall, the results demonstrate that the combination of height- map analysis, standardized surface parameters, and physics- guided modelling provides a powerful framework for predicting and understanding wettability in laser- textured surfaces.

4. Conclusion

1. A reproducible framework for wettability prediction was developed, integrating synthetic height- map generation, ISO- based surface characterization, and physics- guided modelling. The approach enables systematic analysis of structured surfaces and supports rapid evaluation of wetting behavior prior to experimental fabrication.

2. Surface roughness (Sdr) and solid fraction (ϕ) were identified as the dominant parameters influencing wettability, directly governing the predictions of Wenzel and Cassie-Baxter models. High Sdr strongly amplifies intrinsic wettability (favoring Wenzel behavior), while ϕ controls the degree of air entrapment and hydrophobic response in the Cassie-Baxter regime.
3. A clear divergence between Wenzel and Cassie-Baxter predictions was observed, particularly for highly structured surfaces. This confirms that wettability is strongly regime-dependent and highlights the importance of considering both models when designing laser-textured surfaces.
4. The hybrid AI-assisted approach demonstrated improved robustness compared to purely data-driven models, especially under conditions of limited experimental data. The combination of physical modelling and parameter calibration provides a reliable and scalable methodology for the design of functional surfaces with tailored wetting properties.

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Microstructural and Mechanical Performance of SiO₂-Reinforced Nickel-Based Nanocomposite Coatings

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Abstract: Nickel-based nanocomposite coatings reinforced with silicon dioxide (SiO₂) nanoparticles are attracting increasing interest in advanced marine applications due to their superior mechanical properties and resistance to surface wear. In this study, selective Ni-SiO₂ nanocomposite coatings were prepared and investigated to determine the relationship between microstructure, composition, and mechanical properties. The microstructure of the coatings was investigated using scanning electron microscopy (SEM). The analysis showed that the matrix is fine-grained and relatively homogeneous, containing well-dispersed SiO₂ nanoparticles at an amount corresponding to the optimal reinforcement level. Energy-dispersive X-ray spectroscopy (EDS) analysis confirmed that silicon oxide had been successfully incorporated into the nickel matrix and was uniformly distributed within it, and no significant signs of agglomeration were observed in the most effective compositions. Mechanical properties were evaluated by scratch tests to assess the coating's adhesion and resistance to mechanical damage. The results showed that SiO₂-reinforced coatings exhibit significantly higher scratch resistance and higher critical load values. This improvement is attributed to dispersive strengthening, grain refinement, and the barrier effect created by hard ceramic nanoparticles, which together inhibit plastic deformation and crack propagation. In summary, the results of the study demonstrate the potential of Ni-SiO₂ nanocomposite coatings as durable protective solutions in marine environments, where resistance to mechanical wear and surface damage is particularly important. The study provides insights into how to adjust the microstructure and reinforcement distribution to improve the coating's performance characteristics.

Keywords: Ni-SiO₂ NANOCOMPOSITE COATINGS, SILICON DIOXIDE NANOPARTICLES, LASER SINTERING, NANOPARTICLE REINFORCEMENT.

1. Introduction

The maritime industry is a key component of the global economy: it accounts for more than 80% of global trade in goods. It supports key oil, gas and renewable energy extraction processes [1]. However, the components used in this sector, from ship hulls and propulsion systems to offshore platform equipment, are exposed to extremely harsh operating conditions. Constant exposure to salt water, high humidity, temperature fluctuations and abrasive particles accelerates wear and corrosion, which greatly affects the performance and service life of critical systems. This requires the development and implementation of advanced security technologies to ensure the durability and reliability of marine equipment [2]. Corrosion remains one of the most pressing problems in the marine industry. According to estimates by the National Association of Corrosion Engineers, corrosion-related economic losses in this sector amount to 3% of global gross domestic product. These losses include direct component replacement costs as well as indirect costs resulting from equipment downtime, reduced operational efficiency, and increased risk of environmental incidents [3]. Wear is equally important, especially for moving components such as shafts, bearings and screws, which operate under high mechanical loads and are exposed to abrasive particles. The wear and tear of these parts not only increases maintenance requirements but also leads to higher fuel consumption, lower energy efficiency, and higher greenhouse gas emissions, thus requiring effective solutions [4], [5]. Protective coatings are essential to mitigate these challenges as they improve the durability and functionality of materials in marine environments. The most commonly used coatings are epoxy, polyurethane, ceramic and metal coatings. Despite their widespread use, each type has limitations that require further innovation [2]. Epoxy coatings are favoured for their excellent adhesion, water resistance, and chemical resistance, making them suitable for ship hulls, offshore platforms, and pipelines. However, over time, especially when exposed to UV rays, these coatings become brittle and can crack and peel. Furthermore, their effectiveness depends heavily on proper surface preparation and application, and improper methods reduce their protective capabilities [6]. Polyurethane coatings offer excellent UV resistance and a durable, glossy finish, making them ideal for use on the surface and above the waterline. However, they are less resistant to prolonged immersion in water and can degrade when exposed to aggressive marine chemicals. Furthermore, their curing process requires strict control of environmental conditions such as humidity and temperature, which

complicates their application [7]. Ceramic coatings have the properties of hardness, wear resistance, and high temperature resistance, making them suitable for marine components such as propellers and shafts. However, their brittleness makes them prone to cracking under mechanical stress, and their application often requires advanced technology, which increases costs and limits their practicality for large-scale structures [2]. Metallic coatings, such as zinc and aluminium-based systems, provide protective cathodic protection to the underlying metals. Although effective, these coatings are susceptible to erosion in abrasive environments and require frequent recoating. Their effectiveness may also be reduced in areas subject to high mechanical stress or biological contamination [8]. A common drawback of many protective coatings is their environmental impact. Traditional coatings often contain volatile organic compounds (VOCs) and heavy metals, which can leach into the marine environment during degradation and pose a threat to aquatic ecosystems. Maintenance and recoating processes generate additional hazardous waste, and coatings that are prone to degradation or failure increase the risk of corrosion and structural instability, increasing long-term costs and environmental risks. New technologies, such as eco- and nanocomposite coatings, aim to address these challenges by offering improved performance and a smaller ecological footprint. However, these innovative solutions often involve higher initial costs and require specialised knowledge for their application [9]. This research aims to overcome these challenges by developing and evaluating advanced nickel-based nanocomposite coatings reinforced with silicon oxide (SiO₂) particles. These selectively deposited coatings aim to combine the improved mechanical and corrosion properties of nickel with the enhanced wear resistance provided by the SiO₂ particles. Advanced characterisation techniques will be used to investigate the microstructure, adhesion and performance of coatings under simulated marine conditions. The research will prioritise the ability of coatings to withstand the dual stresses of corrosion and abrasion, ensuring their suitability for critical marine applications such as ship components, offshore platforms and subsea systems.

2. Materials and Methods

The substrate material used was martensitic stainless steel 1.4021, also known as X20Cr13 (EN 10088). The substrate plates were supplied by CHIRMED (Poland); with dimensions 20×60×3 mm, and the selectively plated surface area was 20×25 mm. Since the substrate material is primarily used as a base

for coating deposition, its role in the study was limited to the preparation and surface treatment stages. The substrate surface was not subjected for mechanically treatment by grinding/polishing before selective plating. It was used as received. The plated area was masked, and electrochemical surface preparation measures were performed, including electrochemical cleaning, electrochemical etching, and activation of the masked surface. After activation, a nickel interlayer approximately 1 μm thick was deposited by selective plating. This bonding layer was applied to improve the adhesion strength of the subsequent coating and to act as a hydrogen and oxidation barrier. Nickel-based SIFCO Ni 2080 electrolyte was used to deposit the Ni-SiO₂ nanocomposite coating. The electrolyte had a pH of 2.3 and consisted of 20 wt% nickel sulfate, 10 wt% nickel formate, 10 wt% citric acid, 1 wt% aluminium sulfate, and deionised water. To prepare the nanocomposite plating solution, 2 wt% SiO₂ nanopowder with an average particle size of 10 nm was added to the nickel electrolyte. The suspension was dispersed by ultrasonication for 15 minutes before precipitation. During the selective plating process, the electrolyte was continuously stirred with a magnetic stirrer to maintain a stable dispersion of SiO₂ nanoparticles. Ni-SiO₂ nanocomposite coatings were deposited by a selective method. The prepared and activated substrate served as the cathode, and the coating brush served as the anode. During deposition, an electrolyte-saturated brush was moved across the masked substrate area at a speed of 15 m/min. The applied plating voltage was maintained in the range of 6-10 V. After deposition, the coated samples were rinsed with deionised water and dried.

The coating thickness was measured using a CEM DT-156 coating thickness gauge operating on the principle of magnetic induction. Its measuring range is from 0 to 1,250 μm , with a guaranteed reading error of $3\% \pm 1 \mu\text{m}$ and an accuracy of 0.1 μm . The probe creates a magnetic field, and the thicker the coating, the weaker the probe “detects” the ferromagnetic substrate; thus, the layer thickness is calculated from the change in the measured magnetic resistance.

Microstructural analysis of the samples was performed using an FEI Quanta 200 FEG scanning electron microscope (SEM) equipped with a field emission generator (FEG). The microscope was operated under high vacuum to obtain high-resolution images of the sample surface. Before analysis, the samples were prepared using standard metallographic procedures, including cutting, casting, grinding, and polishing.

The elemental composition was determined using an energy dispersive X-ray spectroscopy (EDS) system integrated with a SEM (Bruker XFlash 4030). EDS analysis was performed to determine the chemical composition of the sample, assess the distribution of reinforcing particles (e.g. SiO₂), and detect any impurities or interfacial diffusion. Spectra were collected at random locations using an accelerating voltage of 15 kV to ensure sufficient excitation of characteristic X-rays.

Elemental distribution maps were created using the EDS mapping mode. This allowed us to see the distribution of chemical elements (Al, C, Su, Fe, Ni, Si, O) in the corresponding areas of the studied coatings. The results of EDS mapping allowed us to observe the penetration of SiO₂ particles into the metal substrate, revealed the structural uniformity of the coating, and highlighted the distribution and accumulation of chemical elements.

3. Experimental

SEM and EDS methods were used to study the distribution of SiO₂ nanoparticles in Ni-2%SiO₂ composite coatings and their morphology. SEM images of “Coating 1”, “Coating 2”, and “Coating 3” show a nodular morphology characteristic of electrochemically deposited coatings on a nickel substrate; however, there are noticeable differences in surface uniformity and density. The “Coating 1” samples exhibit a relatively uneven

surface with irregularly shaped protrusions and areas of lower density, which confirms unstable growth conditions (Fig. 1 a).

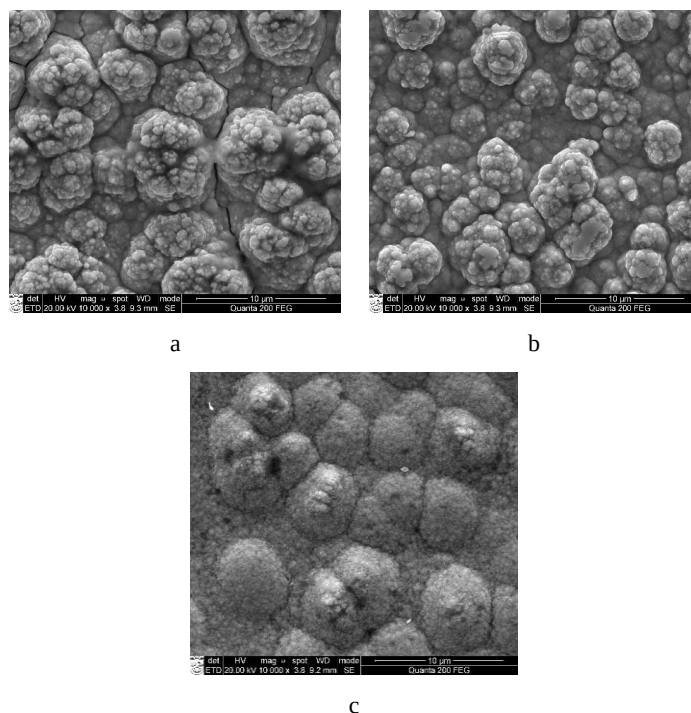


Fig. 1 Surface morphology: a – Coating 1; b – Coating 2; c – Coating 3.

The “Coating 2” exhibits a significantly more uniform nodule structure, characterised by a smaller variation in the range of nodule sizes and a more compact, uniform surface structure. All of this indicates that the conditions for vegetation growth are more stable and that the vegetation density is higher (Fig. 1 b). A nodular morphology is also observed in the “Coating 3”; however, compared to the “Coating 2”, its structure is noticeably coarser and less uniform (Fig. 1 c). The surface is characterised by larger nodules, lower density, and localised irregularities.

The SI map, which shows the localised silicon deposits and the uneven distribution of particles (Fig. 2 a), confirms the unstable growth conditions in the “Coating 1”.

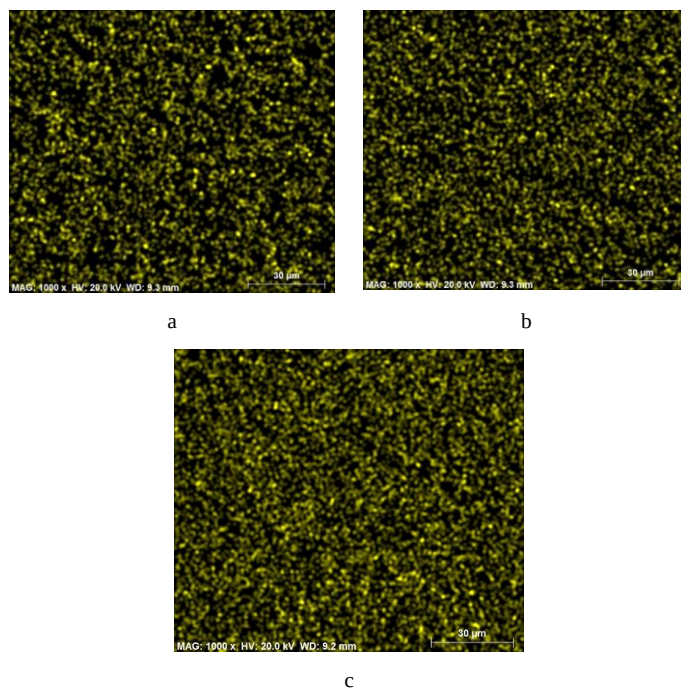


Fig. 2 SI mapping: a – Coating 1; b – Coating 2; c – Coating 3.

The corresponding silicon (Si) distribution map of “Coating 2” (Fig. 2 b), reveals a uniform and finely dispersed silicon distribution, indicating effective nanoparticle incorporation and increased coating density.

Visible microcracks and partially flat areas indicate the presence of internal stresses and less controlled growth dynamics in the “Coating 3”. These characteristics indicate a reduction in the structural uniformity and density of the coating. This is associated with a less homogeneous distribution of silicon, suggesting that uneven particle penetration and local agglomeration contributed to structural inhomogeneity and the formation of internal stresses (Fig. 2 c).

The EDS spectra confirm that the matrix consists of nickel; signals for silicon and oxygen were also detected, confirming the

presence of SiO_2 nanoparticles (Fig. 3). The relatively low intensity of the Si peak indicates that the amount of the nanoparticle reinforcement phase is small (2 wt.%) and that the particles are small. The Fe signals detected in the spectra are attributed to the 1.4021 stainless steel matrix; they arise from the interaction of the electron beam with the material under the applied acceleration voltage. Furthermore, the presence of copper is not related to the composition of the coating and is most likely due to secondary factors associated with the brush electroplating process.

In summary, the results of the SEM and EDS analyses indicate that “Coating 2” exhibited the most favourable balance between coating growth and nanoparticle incorporation, resulting in the densest and most structurally homogeneous coating, whereas “Coating 1” and “Coating 3” exhibited greater heterogeneity associated with a less controlled particle distribution.

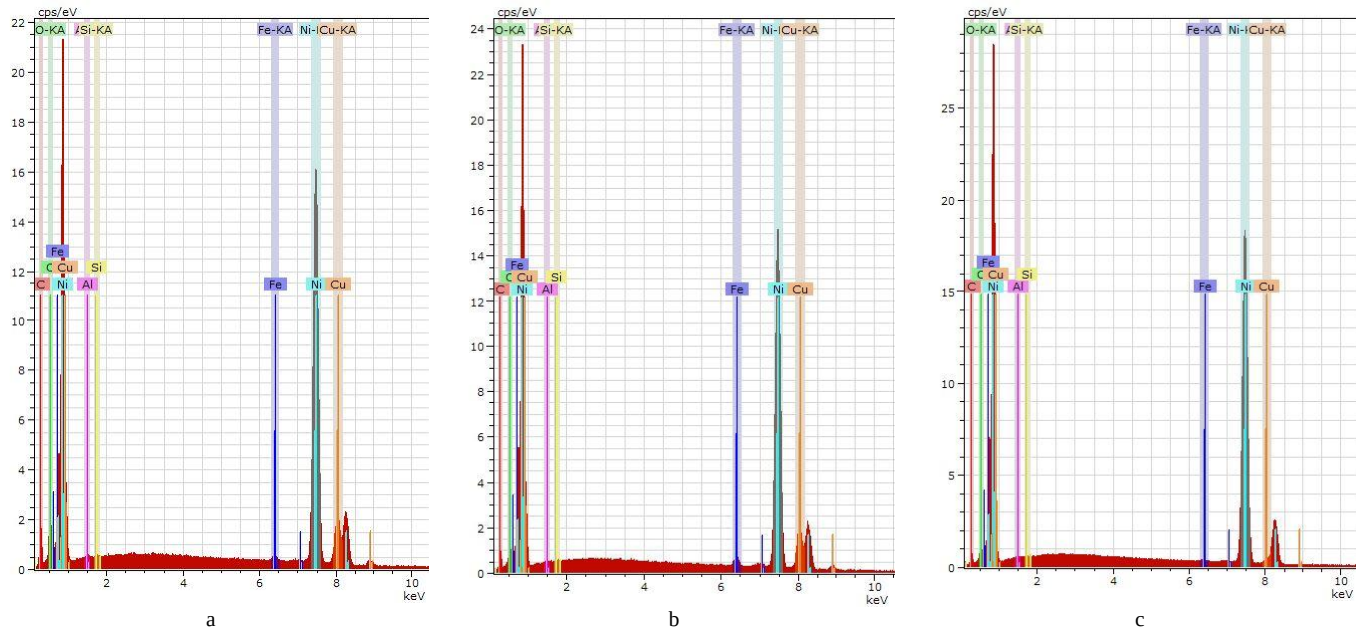


Fig. 3 EDS spectra: a – Coating 1; b – Coating 2; c – Coating 3.

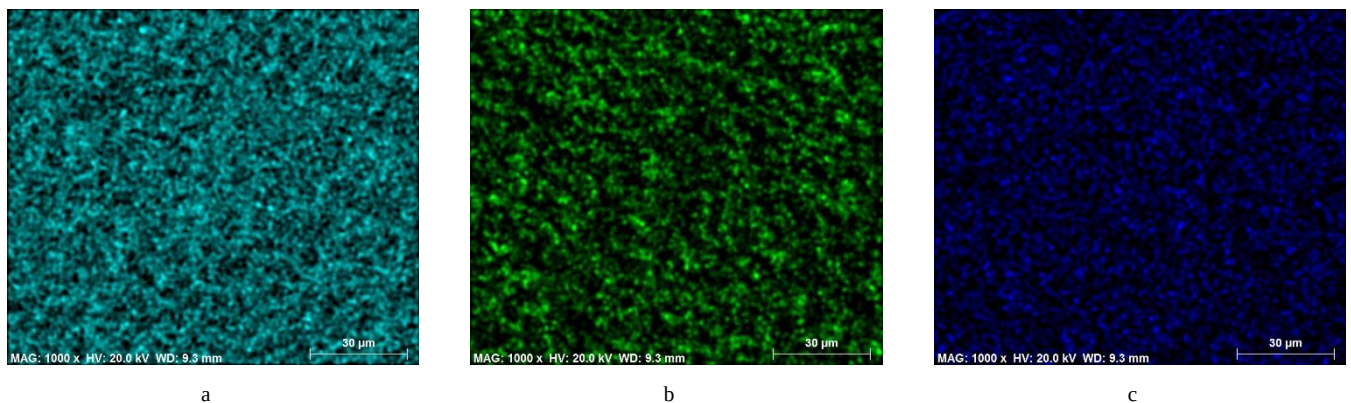


Fig. 4 “Coating 1”. Elemental map of: a – nickel map; b – oxygen map; c – iron map.

The distribution map of the elements in the “Coating 1” shows a continuous but locally heterogeneous Ni matrix (Fig. 4 a), which is consistent with the heterogeneous morphology of the nodules observed in the SEM images (Fig. 1 a).

The Si and corresponding oxygen (O) signals confirm the presence of SiO_2 nanoparticles; however, their distribution is uneven, indicating partial agglomeration. The O map (Fig. 4 b) shows a slightly more dispersed distribution compared to Si, which confirms that slight surface oxidation also contributes to this. The Fe signal is clearly visible (Fig. 4 c) throughout the study area, which clearly indicates the influence of the substrate, caused by limited coverage density or reduced thickness in certain areas.

These results confirm once again that the microstructure of the first layer is not homogeneous, the particles are distributed unevenly, and the surface is not fully compacted.

The distribution map of the “Coating 2” shows that a highly homogeneous and continuous Ni matrix has formed (Fig. 5 a), which confirms stable coating growth and greater structural integrity compared to the first coating. The distribution of silicon (Si) and the corresponding oxygen (O) on the surface (Fig. 5 b) is extremely fine-grained and homogeneous, which confirms that the SiO_2 nanoparticles penetrate effectively without forming distinct clusters. Unlike in the “Coating 1”, the Fe signal here is significantly weaker and more diffuse (Fig. 5 c), which confirms the

limited influence of the substrate and suggests that the coating is denser and more uniform.

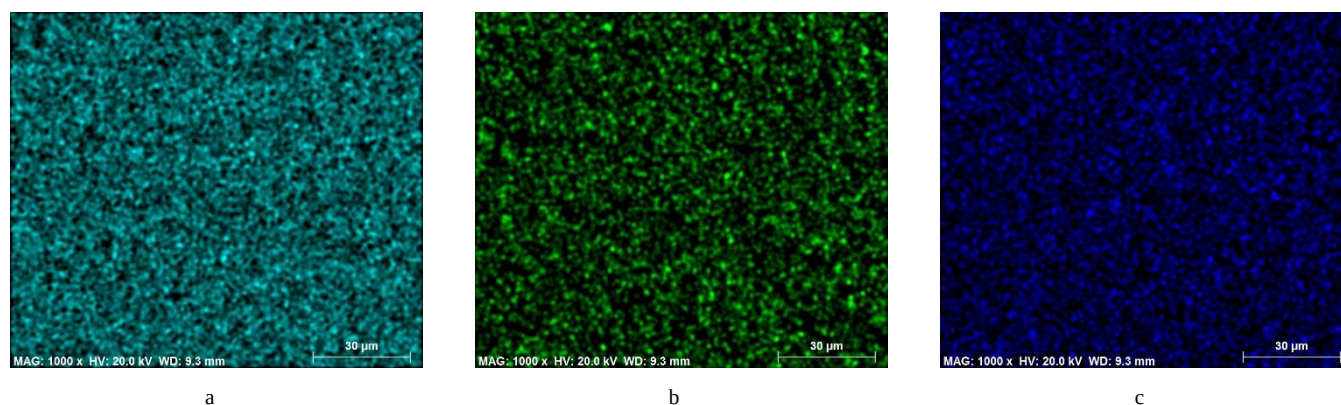


Fig. 5 “Coating 2”. Elemental map of: a – nickel map; b – oxygen map; c – iron map.

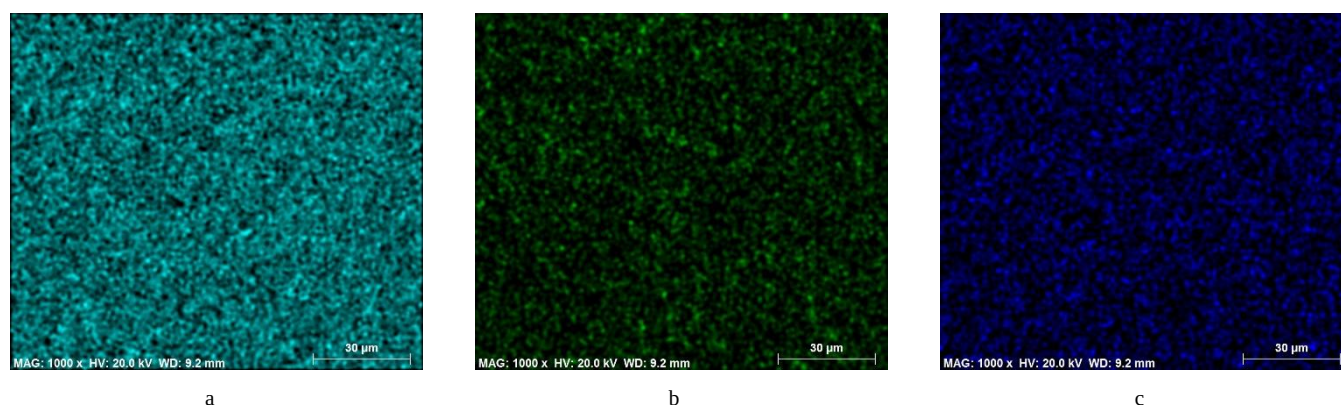


Fig. 6 “Coating 3”. Elemental map of: a – nickel map; b – oxygen map; c – iron map.

All elements are evenly distributed, which is consistent with the refined morphology of the nodules observed in the SEM images, confirming that “Coating 2” has a more homogeneous microstructure and higher coating density compared to “Coating 1”.

The Ni distribution map of “Coating 3” shows a continuous Ni-rich matrix (Fig. 6 a); however, it appears slightly less regular than in “Coating 2”, with minor local variations in intensity that correspond to the coarser and less compact surface morphology observed by SEM (Fig. 1 c). The oxygen distribution map is visible across the entire surface (Fig. 6 b), confirming the presence of an oxide-containing dispersed phase; however, its distribution appears slightly less uniform than in the “Coating 2” and more closely resembles a somewhat disordered particle arrangement. Meanwhile, the Fe map (Fig. 6 c) is fainter than that of the first layer, indicating that the upper layer still covers the bedrock fairly well, although it appears slightly lighter than the densest parts of the second layer. This confirms the earlier findings that, in terms of the influence of the substrate, “Coating 3” is not as defective as “Coating 1”, but structurally it is less homogeneous and less dense than “Coating 2”.

4. Conclusions

Based on a comprehensive analysis of all the studies conducted, namely, SEM observations, elemental distribution maps, and EDS spectra, clear qualitative differences are evident in the microstructure of the Ni-SiO₂ nanocomposite coatings obtained under different deposition conditions. The “Coating 1”, plated at a voltage of 4 V, exhibits the most heterogeneous structure, characterised by irregular node morphology, uneven silicon distribution, and the strongest iron signal, indicating a partial substrate effect and a very low film density. Meanwhile, the “Coating 2”, plated using a higher voltage (8–10 V), exhibits a highly homogeneous and densely deposited nodular surface

characterised by an even distribution of silicon, a continuous nickel matrix, and the weakest iron signal, which confirms better nanoparticle penetration and better coating compaction. The “Coating 3”, plated at a voltage of 4 V and a shorter time (1 min), also forms a uniform coating on the substrate surface; however, its surface is rougher; furthermore, the presence of microcracks and a less uniform distribution of Si indicate insufficient growth and lower structural stability compared to “Coating 2”. The Fe signal in the “Coating 3 is weaker than in the “Coating 1”, which confirms the reduced influence of the substrate; furthermore, the shorter curing time limits the coating thickness and uniformity. To summarise the results obtained, it can be concluded that increasing the deposition voltage to 6–10 V results in more uniform particle penetration and the formation of a more compact layer, whereas a lower voltage and shorter deposition time lead to a non-uniform and less stable microstructure.

Acknowledgments

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Study of the utility properties of selected types of polymer powder coatings

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Abstract: This paper deals with the study and evaluation of the utility properties of selected types of polymer powder coating systems applied to S235JR structural steel. The primary objective was to assess the influence of the coating system composition (combination of primer and topcoat versus individual layers) on its mechanical properties and corrosion resistance. The experimental part included surface preparation by blasting, electro kinetic application of four types of coating systems (Corro zinc 97, Corro coat MX, and Corro coat PE-F), followed by testing of roughness, thickness, adhesion, and bending resistance. Corrosion resistance was evaluated in a condensation chamber. The measurement results confirmed that the plasticity, measured by the bending angle, decreases with increasing coating thickness. The highest adhesion was exhibited by the combined coating system Corro zinc 97 + Corro coat MX. Corrosion tests demonstrated the crucial importance of the zinc-rich primer, which significantly slowed down the spread of sub-corrosion at the site of mechanical damage.

Keywords: POLYMERPOWDER COATING, BLASTING, ROUGHNESS, PULL-OFF STRENGTH, CORROSION RESISTANCE

1. Introduction

Sustainability is becoming a key pillar of modern industry. Manufacturers seek ways to reduce their environmental footprint without compromising quality. Polymer powder coatings are emerging as one of the most eco-friendly surface treatment methods, offering a superior alternative to traditional liquid paints by eliminating harmful emissions and minimizing waste.

The primary environmental benefit of this method lies in the elimination of organic solvents, resulting in virtually zero emissions of volatile organic compounds (VOCs). Toxicological studies indicate that most polymer-based powder coatings are considered inert. Since these coatings contain no solvents, they can be applied immediately without the need for ancillary processes typical of wet coatings, such as dilution or mixing. [1 – 4]

In contrast to wet coatings, where the solids-to-solvent ratio is typically 50:50, the solids content in powder coatings is practically 100%. However, because powder coatings are relatively hygroscopic, they absorb moisture from the surrounding air during production, bringing the actual dry matter content to approximately 99.5%. From an environmental perspective, these coatings play a crucial role by substantially reducing emissions of volatile organic compounds and other hazardous air pollutants.

The protective performance of polymer coatings depends on the chemical nature of the base material and its resistance to aggressive environmental factors. The durability of the protection is primarily determined by the diffusion of corrosive agents into the coating, structural changes caused by sorption and diffusion, and the overall coating thickness.

Most polymer coatings consist of a mixture of resin (e.g., polyester, epoxy), curing agents, flow control agents, catalysts, pigments, and fillers, with the resin serving as the matrix in which all other components are dispersed. This resulting mixture is practically insoluble in water. Similarly, most other components of the powder formulation exhibit very low to zero solubility. Toxicological studies indicate that the majority of powder coatings are considered inert materials. [5 – 12]

In addition to the basic resin system with a curing agent (binder/hardener), the resulting powder coating mass consists of:

- pigments - contribute to the colour and covering properties of powder coatings,
- fillers (fillers) - reduce the price of raw materials and give applications their properties.
- additives - they help with useful properties (film spillage, creation of texture and structure).

The earliest experiments and commercial applications of polymer coatings utilized thermoplastics. While these powder coatings are still used to some extent today, manufacturers now

focus primarily on thermosetting powders. A key property of these reactive powders is that curing occurs during the melting process, triggering a change in molecular structure. This results in a cross-linked polymer that does not melt when reheated. [13 – 15]

Initially, powder coating manufacturers had to adapt materials originally developed for liquid coatings; however, binder systems eventually evolved specifically for powder applications. The requirements for binders in thermosetting powder coatings differ significantly from those used in conventional liquid paints. For reactive powders, it is crucial that the binder system has a relatively high melting point (above 100°C) and a specific viscosity profile once melted. The melting point is also critical for storage stability. Additionally, these systems must offer rapid curing alongside excellent mechanical and chemical properties. Due to these requirements, the number of suitable binders for powder coatings remains limited.

2. Materials and methods

2.1 Basic material

Unalloyed structural steel of usual quality S235JR was used as the basic material. It is used for fusion-welded, statically and dynamically stressed parts of constructions and machines of medium thickness. The chemical composition of the materials is in Table 1.

Table 1. Chemical composition of used steel S235JR in wt. %

Material	C	P	S	N
S235JR	0.17	0.045	0.045	0.009

2.2 Pre-treatment of the surface

The surface of the S235JR steel test samples was blasted with steel shot with a grain size of $dz = 0.71$ mm.

Steel shot is a round metal blasting medium made of hypereutectoid, specially heat-treated steel. It has a fine, homogeneous structure of tempered martensite, which exhibits optimal rebound elasticity and fatigue resistance. This material is optimal for most applications using shot blasting wheels.

Chemical composition: C $\geq 0.75\%$, P $\leq 0.04\%$, S $\leq 0.04\%$,
Mn $\geq 0.40\%$, Si $\geq 0.70\%$.

Average hardness: 460-560 HV.

A pneumatic blasting device, type TJVP - 320, was used for blasting the samples.

2.3 Roughness measurement methodology

Surface roughness of the produced samples was evaluated according to ISO 21920 by the contact method using a stylus profilometer SurfTest SJ-201, Mitutoyo, Tokyo, Japan. This standard defines roughness parameters based on the deviation from the mean line for the primary profile. The measurement parameters used were as follows:

- a measured profile: R, filter: GAUSS, a sampling length $\lambda_c = 0,8 \text{ mm}$, a number of sampling lengths $N = 5$,
- an evaluation length $l_n = 4 \text{ mm}$,

In order to obtain as much information as possible about the produced surfaces in individual positions, the surface roughness was evaluated using a set of several parameters:

- the arithmetical mean deviation of the assessed profile (R_a),
- the maximum height of profile on the basic length (R_z).

2.4 The coatings used, the method of their application and testing of properties

2 coating systems and 2 coatings were chosen for the experiments:

1. coating systems: Corro zinc 97 + Corro coat MX (sample designation Z+MX)
2. coating systems: Corro zinc 97 + Corro coat PE-F (sample designation Z+PE-F)
3. coating: Corro coat MX (sample designation MX)
4. coating: Corro coat PE-F (sample designation PE-F)

Corro zinc 97 [16] is a powder coating material, the basis of which is epoxy resin, the powder is enriched with zinc for increased corrosion resistance. Corro zinc 97 is used as a basic powder coating material.

Corro-Coat MX is a powder coating based on a combination of epoxy resin and polyester (hybrid). This product highly satisfies the requirements, both in the field of aesthetics and functionality. Corro - coat PE-F is a powder coating material, the basis of which is a mixture of polyester resins, inorganic and organic pigments, fillers and additives. The coating meets strict requirements for gloss stability and color fastness.

The samples were coated in an electrokinetic way using an EKP 031 gun for manual application of powder coating materials with an attached powder container.

Coating thicknesses were measured with a DIGI-DERM 179 device from Mitutoyo, Japan. It is a non-destructive method of coating thickness measurement based on the electromagnetic method.

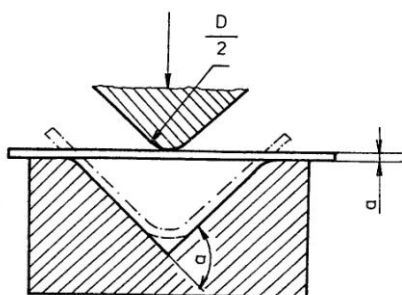


Fig. 1 Scheme figuration of specimen bending

As part of the experimental works, the bending angle of the monitored coating systems was assessed. The ISO 7438 brittleness test was used to determine the bending resistance. The test scheme is shown in Fig. 1.

The bending test was performed on a ZD 40 hydraulic press from VEB Leipzig. The bending process was completed at the moment of

the appearance of a visible crack in the coating at the bending point, and then the bending angle was measured α .

The adhesion evaluation of coating systems was carried out by a modified tear-off test according to ISO 4624:2023. It is expressed as a pull-off strength, which is the proportion of the tensile axial force required to jointly tear off a coating with a defined area that is adhered to the test counterpart

The protective effectiveness of the coating system in an aggressive atmosphere containing sulfur dioxide was evaluated using a simulated condensation chamber test in accordance with ISO 6270-2:2025. To simulate coating pores, the integrity of the system was intentionally breached with a cross-cut, allowing the atmosphere to access the substrate surface. The extent of corrosion along the cut and the spread of corrosion products beneath the coating were evaluated according to ISO 4628-1:2016. The total test duration was 21 days.

3. Results and evaluation

➤ Roughness:

The quality of the blasted surface of the samples was evaluated from 10 measurements. The average values achieved were:

- $R_a = 9.87 \mu\text{m}$,
- $R_z = 56.73 \mu\text{m}$.

In Fig. 2 is a profilogram of a surface blasted by round steel shot. The blasted samples were subsequently coated by electrokinetic method.

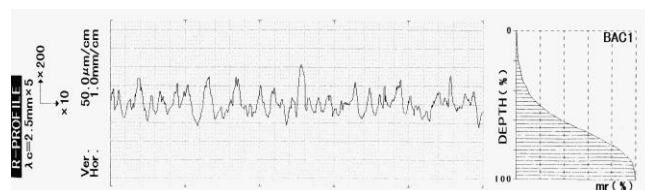


Fig. 2 Surface profile blasted by round steel shot

➤ Coating thickness:

For the Corro coat MX coating, the manufacturer indicates a coating thickness of 60 to 90 μm . The average value we achieved was 86 μm . For the Corro coat PE-F coating, the thickness recommended by the manufacturer is 80 to 110 μm , the coating thickness we achieved was 103 μm . For the base coating type Corro zinc 97, the manufacturer recommends a coating thickness of 90 to 120 μm , the average coating thickness we achieved was 117 μm . The coating system type Z + PE -F reached an average thickness of 191 μm , this value is in the range of values recommended by the manufacturer. The coating system type Z + MX reached an average thickness of 244 μm .

All coating systems achieved an average thickness in the range of values recommended by the manufacturer. Higher thickness values were measured only for the Z + MX coating system, the average value being 34 μm more than recommended by the manufacturer.

➤ Bending angle:

The values of the bending angle in relation to the average thickness of the coating are shown in Table 2.

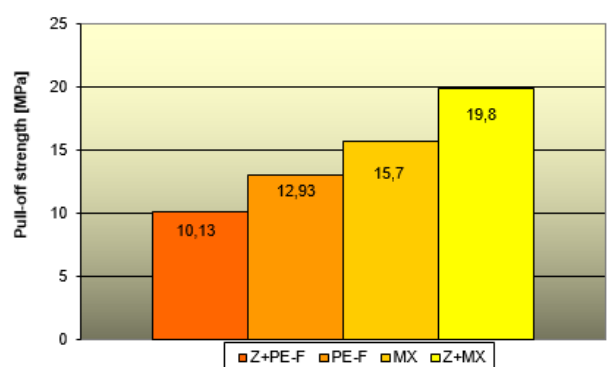
Table 2. The bending angle and the average thickness of the coating

Type of coating	Sample number	Bending angle α [°]	Average coating thickness [μm]
Corro - Zinc 97 + Corro - Coat PE-F	1	120	228
	2	139	147
	3	118	242
Corro - Coat PE-F	1	129	157
	2	135	75
	3	116	211
Corro - Zinc 97 + Corro - Coat MX	1	95	218
	2	85	241
	3	105	151
Corro- Coat MX	1	116	134
	2	137	75
	3	112	103

The experiments confirmed the theoretical assumption that increasing coating thickness leads to a decrease in the bending angle at which the coating fails. A comparison of the average bending angles revealed that Corro-Coat PE-F coatings exhibit slightly higher plasticity than Corro-Coat MX, based on the point of failure. This trend was observed both in individual coatings and in coating systems where both types were applied over the same Corro-Zinc 97 primer.

➤ Adhesion of coating systems:

The average values of the pull-off-strength are shown in Fig. 3. Of the verified coatings, the Z+ MX coating system exhibited the highest tear-off stress, and the Z+PE-F coating system showed the lowest tear-off stress. The Z+MX and Z+PE-F coating systems displayed a type C cohesive failure of the second coating, coating systems MX and PE-F showed cohesive failure of type B (cohesive failure of the first coating).

**Fig. 3** Average pull-off strength values

➤ Protective effectiveness of coating systems

When evaluating the protective effectiveness of the coating systems, a fundamental difference was observed between systems with a primer (Corro-Zinc 97) and those without. These differences were most evident in their respective resistance to corrosive environments.

On samples with a primer-based coating system, the first signs of under-film corrosion—appearing as dark brown spots—were observed only after 14 days of exposure in the condensation chamber. Subsequent spread of the corrosion was minimal. Visual assessment showed no changes in color shade for either primer-

based system. By the end of the test (after 21 days of exposure), the extent of corrosion was within the range of 6% to 8% of the cross-cut length.

In samples without a primer, the first signs of corrosion appeared as early as the second day of exposure. The progression of the corrosion was more pronounced compared to the primer-based samples; by the end of the 21-day test period, the extent of the attack ranged from 10% to 15% of the cut length.

The appearance of the samples after the 21st day of exposure in the condensation chamber is shown in Fig. 4.

**a)** coating MX**b)** coating PE- F**c)** coating system Z+MX**d)** coating system Z+PE-F**Fig. 4** Appearance of the samples after exposure in the condensation chamber

Conclusions

This study aimed to evaluate the properties of selected coating systems consisting of polymer powder coatings. Attention was focused primarily on their service life and corrosion resistance under accelerated environmental conditions. All coatings applied via electrokinetic deposition exhibited equivalent corrosion resistance in terms of adhesion, with no recorded decrease after 21 days of exposure in the condensation chamber. Furthermore, no changes in the appearance of these coatings were observed during the testing period.

A fundamental difference was observed when the integrity of the coatings was intentionally breached prior to exposure in the condensation chamber. The results clearly demonstrated the positive effect of the primer. In systems without a primer, corrosion products spread and accumulated at the site of the mechanical failure, leading to partial delamination of the coating.

Based on the findings above, it can be concluded that all tested coatings and coating systems are corrosion-resistant, provided that technological parameters—especially minimum coating thickness—are strictly maintained. Thinner coatings are more susceptible to porosity, in which case a primer (base coat) plays a crucial role. This also applies to scenarios involving mechanical damage, leading to the recommendation that a dual-layer system consisting of a primer and a topcoat be used.

The experimental results underscore the importance of proper coating selection and application technology in ensuring long-term substrate protection. While polymer powder coatings offer a highly sustainable and efficient alternative to traditional liquid paints, their performance is heavily dependent on maintaining optimal thickness and structural integrity. The integration of a primer into the coating system serves as a critical safeguard, significantly enhancing corrosion resistance and durability even in cases of mechanical failure. These findings provide a valuable baseline for further optimization of surface treatment processes in demanding industrial environments.

Acknowledgement:

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Backdraft Damper for Fully Stopping the Backflow Air through Ventilation Appliances, Including Low Power Fans

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Abstract: Based on the patent number 67081 from 15.06.2020 issued by BPO, a back draft damper (shutter) for fully stopping the backflow air is being developed. The commonly foreseen butterfly shutters, have slits and allow odors, wet and pathogens to enter through the vents when ventilating devices are turned off. Available are shutters, using blades, with additional sealing mounted, which can solve the problem, but they can operate only with powerful fans. Opening becomes problematic if used with low power domestic fans. On the world market there is no fully closing shutter capable to work with the common low power fans. The present innovation works on the principle of the ball check valve, as an assembly of multiple truncated cones containing low weight balls. It offers a solution of the shutter's incomplete closure problem, suitable to operate with any fan. During the research, many parameters are being investigated to reach the optimal solution.

Keywords: BACKDRAFT DAMPER, SHUTTER, BALL-CHECK VALVE, HERMETICAL CLOSURE

1. Introduction

In today's multiple store residential buildings, the ventilation of bathrooms and kitchens of the individual flats is achieved mainly with exhaust fans and extractor hoods, respectively. Although butterfly dampers are commonly foreseen, undesirable wet and odors quite often are entering through the vents when the ventilating devices are turned off. On the other hand, individual houses have problems with the wet and cold entering through the ventilation devices in wet or cold environments. The reason for this disturbing effect is simple: the commonly used dampers, are not capable to shut completely the vent due to an unavoidable shortcoming in their design: whenever flaps are being used for making an easy operating damper, inevitably slits may appear when the damper is supposed to be completely shut. Improving the flap attachment and addition of sealing can fix to some extend the problem, but the easy movement of the closing members can get lost and they can operate only with really powerful fans. In fact, the most common fans of diameter 100 mm, presently can operate, only with the simple butterfly shutter.

A solution was found in a patent [1] from 2020, issued by the Bulgarian Patent Office. Instead of a flap based mechanism, a truncated cone- with or without apertures, being the valve body, is mounted airtight and slightly inclined into a housing with a spherical closing member (ball) freely moving inside the truncated cone, as shown in Fig. 1. The ball is light weighted, preferably hollow, deformation resistant. The dimension of the ball is such that it closes tightly the lower narrow end of the inclined truncated cone when the fan is turned off. The damper opens, when the fan is being turned on – when the ball frees the narrow end of the cone. When closed, there are no slits between the ball and the round end of the truncated cone, and the damper seals the vent basically hermetically. It is recommended for the damper to include multiple valve bodies and to be place in front of a fan.

2. Previous innovations for ball valve backdraft damper and the advantages of the present innovation

The first patented air backdraft damper with a ball as a closing member [2] is from 1996. The ball is moving within a curved duct at whose lower end as a separate part, a ring-shaped seat is mounted. It is presented as to be placed outside of the home's interior and it is a voluminous body of considerable size. It can hardly be used inside of apartments. There is also an abandoned patent application [3], where the ball is supposed to move inside of a cylinder inclined at angle 5° - 10° , containing an inner rim with padding for stopping the ball and closing the valve. In this case, the ball must fit tight into the duct, which is necessary when the valve has to be tightly closed. In this case, however, the unhindered movement of the ball could be easily obstructed. There is also a third document, an utility model [4], which describes a vertical cylinder with a conical tapered seat for the ball at its end and a cover on top. It resembles the well known ball check valve.

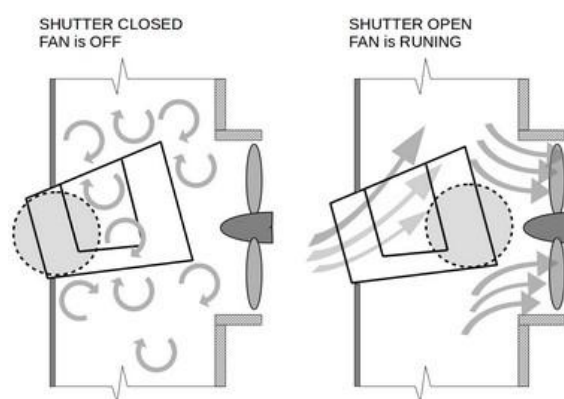


Fig. 1 Schematic drawing of the assembled back-draft damper in front of a bathroom extractor fan.

Combining a cylinder with a tapered cone seat or with a narrowing of another kind, or with a rim, flange, edges, suggests that the obtained body is axially symmetric. Placing a ball inside that body, whose diameter is smaller than the diameter of the cylinder, which is necessary for the free movement of the ball for the discussed application as a back-draft damper, and if the body is not vertically oriented, then the ball's center can be offset from the body's symmetry axis. As a consequence, at certain inclinations of the valve, due to the differing diameters and the misalignment of the ball with respect to the symmetry axis, a slit may appear when the valve is expected to be shut. By a dedicated choice of inclinations and geometry of the valve body - valve closure assembly, the appearance of the slit can be avoided and certainly this has to be carefully examined if such layout is considered.

All previously proposed as inventions air backdraft dampers (shutters) have cylindrical kind of shapes (curved, elbow or straight) and they all use only one valve body with an additional closure for the ball in a form of ring-shaped seat, rim, or flange. In the present invention being developed, just a truncated cone is proposed as a valve body, preferably without apertures on its surface, being placed in a way that the lower located narrow end of the truncated cone is actually the conically tapered valve's inlet. In this way, there is no need of attaching an additional closing part to the valve body. The inclination of the truncated cone can be any angle from small angle with respect to the horizontal plane to vertical inclination. In this case, the appearance of a gap when the check valve should be in closed position for all possible mounting angles is avoided, unlike the proposed products in the prior art. The truncated cone as a valve body eliminates the need of precisely match the dimensions of the ball and a valve seat, flange, rim, as the ball will naturally stop when it completely covers the decreasing cross-section of the cone. The larger opening of the truncated cone can serve as a natural outlet for ventilation without the need for

apertures on the surface of the truncated cone or providing an additional branch to keep the ball away from the air flow. An important innovation is the recommended use of several smaller ball containing valve bodies, instead of one large valve body having the dimensions of the vent, containing a correspondingly large ball as in the previous innovations, which leads to a complicated indoor installation and an unaesthetic and disturbing appearance. In this way, the size of the shutter is significantly reduced without significantly reducing the flow rate, which makes it particularly suitable for use with bathroom fans, and even placing it in front of the exhaust fan, not behind it. In addition, a hollow ball is proposed. Using many valve bodies in one damper housing, together with the hollow plastic balls, makes the damper more sensitive and suitable for weak fans. It also allows the so-called self-ventilation effect to take place, when under favorable conditions the backdraft damper opens and lets the air flow to the ventilation shaft without the fan being turned on. In this way, the home is protected, but without at the same time being deprived of air exchange. An illustrative example of the innovative product is presented in Fig. 2.

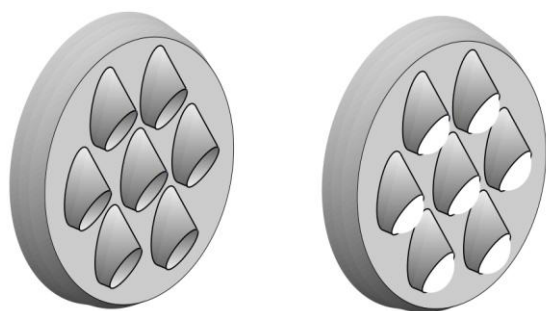


Fig. 2 Illustrative example of the back-draft damper.

3. Research and development of the patented product

The aim of the development of the product was to achieve at least the air flow as obtained with a simple butterfly damper, which is currently the only damper which can work with a low power fans of 100 millimeter diameter. However, these dampers are far from providing an airtight closure, enabling severe backdraft to pass through them under unfavorable conditions. The development of the current innovation will provide an airtight closing backdraft damper (shutter), which can work with the weakest low power fans on the market. Currently, to our knowledge, the world market does not offer a product satisfactory fulfilling these requirements, although the demand is present.

The working principle of the innovation is simple, but for the development of an optimal product, many options have to be considered altogether. Being basically a truncated cone, the valve body has a certain opening angle which has to be carefully determined. This angle must not be too shallow, so that the ball shall not have a possibility to remain stuck in the valve body, but also not too large in order not to take too much space inside the damper. In addition, this angle must be determined consistently with the inclination of the valve body, the diameter of the ball and the material and smoothness of the ball. The inclination must be such, that the closure to be guaranteed, as well the maximum airflow and the self-ventilation at proper conditions to be allowed. Using balls of bigger diameter will allow better rate of the airflow, but using smaller balls will allow a more elegant appearance, smaller dimensions of the damper, also serving as a decoration and providing at the same time an airtight closure of the vent.

Series of measurements of the airflow with various extractor ventilation fans, together with various shutters, various fan's front decorations, and with various front shutter's decorations, were performed. Measurements with a powerful fan of 120 millimeter diameter and airflow of about 160 m³/h show an acceptable, even if not perfect airflow with most shutters and decorations being attached, as can be seen in Table 1. However, that is not the case with a less powerful fan of 100 millimeter diameter with airflow of 60 – 90 m³/h, which is actually the more common one. The measurements of the airflow through a low power fan of 100 millimeter diameter show that introducing a butterfly damper decreases the airflow by 60%. The airflow becomes heavily obstructed when introducing a throttle flap. Such a low power fan also can hardly open a shutter with well sealed slats. Considering that most commonly there is a decoration in front of a fan, the airflow will be additionally lowered. There are well developed grid decorations, which decrease the airflow by less than 20%, but there are also decorations which decrease the airflow by more than 40% even without a shutter being placed behind the fan.

Table 1: Relative airflow through ventilation fan with added backdraft damper (shutter) or decorative element in percent with respect to the undisturbed airflow passing through the fan without damper or decorative element. The presented air flow rates are estimated with our set up.

Backdraft damper attachments	Relative airflow through a fan with d = 100 mm and Q ~ 70m ³ /h	Relative airflow through a fan with d = 100 mm and Q ~ 140 m ³ /h	Relative airflow through a fan with d = 120 mm and Q ~ 160 m ³ /h
Butterfly damper only	40%	31%	75%
Decorational grid only	82%	--	81%
Decorational grid and butterfly damper	44%	-	73%
Square decoration only	65%	71%	80%
Square decoration and butterfly damper	Air flows only through the slits of the closed damper	76%	65%
Single flatter damper with sealing rim, without grid	Damper does not open	4%	Damper does not open
Double flatters damper with sealing rim, without grid	34%	20%	45%
Ball back draft damper with 7 valve bodies and angles of inclination of 4° (upper value) and 6° (below)	55% 50%	54% 50%	75% 75%

With the present innovation, the necessity of a shutter and front decoration is omitted. The backdraft damper is preferably placed in front of the fan, serving that way both, as a back-draft damper fully stopping the backflow air and as a decoration.

Few general results were obtained. It was found that if the balls can be allocated away from the closing position by 75% of their diameter, then the airflow through the back-draft damper is as there were no balls at all. This can be interpreted as a sign of an undisturbed airflow, which was not expected when the balls are present. Thus keeping the airflow disturbances at a minimum is

another aiming point in the design of the damper, together with the damper's overall appearance and airflow's maximizing. Although the damper is functional with a ball's path slope of just more than 1° , the inclination of the valve body must be such that the ball faces a slope of more than 4° to take into account possible deviations from the ideal positioning of the mounted damper. With the fans of 120 mm diameter available, and the cones chosen, an inclination of not more than 12° , shows an appropriate reference, since its further increase leads to decrease of the air flow through the damper. However, that is not the case with 100 mm in diameter low power as well as higher power fans, where a smaller angle is more appropriate in order to obtain a higher airflow. The hollow balls of Acrylonitrile Butadiene Styrene (ABS) or Polypropylene (PP) plastic materials are considered as the most proper. It was concluded that the best diameters for the balls is the diameter of 40 mm as are the ping-pong balls and 34 mm. The first case will allow better airflow when it is needed, while the second will make the damper more attractive in appearance. The initial choice of the ping-pong balls is based on the fact that they have properties crucial for the operation of the damper: smooth almost perfect spherical shape, resistance to deformation, light-weight, and easily available.

The ball backdraft damper with multiple valve bodies, and smaller and hollow plastic balls, makes the damper more sensitive to weaker air flows, and thus functioning with very low power fans. Indeed, when the ball pops out, it no longer opposes the airflow and there is no need to increase the fan power. That is not the case with the flap-based dampers, in which the flaps oppose the air flow until fully opening, which is achievable only with more powerful fans.

Number of prototypes were prepared. The optimal angle of inclination of the valve body for the case with 40 mm ping-pong ball was obtained and incorporated in prototypes in Fig. 3 and Fig. 4. The optimal linear dimensions of the casing of the back-draft damper were determined within dedicated measurements.



Fig. 3 A prototype of the developed innovative product with four valve bodies and spherical closing members with diameter of 40 mm. The ventilation fan is behind the backdraft damper.

It was found that using a low power fan of 100 mm diameter and airflow of about $70 \text{ m}^3/\text{h}$ with the backdraft damper presented in Fig. 5, the airflow received is by 10-15 % higher than that with a butterfly damper. So, the aim to receive at least airflow rate as with a butterfly damper with a low power fan is not only achieved, but is actually exceeded. The airflow rate through the present backdraft damper and through a butterfly damper is similar when used with a fan of 120 mm diameter and airflow of $162 \text{ m}^3/\text{h}$ measured with our set up. It was also found that one of the most proper fans with which the developed backdraft damper to work with is the high power fan of 100 mm diameter and airflow about $140 \text{ m}^3/\text{h}$, as

measured with our set up. With this fan, the present damper provides about 20 % higher airflow than the butterfly damper and 30 % more than the damper with well sealed slats. Of course, the absolute rate through this fan with any damper is higher than the rate through the low power $d = 100 \text{ mm}$ fan with the corresponding damper. One can see in Table 1 that nonlinear effects emerge with different fans and dampers.



Fig. 4 A prototype of the developed innovative product with five valve bodies and spherical closing members with diameter of 40 millimeter.

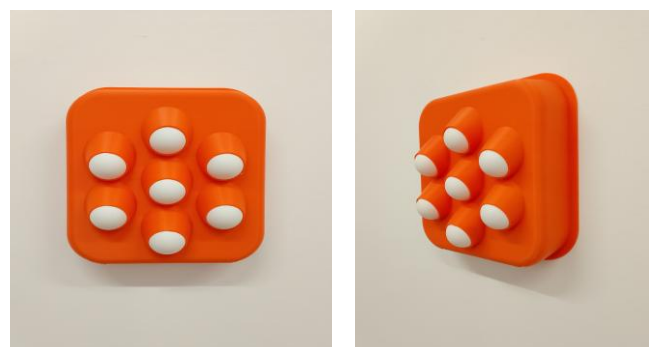


Fig. 5 A prototype of the developed innovative product with seven valve bodies and spherical closing members with diameter of 40 mm.

4. Summary

A back-draft damper for fully stopping the backflow air, based on the patented invention [1] from 2020, issued by the Bulgarian patent office, is being developed. It was found that the invention works properly not only with powerful fans, but also with low power fans. To our knowledge, it would be the only product on the market to satisfactory fulfilling both requirements- to work with low power fans and to fully stop the backflow air. Pointing out that the invention can work properly with low power fans, in fact it actually provides a higher airflow than the most common not fully closing butterfly dampers. Taking into account that the present invention combines the role of a backdraft damper and a decoration, then the achieved airflow is effectively higher. A considerable market demand for such a product is expected.

5. Acknowledgements

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Investigating the effectiveness of compost and liquid fertilizer obtained from an electro-generative composter

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Abstract: This study investigates the effectiveness of a liquid organic soil fertilizer and compost obtained through the degradation of green waste in a bio-electrochemical system. The substrate produced by an electro-generative composter was applied to humus- and nutrient-poor soil planted with *Lens culinaris* (lentils). The results demonstrate a clear positive impact of the organic fertilizer and compost on soil fertility and plant growth. Compared to a control group, the treated soil exhibited higher concentrations of nitrogen (N), phosphorus (P), and potassium (K), along with improved moisture retention and lower acidity. Consequently, plants grown in the treated soil displayed significantly greater stem and root lengths, fresh and dry weights, and overall biomass. These findings highlight the potential of bio-electrochemical systems for sustainable waste management and the production of valuable organic fertilizers that enhance soil health and crop productivity.

Keywords: BIO-ELECTROCHEMICAL SYSTEMS, GREEN WASTE, ORGANIC SOIL FERTILIZER, COMPOST

1. Introduction

Environmental pollution caused by solid organic waste is one of the most serious global problems. The accumulation of large quantities of agricultural waste, animal excreta, and municipal solid waste poses a significant ecological challenge that is difficult to resolve. Waste contains a considerable amount of energy, which is why converting it into energy is considered a viable alternative. [1] Widely used and researched biological treatment methods include composting and anaerobic digestion. The latter, also known as anaerobic composting, offers the possibility of converting solid waste into usable energy and biofuel. However, modern research shows that anaerobic digestion has several limitations – long residence time, low degree of biomethane purification and its conversion into electricity, as well as safety concerns, making it an imperfect solution for achieving zero discharge. [2] On a global scale, the management of wastewater and solid waste lags behind the rate of their generation, leading to serious environmental and health consequences. This highlights the need to develop new and more efficient technologies for the treatment and utilization of waste. [3]

The application of microbial fuel cells can be used for the treatment of organic waste with simultaneous energy generation. A microbial fuel cell (MFC) is a device that converts chemical energy into electrical energy through the action of microorganisms. [4] Most MFCs use an organic electron donor (from natural resources) that is oxidized to produce CO_2 , protons, and electrons, thus making the technology significant among other methods for treating organic waste, particularly in terms of renewable energy production. [5] In recent years, microbial fuel cells (MFCs) have increasingly been studied as devices for alternative treatment and electricity generation from waste (waste valorization) without intermediate processing steps. [6]

Microbial fuel cells are classified according to the substrate used – they are either liquid-phase or solid-phase microbial fuel cells. The difference between the two lies in whether the substrate is in a solid or liquid phase. The substrate used in liquid-phase microbial fuel cells is usually domestic or industrial wastewater, while the substrate used in solid-phase microbial fuel cells consists mainly of solid organic waste – plant residues, food waste, animal excreta, and others. [7] The resulting new processed substrate has a highly valued agronomic potential as an organic fertilizer and liquid soil conditioner. After the decomposition of the primary organic waste in the microbial fuel cells, a new sustainable product with added value is obtained, such as an organic soil conditioner. [8]

The growing global population, combined with urbanization, leads to increasing food consumption. At the same time, modern agriculture is under pressure to ensure food security while reducing its dependence on synthetic chemical fertilizers, whose production

is energy-intensive and can harm ecosystems. In this context, organic fertilizers derived from organic and natural sources are emerging as a promising solution. [9] By transforming organic waste into nutrient-rich organic fertilizers, it is possible to bridge the gap between waste management and sustainable agriculture. This process not only reduces the environmental burden caused by the disposal of organic waste but also supports soil health, lowers agricultural costs, and promotes the principles of the circular economy. [10]

Another important aspect is related to water resource management and agriculture, focusing on soil salinization. It is one of the most serious abiotic stresses facing agricultural systems worldwide, posing a threat to global food security and ecosystem health. Soil salinization reduces agricultural productivity through several mechanisms – high sodium concentrations destroy the structure of soil aggregates and the porous network, salt stress suppresses the diversity of soil microbes and enzyme activity, and through ionic antagonism and osmotic effects, the uptake of nutrients by crops and water availability are reduced. Organic fertilizers and compost can provide sufficient amounts of natural moisture-retaining agents, ensuring longer soil moisture retention and salinity reduction. [11]

Partially replacing chemical fertilizers with organic ones proves to be an effective technique for improving soil nutrients and increasing yields. Organic fertilizers play a key role in enhancing soil conditions. They effectively support the formation of suitable pore structures in the soil, facilitate the formation of macroaggregates, improve water transfer within the soil profile, regulate the ionic composition of the soil, and alleviate saline stress. [12] Moreover, organic fertilizers optimize the microbial environment in the soil and stimulate enzymatic activity in the root zone, accelerating the decomposition of organic matter and nutrient recycling processes. These synergistic effects ultimately increase crop productivity. [13]

The application of organic fertilizers obtained from household food waste and other organic sources represents a key tool for sustainable agriculture. It allows for simultaneous waste management, improvement of soil health, and increased crop productivity. [14] Despite existing challenges related to standardization, safety, and scalability of technologies, integrating organic fertilizers into agricultural practices is essential for achieving global food security and protecting the environment. [15]

The aim of this study is to determine the effectiveness of a liquid organic soil fertilizer and compost obtained through the degradation of green waste in a bio-electrochemical system. The substrate produced by the electro-generative composter was applied to humus- and nutrient-poor soil with planted *Lens culinaris*.

2. Materials and methods

Liquid soil fertilizer and compost

After three months of vegetation staying in the electro-generative composter, two products with potentially beneficial effects on soil quality were obtained – a liquid soil improver and compost. The resulting liquid soil improver has the following characteristics – pH 5.3, COD 5214 mg O₂ /L, N 4.4 g/L, P 2.3 g/L, K 7.7 g/L. The obtained compost was air-dried for two weeks, after which it was sieved to a size of 2–3 mm.

Soil

The soil used for the experiment is extremely poor in humus and infertile, with low nutrient content. It has the following main characteristics – humus content 3 g/kg, N 3.81 mg/kg, P 5.47 mg/kg, K 15.02 mg/kg, pH 4.89.

Description of the experiment

In each of two containers, 1.5 kg of soil was placed. In one of the containers, compost was added at a ratio of 20 g of compost per 1 kilogram of soil. Then, an equal amount of *Lens culinaris* was planted in the soil of both containers. The container with soil and compost was irrigated with a liquid soil fertilizer diluted with water at a ratio of one to two. After planting, the containers were illuminated with LED grow lights until the stem length of the plants reached 10 cm (Fig. 1). Afterwards, the containers were moved outdoors into sunlight. Following four weeks of vegetation, the plants were removed, and their root system length, stem length, fresh weight, and dry weight were measured.

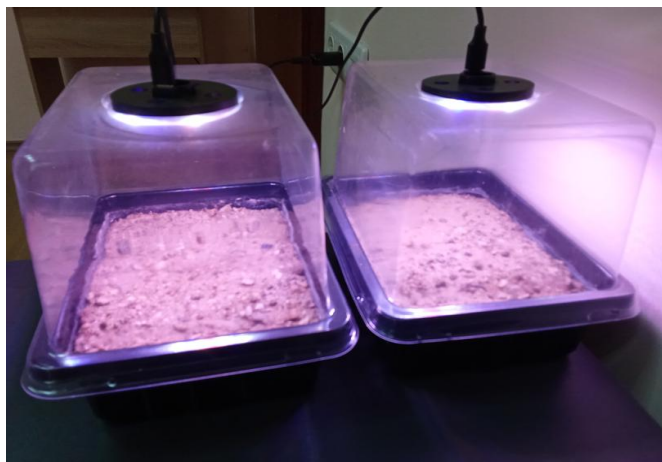


Fig. 1 Illumination with LED grow lights at the beginning of the experiment

The main soil characteristics were monitored throughout the entire experiment, being measured every third day after irrigation. Measurements of the main soil characteristics – moisture, pH, EC, N, P, K – were carried out using a CWT soil analyzer (Fig. 2).



Fig. 2 Measurement of basic soil characteristics

3. Results and discussion

Figure 3 presents averaged data for N, P, K measured during the experiment.

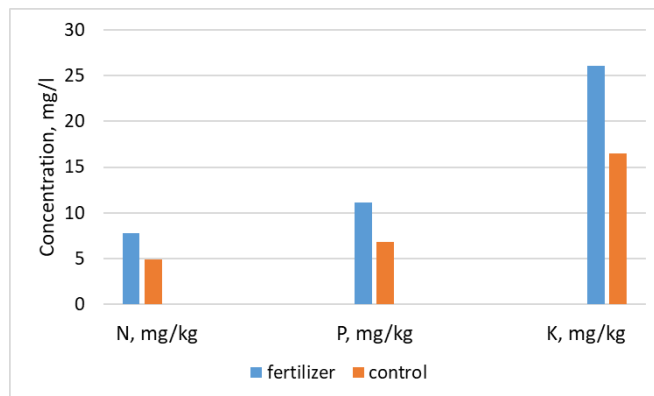


Fig. 3 Concentration of N, P, K in two types of soil

The experiment clearly demonstrates a positive effect of organic fertilizer and dry compost on the availability of the primary nutrients—nitrogen (N), phosphorus (P) and potassium (K)—in the soil. Data from the graph indicate that plants grown in soil amended with compost and watered with organic fertilizer had significantly higher concentrations of all three macronutrients compared with the control group.

The mean nitrogen concentration in the compost- and fertilizer-treated plants is 7.75 mg/kg, whereas the control plants show 4.87 mg/kg. This 2.88 mg/kg difference shows that the additional nutrients, especially nitrogen, were more readily available to the plants. Nitrogen is a key element for the synthesis of proteins, chlorophyll and other organic compounds required for growth and photosynthesis. The higher nitrogen concentration in the treated soils is an indicator of improved mineralisation of organic matter and more efficient root uptake.

The mean phosphorus concentration in the compost-treated plants is 11.12 mg/kg, compared with 6.87 mg/kg in the control. The 4.25 mg/kg increase is especially important because phosphorus is critical for energy metabolism (ATP), root development and flower/fruit set. The higher phosphorus level suggests that the compost and fertilizer enhanced the bio-availability of this element, likely by reducing its fixation in the soil or by releasing it from organic forms.

The mean potassium concentration in the treated plants is 26.12 mg/kg, while the control plants have 16.5 mg/kg. This nearly 10 mg/kg difference is the most pronounced and indicates that potassium was the best supplied in the amended soil. Potassium plays a pivotal role in water-balance regulation, enzyme activity and nutrient transport within the plant. The elevated potassium level is a sign of greater stress tolerance and more efficient metabolism.

After three months of vegetation, the plants were uprooted and the parameters of stem length and root length were measured. The results of the study are presented on figure 4. The conducted experiment clearly demonstrates the positive effect of organic liquid fertilizer and dry compost on *Lens culinaris* development. The data from the graph indicate that plants grown in soil with added compost and irrigated with organic fertilizer showed more intensive growth compared to the control group. The average stem length of the plants treated with compost and fertilizer was 25.07 cm, while for the control group it was 23.31 cm. This difference of 2 cm greater stem length in the plants treated with compost and fertilizer is an indicator of better photosynthetic activity and more efficient light absorption. This means that the additional nutrients, especially nitrogen, phosphorus, and potassium, stimulated cell elongation and the formation of more leaf mass. A larger leaf surface allows the plant to capture more solar energy and produce more organic substances necessary for growth. Root length is an important

indicator of the plant's ability to absorb water and mineral substances from the soil.

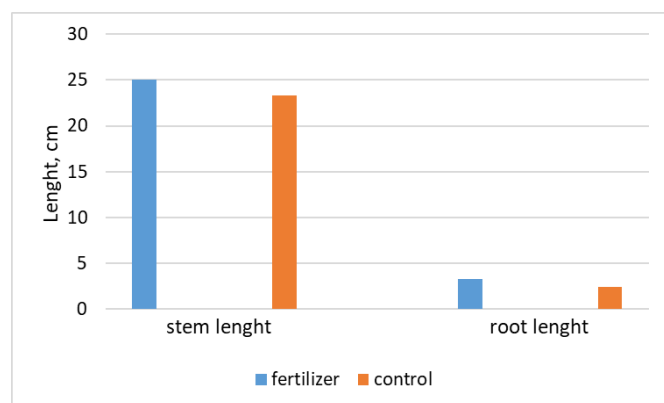


Fig. 4 Average measured length of the stems and roots of the plants

The average root length of the plants grown with compost and fertilizer was 3.27 cm, while for the control group it was 2.48 cm. The difference of 1 cm indicates that even when sufficient nutrients are present in the soil, the plant has developed a more effective root system. This is likely due to the improved soil structure provided by the compost, which facilitates root penetration and branching. A longer root system enables the plant to utilize a larger volume of soil for absorbing water and nutrients.

Figure 5 presents other important parameters for the effectiveness of the applied liquid organic fertilizer and compost – the fresh and dry weight of the plants.

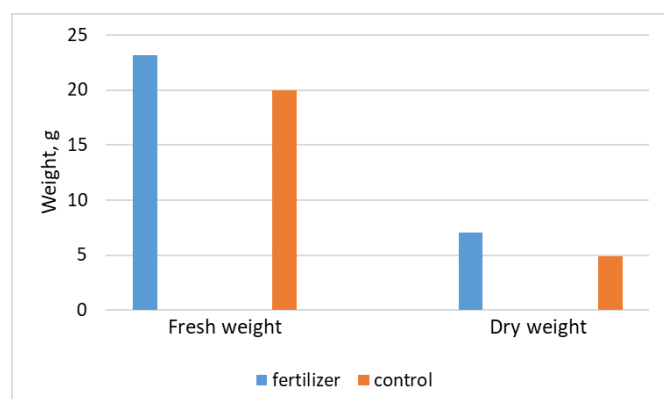


Fig. 5 Measured fresh and dry weight of the plants

The experiment clearly shows the positive influence of organic liquid fertilizer and dry compost on the biomass of *Lens culinaris*. The data from the graph indicate that plants grown in soil with added compost and irrigated with organic fertilizer achieved significantly higher fresh and dry weight compared to the control group. The fresh weight of the plants treated with compost and fertilizer was 23.15 g, while for the control group it was 19.98 g. This difference of 3 g is statistically significant and shows that the additional nutrients have stimulated not only growth but also the accumulation of water and organic substances in the plant tissues. Higher fresh weight is an indicator of better hydration and more intense metabolism, which is a result of the more efficient absorption of water and minerals from the soil.

The average dry weight of the plants grown with compost and fertilizer was 7.08 g, while for the control group it was 4.87 g. The difference of about 2 g is significant, as the dry weight reflects the amount of true biomass – i.e., the organic substances that the plant has synthesized through photosynthesis and accumulated in its tissues. The higher dry weight indicates that the plants with fertilizer and compost had better conditions for photosynthesis and the accumulation of nutrients, which is key to their development and future productivity. The dry compost improves the structure of the soil, increases its water-holding capacity, and creates a favorable

environment for the development of beneficial microorganisms. These microorganisms aid in the breakdown of organic matter and the release of nutrients in a form accessible to plants. The organic fertilizer additionally provides slow-release nutrients, which prevents stress from excessive concentrations and maintains stable growth. The combination of the two improves not only the quantity but also the quality of the biomass, as seen from the higher dry weight. Table 1 presents averaged data of soil parameters measured during the experiment.

Table 1: Mechanical properties of selected powder materials ^{Грешка! Источникът на препратката не е намерен.} *Note: Values in brackets are valid for heat-treated material.

	Soil moisture, %	EC, μ S	pH
Soil with compost and fertilizer	20.16	238	4.21
Control soil	15.21	90.5	4.71

The measured soil parameters – moisture, electrical conductivity (EC), and pH – provide information about the environment in which the plant roots developed. These data not only explain the observed differences in growth and biomass, but also confirm the mechanism of action of the compost and organic fertilizer.

The results show a significant difference in moisture between the two groups. The soil with compost and fertilizer retained 20.16% moisture, while the control soil had only 15.21%. This difference of nearly 5% is crucial for the success of the experiment. The organic matter in the compost increases the soil's capillarity and water retention capacity. The higher availability of water in the fertilized soil is a direct cause of the higher fresh mass measured earlier. Plants in the treated soil were less subjected to water stress, which allowed them to maintain turgor and sustain a more intensive metabolism.

Electrical conductivity is an indicator of the total concentration of soluble salts and ions in the soil. The value for the fertilized soil is 238 μ S, which is more than double compared to the control (90.5 μ S). This confirms the hypothesis that the addition of organic fertilizer and compost significantly increases the availability of soluble nutrients. The high EC value correlates directly with the previously measured higher concentrations of nitrogen, phosphorus, and potassium (N, P, K). This means that the soil was more fertile and provided a greater influx of minerals to the roots, which stimulated cell division and stem elongation.

Both soils are in an acidic environment, with the soil containing compost having a pH of 4.21 and the control soil having a pH of 4.71. The difference indicates that the process of decomposition of organic matter in the compost led to the release of organic acids, which lowered the pH. Although lentils generally prefer a slightly acidic to neutral environment (6.0–7.0), the fact that the plants in the more acidic soil showed better growth indicates that the positive effect of increased nutrient and moisture availability outweighed the potential stress from the low pH. This is an important point showing that, in the absence of other limiting factors, nutritional status is more decisive than a slight deviation in pH.

4. Conclusion

The conducted studies clearly demonstrate the positive impact of the organic liquid fertilizer and dry compost obtained from an electro-generative composter on the development and biomass of lentil (*Lens culinaris*). The application of these organic amendments leads to a marked increase in soil fertility, characterized by higher concentrations of the major macro-elements, enhanced moisture retention, and an optimized soil structure. As a result, the treated plants exhibit superior growth performance, reflected in longer stems and roots, higher fresh and dry biomass, and intensified photosynthetic activity.

Specifically, the mean stem length of the plants treated with compost and fertilizer is about 7% greater than that of the control

group. The mean root length is also greater in the treated plants—approximately 32 % longer compared with the control. These results indicate that, even when the soil already contains sufficient nutrients, the organic amendments stimulate the development of a more effective root system.

Regarding biomass, the fresh weight of the plants receiving compost and fertilizer is roughly 16 % higher than that of the control. The dry weight shows an even more pronounced increase—approximately 45 % higher. The higher dry weight is especially indicative because it reflects the amount of true biomass (the organic material synthesized by the plant).

The measured soil parameters—moisture, electrical conductivity (EC), and pH—confirm the mode of action of the compost and organic fertilizer. The amended soil retains about 32 % more moisture than the control soil. The EC of the treated soil is more than twice that of the control, evidencing a substantially greater availability of soluble nutrients.

These findings unequivocally highlight the effectiveness of using electro-generative composters to convert green waste into high-quality organic fertilizers. In addition to contributing to sustainable waste management, this approach improves soil health and promotes environmentally friendly agriculture. Future research should focus on optimizing the operating parameters of the electro-generative composter and scaling the technology for broader practical applications.

Acknowledgements

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Synchronous Electric Motor with Permanent Rare Earth Magnets and with Increased Power

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Abstract: The present innovation represents an improved version of an synchronous electric motor with permanent rare earth magnets and increased power, revealed in the utility model certificate No. 2609/05.06.2017, which has one two sites active rotor and two independent stators in one compact module. That way the synchronous electric motor uses at the same time insite and outside active zones. The aim is to upgrade and further develop through research and experimental realization the concept presented in the utility mode in order to receive increased rotational moment and output power. The estimated characteristics, as the efficiency and the output power, of the electric motor with permanent rare earth magnets to be built is expected to be higher than any electrical motor with permanent rare earth magnets presently available at the global level.

Keywords: SYNCHRONOUS ELECTRIC MOTOR, PERMANENT RARE EARTH MAGNETS, INCREASED POWER
- High power per unit mass;

1. Introduction

Electric motors with permanent magnets are a promising direction in the electric drive systems. This has been particularly accelerated by the creation of powerful key transistors such as IGBT, MOSFET, and thyristors GTO, IGCT, SGCT, which have the capability of switching off via the control electrode. Synchronous motors are indispensable for use in ultra-high power applications. A synchronous motor requires the excitation of a constant magnetic field. This can be achieved in several ways:

- External (independent)
- Internal (with an exciter machine on the shaft of the asynchronous motor)
- Self-excitation

The most promising solution is through permanent magnets. Most modern synchronous motors use neodymium magnets. These are permanent magnets made from an alloy of neodymium, iron, and boron (Nd₂Fe₁₄B) or samarium-cobalt (Sm-Co). Permanent magnets of the types AlNi, Alnico, and Ticonal, which are alloys based on Fe, Al, Ni, Co, Cu, and Ti, are also used. They are characterized by relatively high residual magnetization (Br) and high magnetic energy (BH)_{max}, low temperature coefficient of changes - 0.02%/°C, high Curie temperature - 850°C, and operating temperature up to 450°C. These characteristics make them indispensable for use not only in electric motors but also in measuring instruments, precision acoustic transducers, sensor and other devices. The new technologies in their production, created under high pressure, laser welding, and unique magnetization processes, have allowed their widespread use in synchronous motors (Permanent Magnetic Synchronous Motor).

In the last decade, preference has been given to high-energy magnets based on rare earth metal alloys, which have high coercive force. This significantly improves the mass and dimension characteristics and achieves higher torque while reducing the volume of the stator. Samarium-cobalt (Sm-Co) and neodymium-iron-boron Nd₂Fe₁₄B (Nd-Fe-B) are the most common materials for modern magnets. Today's permanent magnets are usually divided into the following groups: ferrite and AlNiCo (alnico) and rare earth: SaCo (samarium-cobalt) and NdFeB (neodymium or simply "neo"). Of course, each group has its variations and areas of application.

The advantages of the described electric motor with permanent rare earth magnets and increased power can be summarized as follows:

- High energy performance and high efficiency;
- Absence of excitation losses;
- High stability of rotational speed;
- Increased overload capacity;

- Ability to increase the air gap, and therefore greater dynamic stability, without reducing efficiency;

- Lower temperature compared to classical synchronous motors;

- The torque depends on the first degree of the supply voltage, unlike asynchronous motors whose torque

depends on the second degree;

- Possibility of installing a larger number of pole pairs;

- Ability to produce high-torque electric motors;

- Brushless - electronic commutation replaces traditional mechanical commutation, providing reliable operation, lack of wear, low failure rate, and a lifespan about six times higher than brush motors, representing the direction of development for electric motors;

- Brushless motors are more efficient because their speed is determined by the frequency of the current supply, not the voltage;

- Since there are no brushes, mechanical energy loss due to friction is lower, which increases efficiency;

- Brushless motors can operate at high speed under any conditions;

- During operation, there are no sparks and much less noise;

- Brushless motors accelerate and decelerate easily due to low rotor inertia.

There is an innovative electric motor with permanent rare earth magnets and increased power, for which a utility model certificate No. 2609/05.06.2017 has been obtained.

It has characteristics as output power 2600 W, weight 12 kg, volume 1500 cm³, efficiency 82%. As the state of technology has significantly improved since 2017, using this utility model as a base, a further development under new innovative solutions, is aimed.

2. Expected characteristics of the innovation and comparison with the characteristics of previous innovative solutions

Some of the most important characteristics of electric motors include: 1. their efficiency, 2. the output power-to-weight ratio, indicating how many watts of power correspond to each gram/kilogram of the motor, and 3. the output power-to-volume ratio, indicating how many watts of output power the motor provides for each cubic centimeter of its total volume. These characteristics are crucial because the goal of every machine and equipment manufacturer is to ensure maximum power and efficiency in minimal volume and weight of the driving force - the motor of the machine/equipment, which in turn improves the

operational characteristics of the respective machine/equipment. Therefore, the most important indicators for comparison with available alternative solutions on the market globally are determined as: Indicator 1 "Efficiency," Indicator 2 "Output power-to-weight ratio (in kg)," and Indicator 3: "Output power-to-volume ratio (in cubic centimeters)."

The electric motor with permanent rare earth magnets and increased power with an utility model [1] is given as characterised by output power 2600 W, weight 12 kg, volume 1500 cm³, efficiency 82%. To the best of our knowledge there are few other solutions available on the market. One of them is of the electric motor with permanent rare earth magnets and increased power of the QS Motor Jin Bei Avenus electric motor with characteristics relevant to the comparison indicators as: output power - 2000 W; motor volume - 2374 cubic cm; weight - 18.7 kg; efficiency - 84%. Another solution with which the electric motor with permanent rare earth magnets increased power is the GEM MOTORS from Kamnik, Slovenia. Its characteristics relevant to the comparison indicators are as follows: Output power - 4000 W; motor volume - 5785 cubic cm; weight - 19 kg; efficiency - 82%. And the another solution known is that of the Golden Motor CHANGZHOU, JIANGSU CHINA. Its characteristics relevant to the comparison indicators are as follows: Output power - 1000 W; motor volume - 1325 cubic cm; weight - 6.8 kg; efficiency - 85%.

Starting with the innovation in utility model [1], further innovative solution at higher level is developed with which the following characteristics are expected to be achieved: Output power 3500 W, weight - maximum 13 kg, maintaining the volume of 1500 cm³, and efficiency - minimum 86%. Thus, the values of the comparison coefficients for the electric motor with permanent rare earth magnets and increased power, developed under this project, should reach the following levels:

1. "Efficiency": 86%;
2. "Output power-to-weight ratio (in kg)": $3500\text{W} : 13\text{kg} = 269$ watts per kilogram;
3. "Output power-to-volume ratio (in cubic centimeters)": $3500\text{W} : 1500\text{ cm}^3 = 2.33$ watts per cubic

3. Technical Description of the Innovation

The motor consists of a body in the shape of two hollow cylinders, positioned one inside the other and connected at one end by a common wall. Along the inner circumferential surface of the outer cylinder and the outer circumferential surface of the inner cylinder, an outer stator with corresponding winding and an inner stator with winding are pressed. Between the two stators, there is a space for the free rotation of the rotor, which is a hollow metal cylinder, with external and internal radially magnetized magnets fixedly attached to its outer and inner circumferential surfaces. At one end, the rotor is fixedly connected to a shaft, which is supported by bearings in the opening of the inner cylinder of the body. A diagram of the motor can be seen in Fig. 1. A characteristic of the electric motor is that the number of channels/teeth on the outer and inner stators is equal, and the number of magnets fixed on the sleeve is equal, with each pair of external and internal magnets

The working principle is that the two stators create rotating magnetic field, which magnetic field interacts with the permanent magnets of both sides of the rotor at the same time. That way the sum of the vectors of the electromagnetic forces is achieved, which shall increase the rotating moment.

The innovative part of the described electric motor is the use of two sides active rotor, which works at the same time with two independent stators. In that way, two electric motors are integrated in one compact module.

The present innovation represents an improved version of the described synchronous electric motor with permanent rare earth magnets and increased power, mainly through innovative procedures in the experimental realization.

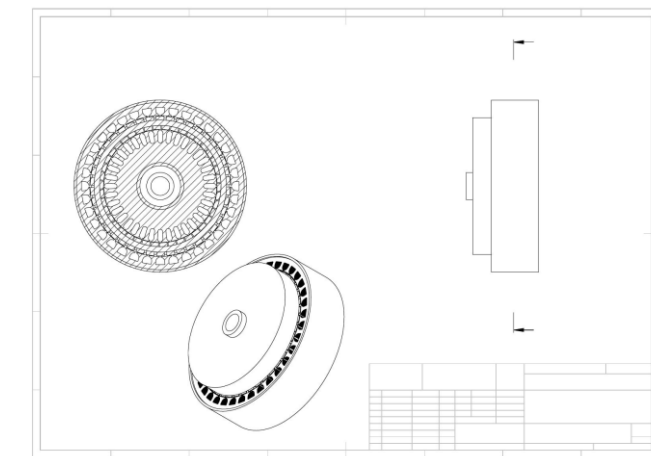


Fig. 1 A diagram of the electric motor with permanent rare earth magnets and increased power.

4. Experimental upgrade, development and realization of the innovation

The development and upgrade of the electric motor with permanent rare earth magnets and increased power based on the utility model [1], through new innovative experimental procedure and realization is a novelty on a global level and will be of interest in many applications.

Activities related to the experimental development and physical realization of an innovative electric motor with permanent rare earth magnets and increased power were performed. Most of the basic constructive elements as the corpus, axle, rotor and stators with appropriate materials. The preliminary experimental results, obtained from the measurements of the induced voltage when rotating the rotor by hand revealed the presence of phase matching between the two stators. A diagram of the corpus of the electric motor is presented in Fig. 2.

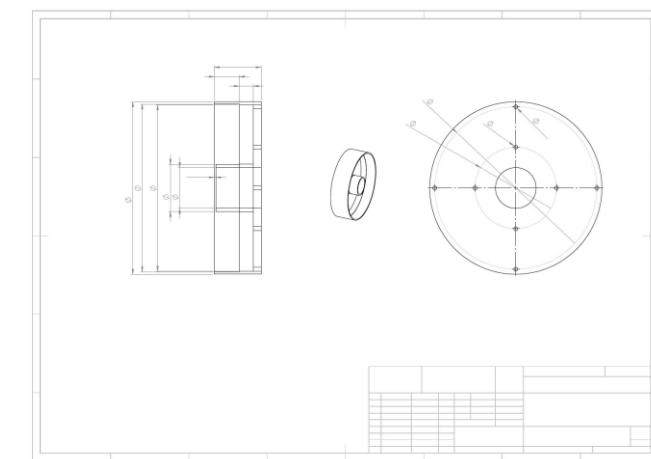


Fig. 2 A diagram of the corpus electric motor with permanent rare earth magnets and increased power.

The obtained results revealed that the aim of the task, an increase of the rotating moment up to two times than the standard Permanent Magnet Synchronous Motor (PMSM), higher density of the power, decrease of the relative dimensions and increased energy efficiency, can be achieved by the chosen methods. Presenting that more explicit means that the output power of 3500 W, weight of maximum 13 kg, maintaining the volume of 1500 cm³, and efficiency of minimum 86%, is possible. A physical prototype can be seen in Fig. 3.



Fig. 3 A physical prototype of the electric motor with permanent rare earth magnets and increased power.

5. Application

The developed innovative electric motor with permanent rare earth magnets and increased power, can be used by manufacturing enterprises that can incorporate it into their products. The innovation is a module that can be integrated into a wide variety of products - household appliances, ventilation systems, garden tools and machines, electric mobility devices, and more.

6. Acknowledgments

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A Study of Hybrid Adhesive-Mechanical Joints Between Metals and Composites Formed Using Thermal Drilling Technology

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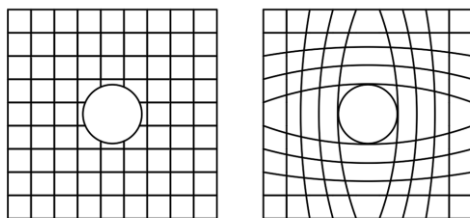
Abstract: This article presents a study of the possibility of creating adhesive-mechanical bonds between aluminum and a thermoplastic matrix composite. In detail, the influence of drilling process parameters on the shape of the bushing and the formation of joints with fiber-reinforced composites during direct drilling using various tool speeds and feeds is examined. Finally, the load-bearing capacity of the formed joints is presented.

Keywords: COMPOSITE-METAL JOINING, THERMAL DRILLING, HYBRID ADHESION-MECHANICAL JOINT, LOAD-BEARING CAPACITY, ADHESION PROMOTER

1. Introduction

In today's engineering industry, particularly in the automotive and aerospace sectors, there is a growing need to join dissimilar materials in order to reduce the weight of structures while maintaining their load-bearing capacity and safety. Joining thin-walled components made of aluminum alloys and composites is relatively complex because these materials have different physical and mechanical properties. It is precisely the complexity of joining these materials that requires the use of advanced technologies that employ multiple joining principles simultaneously, such as the application of pressure, heat, and mechanical interlocking of materials [1-3]. In the joining of thin-walled materials, the geometry of the mechanical joint plays a particularly important role, as it significantly influences its load-bearing capacity [4-7]. By appropriately modifying the shape and dimensions of the joint, it is possible to increase its load-bearing capacity without the need to add additional fasteners, which also helps maintain low weight and reduce manufacturing costs.

The aim of the experimental work was to investigate the possibilities of creating hybrid adhesive-mechanical joints between fiber-reinforced composites with a thermoplastic matrix and glass and carbon reinforcement and aluminum alloy sheets using thermal drilling technology without the use of fasteners. The adhesive joint is formed by pressing the heated composite with the thermoplastic matrix and the sheet metal across the entire overlap area. At the same time, the joint is secured by a metal bushing, which is created by drilling through the overlapped pair with a thermal drill bit, such that, thanks to the heated thermoplastic matrix, the reinforcing fibers in the vicinity of the forming bushing deflect without breaking. This prevents any weakening of the composite part's load-bearing capacity at the joint, Fig. 1.



a) fiber breakage (conventional drilling), b) fiber deflection (friction drilling)

Fig.1 The effect of hole-making technology on the failure of composite fiber reinforcement

To improve adhesion between the composite and the aluminum sheet, an organosilicate agent with organomodified silica nanoparticles was used in the study; this agent is applied to the steel surface using the sol-gel method, where it forms a colorless, transparent gel layer. After dehydration, a three-dimensional network of silicate compounds linked by siloxane bonds is formed. The organosilicate molecule has three key parts:

- a molecular core of aryl or alkyl origin $((CH_2)_n)$, where $n = 0, 1, \text{ or } 3$
- a molecular end group containing an organic functional group (amino, vinyl, alkyl, etc.) that enables bonding to a specific organic monomer or polymer molecule via functional group interaction
- the other end of the molecule consists of an alkoxy silane group $(Si(OR)_n)$, where $n = 3$, which can bond to inorganic materials (metals, minerals, etc.).

By applying this preparation, we expect the formation of a strong bond between the metal substrate and the thermoplastic composite matrix via chemical bonds, which could result in increased adhesion of the joint.

2. Materials and Methods

EN AW-6082 T6 (AlSi1MgMn) aluminum alloy, a precipitation-hardened silumin, was used to form the joints in the form of 2 mm thick sheet metal.

Two types of composites were used: TEPEX Dynalite 102-RG600(3)/47% and Tepex® Dynalite 202-C 200(7)/52%, both with a thickness of 1.55 mm. The matrix is PA6 thermoplastic with a melting point of 220°C; the bidirectional reinforcement is carbon or glass roving fabric (Twill 2/2), Tab. 1.

Tab. 1 Mechanical properties of materials used

Mechanical properties	EN AW-6082 T6	PA6-GF	PA6-CF
Re [MPa]	299	-	-
Rm [MPa]	345	340	487
A ₈₀ [%]	16	1.8	0.87

A Flowdrill Long tool with a diameter of 5.3 mm was used for thermal drilling. The shape and dimensions of the test specimens were derived from the tool diameter in accordance with STN EN ISO 12996 and are shown in Fig. 2.

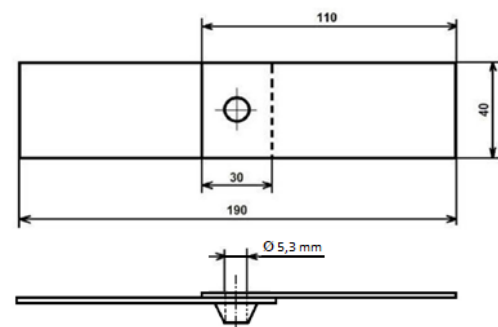


Fig. 2 Shape and dimensions of test specimens and the single-lap joint for the Flowdrill Long tool, Ø 5.3 mm

The surface of the aluminum sheet was degreased with an alkaline degreaser, followed by rinsing, immersion in a solution of an organosilicate compound in demineralized water, and then air-dried.

The materials to be joined were placed in a clamping fixture, where the composite was also heated; after reaching the melting temperature of the PA6 matrix ($>220^{\circ}\text{C}$, approx. 240°C), friction drilling was performed to join the two materials. The joint was then rotated, and a flange was created using the same tool to close the joint, Fig. 3. During thermal drilling, the effect of tool speed and feed rate on the formation of the bushing was also tested separately in aluminum sheet metal, as well as in interaction with the composite. The tested tool speeds were 2400 and 4800 min^{-1} , and the feed was manual, slow (S, approx. $60\text{ mm}\cdot\text{min}^{-1}$) and fast (F, approx. $240\text{ mm}\cdot\text{min}^{-1}$).

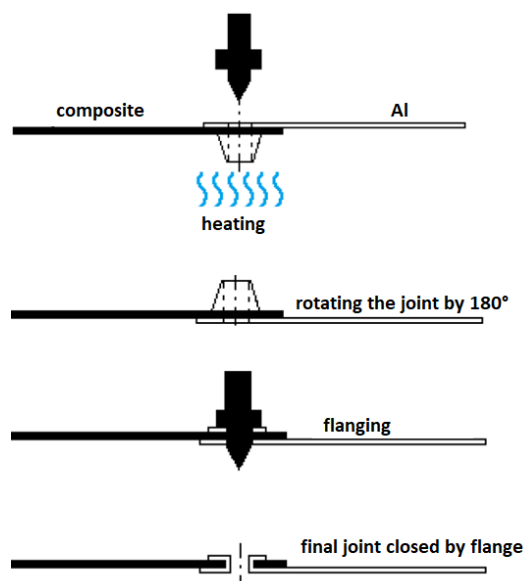


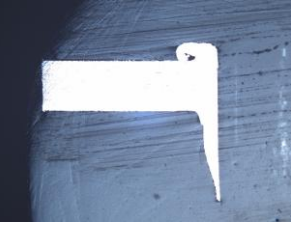
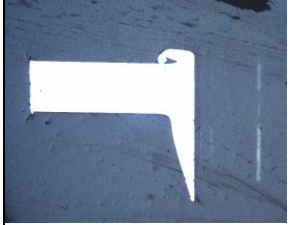
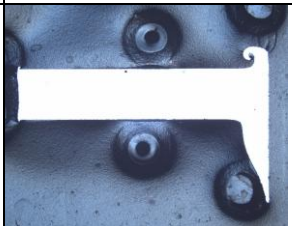
Fig. 3 Procedure for creating joints

The joints were then tested for load-bearing capacity using a tensile-shear test with a loading rate of $10\text{ mm}\cdot\text{min}^{-1}$ in accordance with STN EN ISO 12996.

3. Results

Metallographic sections through the bushing, created by thermal drilling of an aluminum sheet at two tool speeds and feed rates, are shown in Tab. 2.

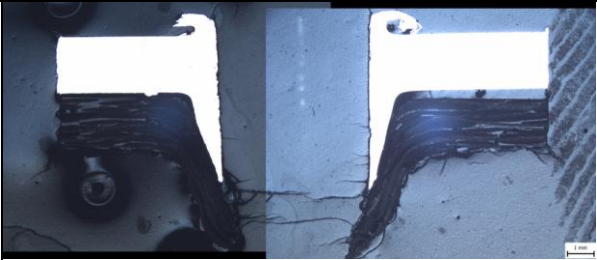
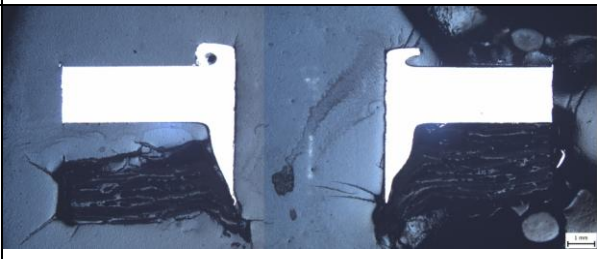
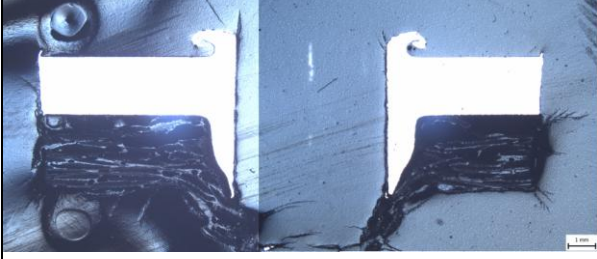
Tab. 2 Metallographic sections through the bushing created under various process parameters

	2400	4800
S		
F		

Tab. 2 shows the effect of process parameters on the shape of the bushing. The ideal bushing should be long enough to pass through a composite plate with a thickness of 1.55 mm and should have a shape that tapers smoothly. The greatest thickness of the bushing is just below the level of the sheet metal. It is precisely this area that should ensure sufficient joint strength and should be the point of failure of the bushing under tensile shear test.

Subsequently, direct joints were created under the given process parameters. Their cross-sections are shown in Tab. 3.

Tab. 3 Metallographic cross-sections of Al-PA6CF joints created under various process parameters by direct drilling

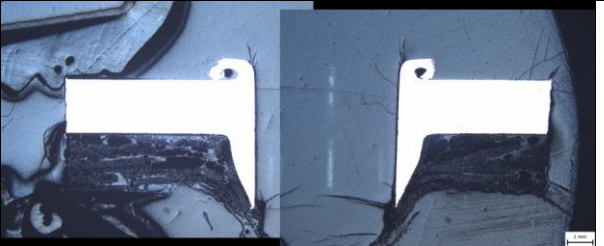
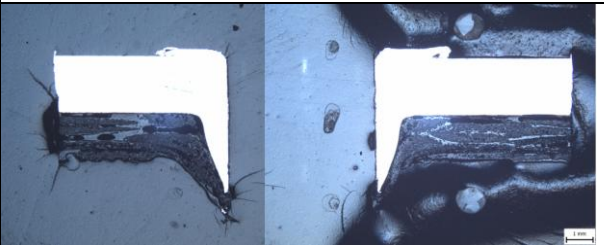
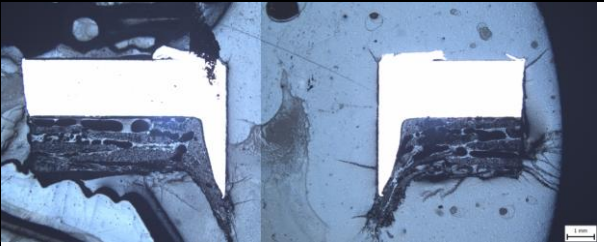
	Al-PA6CF
2400 S	
2400 F	
4800 S	
4800 F	

Tab. 3 shows changes in the shape of the bushing under various process parameters. The most suitable shape is observed at 2400S and 4800S . A slower feed rate creates better conditions for forming a bushing with the desired shape. From previous research, we know that for non-ferrous metals, it is more appropriate to select higher speeds, which is also recommended by the manufacturer of thermal drilling tools. Delamination of the composite around the bushing is also visible, which may be related to insufficient heating. However, this problem is mitigated by flanging the joints. The same cuts were made for Al-PA6GF joints, Tab. 4.

When drilling aluminum sheet on a composite panel, the influence of process parameters is less noticeable because the glass-fiber composite consists of only three layers of prepreps (unlike CF, which has seven layers for the same thickness), the fibers are thicker, the mat strands are more robust, and the fibers as a whole offer less resistance to tool penetration during thermal drilling. For

the subsequent creation of joints intended for load-bearing capacity testing, a tool speed of 4800 rpm and a slow feed rate (approx. 60 mm/min) were used.

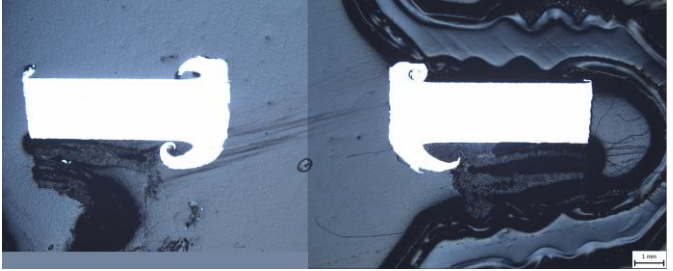
Tab. 4 Metallographic cross-sections of Al-PA6GF joints created under various process parameters by direct drilling

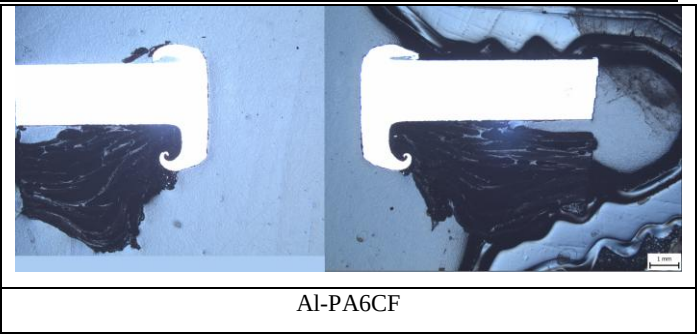
	Al-PA6GF
2400 S	
2400 F	
4800 S	
4800 F	

Cross-sections of joints created under these process parameters and closed with a flange are shown in Tab. 5.

Tab. 5 (Al-PA6GF) also shows potential defects resulting from manual feeding, namely excessive flattening of the bushing during flanging. CNC control of the process is, of course, possible, but it is very difficult to integrate the heating unit into a CNC-controlled process.

Tab. 5 Cross-sections of joints closed with a flange


Al-PA6GF



A properly executed flange closes the layers of composite fibers and prevents their delamination, Fig. 4.

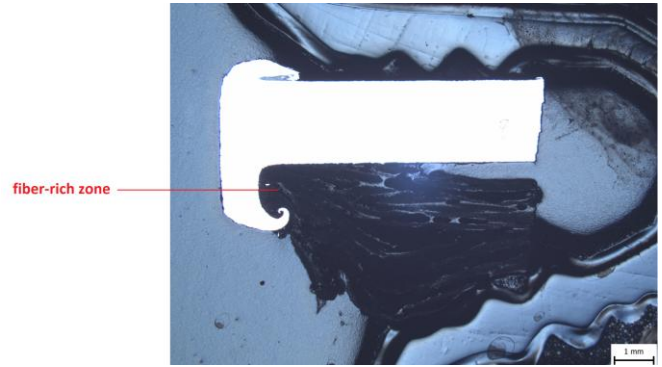
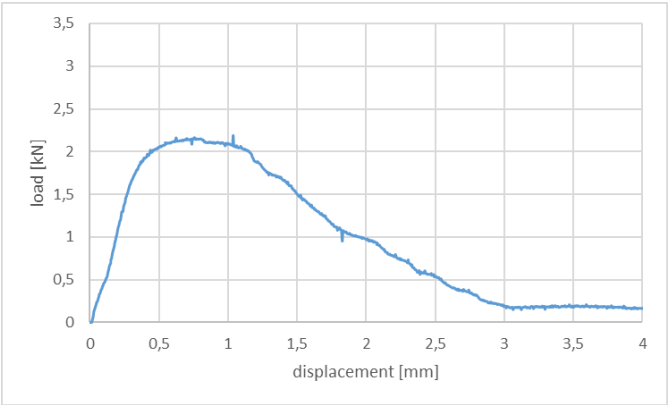


Fig. 4 Proper hem finishing

Figures 5 and 6 show the load-displacement curves obtained during joint load-bearing capacity testing, as well as the failure patterns.



a) load-displacement curve of Al-PA6CF joint



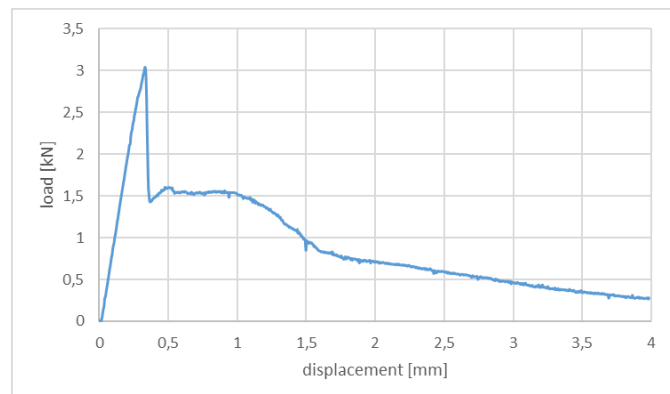
b) failure mode of Al-PA6CF joint

Fig. 5 Load-bearing capacity testing and failure mode of the Al-PA6CF joint

Fig. 5 clearly shows that the tensile loading of the Al-PA6CF joint exhibits a behavior typical of the progressive shear failure of the bushing. The maximum load-bearing capacity of the joint,

which consists solely of mechanical interlocking, is 2.1 kN. Failure occurs over a distance of approximately 2 mm, which would ideally correspond to the gradual shearing of the bushing—an aluminum alloy ring. However, observation of the joint failure surface shows that the bushing was only deformed when the joint was stressed; no shearing occurred. The composite slid along the outer conical surface of the bushing, causing it to move away from the sheet metal and finally pull out.

The loading history of the AIOS-PA6GF joint, Fig. 6, is different; it exhibits the characteristics of a hybrid adhesive-mechanical joint.



a) load-displacement curve of AIOS-PA6GF joint



b) failure mode of AIOS-PA6GF joint

Fig. 6 Load-bearing capacity testing and failure mode of the AI-PA6GF joint

The load-displacement curve shows two distinct regions: first, a peak is observed, corresponding to the transfer of forces through the adhesive bond between the two materials via the PA6 thermoplastic matrix across the entire overlap area. The adhesive bond fails at a load of 3 kN, and subsequently, the connection between the two materials is maintained only by the bushing, which gradually deforms, just as was described for the AI-PA6CF joint.

The measured data indicate that the organosilicate layer has a positive effect on the adhesive bond between the materials; however, there must be sufficient polymer matrix on the composite side, which, after melting, would contribute to the formation of the adhesive bond. According to the results, the glass fiber composite has more matrix available than the carbon fiber composite. Therefore, a hybrid bond does not form in the carbon fibre composite.

However, deformation of the bushing is not an ideal mode of joint failure; it does not guarantee that the mechanical properties of the Al sheet are fully utilized. Maximum utilization would occur if the failure took place immediately below the level of the sheet, at the point where the bushing is thickest, where there is the most material ensuring load-bearing capacity. To achieve this, it is necessary to eliminate the tangential component of the force during loading, which causes the composite to slip out of the bushing. We will address this issue in future research.

Conclusion

Based on the experimental results, it can be concluded that thermal drilling technology is an effective method for creating hybrid adhesive-mechanical bonds between aluminum alloys and thermoplastic composites without the need for additional fasteners. The study confirmed that the process parameters, specifically higher rotational speed (4800 min^{-1}) and slow feed rate ($60 \text{ mm} \cdot \text{min}^{-1}$), ensure optimal formation of the aluminum sleeve and flange, which seals the composite layers and prevents their delamination. The use of an organosilicate primer demonstrated a positive effect on adhesion, which was particularly evident in the glass-fiber composite (PA6-GF), where the joint achieved a load-bearing capacity of 3 kN due to a combination of adhesive and mechanical principles. In contrast, for carbon-fiber composites (PA6-CF), the load-bearing capacity was lower (2.1 kN), and the joint was purely mechanical in nature due to the lack of a polymer matrix to form an adhesive bond. The primary failure mechanism remains deformation and pull-out of the sleeve, which opens the door for further research aimed at optimizing the joint geometry and eliminating the forces causing the composite to slip.

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Vibration-Based Monitoring of DMLS Ti-6Al-4V Micro-Milling

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Abstract: This paper deals with vibration-based monitoring of micro-milling of DMLS Ti-6Al-4V ELI using a SCHUNK iTENDO² smart toolholder. The study evaluates the applicability of vibration signals for assessing process conditions during machining with a 1 mm diameter end mill. Annealed and non-annealed samples were machined under different cutting directions relative to the build layers and different initial surface states. The tests were carried out at constant cutting speed, feed per tooth and depth of cut, while vibration data were recorded continuously. The machined grooves were then evaluated by optical and profilometric methods with emphasis on burr formation and edge quality. The results showed that annealing had the strongest positive effect on process stability, reducing vibration levels and significantly improving edge quality. The lowest burr formation was observed in annealed samples machined perpendicular to the printed layers, whereas the non-annealed material exhibited higher dynamic loading and substantially larger burrs. The study confirms that smart toolholder-based vibration monitoring can provide useful information about changes in machining conditions during micro-milling of DMLS titanium alloy and can support further development of process diagnostics in finishing of biomedical components.

Keywords: TITANIUM ALLOY, DMLS, MICRO-MILLING, PROCES MONITORING, VIBRATIONS, BURR

1. Introduction

Additive manufacturing of Ti-6Al-4V ELI has become an important route for producing patient-specific spinal implants and other biomedical components with complex geometry [1–4]. Despite the high geometrical freedom offered by DMLS, functionally critical surfaces still require finishing operations in order to achieve the required dimensional accuracy and surface integrity [1,3]. In this context, micro-milling represents a promising finishing technology for small titanium features and implant components, especially where local geometric correction and precise edge generation are required [3,5,6].

However, micro-milling of titanium alloys remains technologically demanding due to the low thermal conductivity of titanium, its high chemical affinity to the cutting tool, strong heat accumulation in the cutting zone, and the tendency toward burr formation and rapid edge degradation [5,6]. These effects become even more pronounced in additively manufactured material, where the as-built state is characterized by a hard martensitic microstructure and significant residual stresses [2,3]. As reported in studies dealing with DMLS Ti-6Al-4V, post-process heat treatment substantially modifies the microstructure and mechanical response of the material, which is expected to affect its machinability as well [2].

From the viewpoint of process stability, additively manufactured Ti-6Al-4V cannot be treated as an equivalent substitute for conventionally produced material [2,3]. The specific layer-wise microstructure, anisotropy and residual stress state can significantly influence machinability, vibration response and the quality of machined edges [2,5]. For this reason, process monitoring is particularly important in micro-milling, where the small tool diameter and limited stiffness make the process highly sensitive to instability [7–9]. Recent research on burr formation in slot micro-milling of Ti-6Al-4V further confirms that burr size and morphology are strongly dependent on cutting conditions and process stability, making burr evaluation a suitable indicator of machinability in micro-scale finishing [5,6].

The presented experiment was carried out as an initial study focused on the finishing of spinal implant components by micro-milling. Its purpose was to verify the machinability of DMLS Ti-6Al-4V ELI and to assess whether heat treatment should also be considered for smaller implant parts, for which annealing is currently often omitted in manufacturing practice. In current manufacturing practice, annealing is more commonly associated with larger implant components, while smaller parts may remain in the as-built condition; from the viewpoint of subsequent finishing, however, this approach may not be optimal. The comparison of annealed and non-annealed samples was therefore motivated not only by material science considerations, but also by the practical

need to determine whether annealing can improve process stability, preserve micro-tool cutting ability and reduce burr formation during finishing [2,5,6].

In this study, the micro-milling process was monitored using a SCHUNK iTENDO² smart toolholder, which allows vibration data to be acquired directly near the cutting zone [7–9]. This approach corresponds with broader trends in intelligent and digitally supported manufacturing, where process quality, repeatability and production efficiency are increasingly linked with sensor-based monitoring, virtual engineering and data-driven optimization [9–11]. The experiment was designed to evaluate the influence of heat treatment, cutting direction relative to the build layers and initial surface state on chatter-related vibration response and burr formation in DMLS Ti-6Al-4V ELI.

2. Experimental Procedure

The experimental part of this study was focused on evaluating the machinability of additively manufactured Ti-6Al-4V ELI by means of micro-milling under controlled cutting conditions. The experiment was designed to assess the influence of three main factors on process stability and surface quality: heat treatment, cutting direction relative to the build layers, and the initial topography of the workpiece surface. The process was monitored in real time using a SCHUNK iTENDO² smart toolholder, while the resulting micro-grooves were subsequently evaluated by digital microscopy and profilometry.

The workpiece material was Ti-6Al-4V ELI (Grade 23) produced by the DMLS process. Experimental samples were manufactured on an EOS M280 system. The powder bed fusion process was carried out with a constant layer thickness of 30 µm, which was selected in order to ensure sufficient geometric precision and a material density close to full consolidation. From the viewpoint of the present study, this material state was particularly relevant because DMLS Ti-6Al-4V ELI is characterized by a layer-wise structure, directional anisotropy and a specific as-built microstructure, which can significantly affect the cutting response during finishing.

A total of eight samples with dimensions 32x12x12 mm were prepared for the experiment. Four samples were subjected to heat treatment, while the remaining four were left in the as-built condition. The purpose of annealing was to reduce residual stresses naturally present in the martensitic structure formed during rapid solidification of the melt pool. The selected heat treatment cycle consisted of gradual heating to 680 °C over a period of 2 h, followed by a holding time of 4 h at this temperature. The process was completed by slow cooling inside the furnace.

To isolate the influence of the selected variables, the samples were classified into eight test scenarios based on three factors. The

first factor was heat treatment, i.e. annealed versus non-annealed material. The second factor was the cutting direction relative to the build layers, with half of the samples machined parallel to the layer orientation and the other half perpendicular to it. The third factor was the initial surface condition prior to micro-milling. In four cases, the samples were face milled before the main experiment in order to remove the rough DMLS surface layer and create a reference plane. The remaining four samples were left in the original as-built condition. The resulting experimental matrix consisted of the combinations shown in Table 1.

Table 1: Test scenarios

Sample index	Heat treatment	Cutting direction	Initial surface
1-1	annealed	parallel	pre-milled
1-2	non-annealed	parallel	pre-milled
2-1	annealed	perpendicular	pre-milled
2-2	non-annealed	perpendicular	pre-milled
3-1	annealed	parallel	as-built
3-2	non-annealed	parallel	as-built
4-1	annealed	perpendicular	as-built
4-2	non-annealed	perpendicular	as-built

The machining tests were carried out on a 5-axis DMG MORI DMU 60 eVo machining centre. This machine was selected because of its high structural rigidity and its capability to provide spindle speeds required for micro-milling with a 1 mm diameter tool. The cutting tool used in all tests was a GARANT Master Titan solid carbide end mill with a diameter of 1 mm. The tool was TiAlN coated and had two flutes.

Process monitoring was performed using a SCHUNK iTENDO² intelligent sensory toolholder. This holder combines hydraulic expansion clamping with an integrated single-axis MEMS accelerometer. The sensor measures radial acceleration in the vicinity of the cutting zone, which makes it suitable for tracking process instability and vibration-related events during micro-milling. A major advantage of this system is that the sensing unit is integrated directly in the rotating toolholder and the measured data are transmitted wirelessly in real time to an external receiver station for further evaluation.

Constant cutting parameters were used throughout the main experimental series in order to make the effect of the tested material-related factors directly comparable. The cutting speed was set to $v_c = 60$ m/min, the feed per tooth to $f_z = 0.004$ mm/tooth, and the axial depth of cut to $a_p = 0.05$ mm. These values were chosen as a compromise between process stability, preservation of the fragile micro-tool edge and sufficient material removal for surface quality assessment. Machining was performed with coolant emulsion.

For each sample, the NC program was designed to generate 20 parallel micro-grooves shown on Fig. 1. The simulated machining time for one sample was approximately 125 s. After spindle start-up and positioning to the initial point, the iTENDO² measurement was activated immediately before the tool entered the material. The vibration signal from the integrated accelerometer was transmitted and stored continuously during the entire cutting cycle.

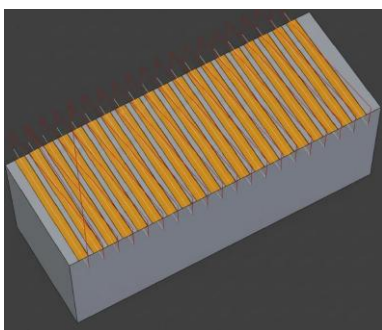


Fig. 1 Programmed toolpath

During post-processing of the experimental data, process stability was evaluated using the Chatter index extracted from the recorded vibration signal. Surface integrity and burr formation were

assessed by optical inspection using a ZEISS SmartZoom 100 digital microscope and by contact profilometry using a Mitutoyo FORMTRACER Avant system. In the case of the samples left in the as-built condition, it was necessary to distinguish between the initial leveling pass and the subsequent stable pass. Therefore, for the rough as-built group, the statistical evaluation of vibration data was based on the second pass, which corresponded to a finishing cut with a constant chip cross-section and was therefore considered comparable with the pre-milled group.

3. Results and discussion

The obtained results showed that heat treatment had the strongest influence on both the vibration response and the resulting groove quality. In general, the annealed samples exhibited lower mean chatter index values and a more stable cutting behaviour than the non-annealed material. This trend is evident from the overall comparison of all eight tested conditions summarized in Table 2, where samples 1-1 and 3-1 reached the lowest mean chatter levels, while sample 1-2 showed the highest overall vibration level. The dominant beneficial effect of annealing is also consistent with the overall outcome of the experimental study.

The differences between the individual conditions are clearly visible in the vibration trends shown in Fig. 2. In the pre-milled group, sample 1-1, representing annealed material cut parallel to the build layers, showed the most stable behaviour during full engagement. The maximum chatter index decreased from 2.22 at the beginning of the cycle to 1.85 at the twentieth groove, while the mean value gradually decreased from 1.93 to 1.64, indicating progressive stabilization of the process. In contrast, sample 1-2, machined under the same kinematic condition but without heat treatment, exhibited a markedly stronger initial vibration response, with a maximum chatter index of 2.43 and a mean value of 2.20 in the first groove. This confirms that the harder as-built structure generated significantly stronger dynamic impacts during the first cutting passes.

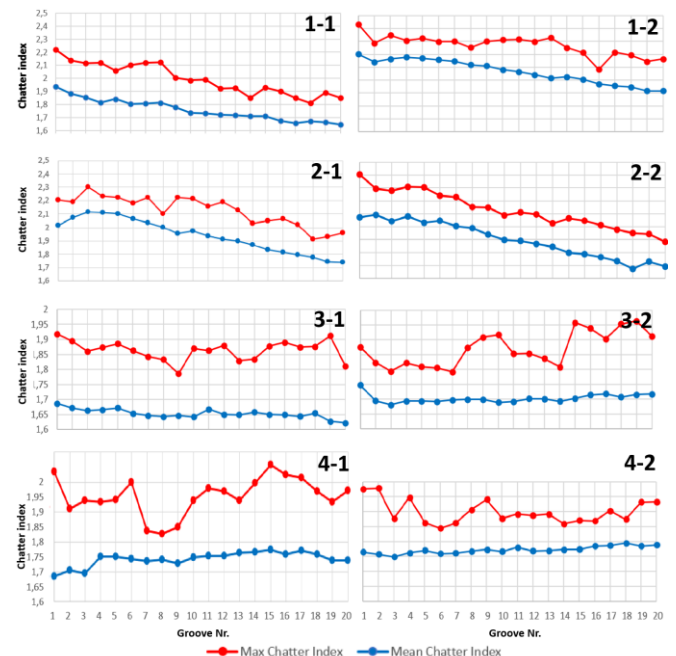


Fig. 2 Chatter index trends for all tested samples

Changing the cutting direction from parallel to perpendicular to the printed layers led to a moderate increase in vibration level. For sample 2-1, the maximum chatter index remained in the range of approximately 2.20–2.30 during the initial grooves and the mean values were higher than in sample 1-1. This behaviour indicates that repeated crossing of the printed layer boundaries resulted in a periodically varying mechanical load on the cutting edge. The most

dynamically exposed condition in the pre-milled group was sample 2-2, which combined non-annealed material with perpendicular cutting. In this case, the initial maximum chatter index reached 2.40 and the mean value 2.07, followed by a pronounced decrease after the twelfth groove. Such behaviour suggests progressive deterioration of the cutting edge and a shift from stable cutting toward a more deformation-dominated material removal mode. These trends are visible in Fig. 2 and quantitatively summarized in Table 2.

A different behaviour was observed for the samples machined from the original rough DMLS surface. In this group, the first pass served only to remove the irregular surface layer and create a reference plane, whereas the statistical evaluation was based on the second pass corresponding to a stable finishing cut with a constant chip cross-section. As a result, the chatter-index curves in this group were flatter and the overall values were lower than in the pre-milled group. Nevertheless, the material state still had a clear influence. Sample 3-1, corresponding to annealed material machined parallel to the layers, showed the calmest finishing behaviour, with mean chatter index values between 1.62 and 1.68 and a peak value below 1.92. In contrast, sample 3-2, although relatively stable in terms of mean value, exhibited rising peak vibrations in the second half of the cycle, indicating faster loss of edge sharpness in the harder non-annealed material.

A similar tendency was found for perpendicular cutting on the rough as-built surface. Sample 4-1 showed a relatively stable mean chatter index in the range of approximately 1.73–1.77, although the signal was influenced by alternating engagement caused by local irregularities of the original surface. Sample 4-2, representing the non-annealed material cut perpendicular to the layers, maintained a relatively constant mean chatter index between 1.76 and 1.79, with peak values approaching 1.98. Even though this condition did not produce the single highest peak value in the entire experiment, it represented the highest sustained vibration level in the second group and confirmed the increased cutting resistance of the hard martensitic structure when the tool repeatedly crossed the layer boundaries. These relationships are also reflected in Table 2.

Table 2 Summary of vibration response for all tested sample conditions

Sample	Mean chatter index	Peak chatter index	ΔChI (1.-20.)	Interpretation
1-1	1.75	2.22	-0.29	Most stable full-cut condition
1-2	2.04	2.434	-0.28	Highest initial impacts
2-1	1.91	2.302	-0.27	Higher load due to layer crossing
2-2	1.87	2.402	-0.38	Most critical pre-milled condition
3-1	1.65	1.918	-0.06	Lowest overall vibration level
3-2	1.70	1.963	-0.03	Stable mean, rising peaks
4-1	1.74	2.057	+0.05	Stable but locally alternating load
4-2	1.77	1.979	+0.02	Highest sustained level in group 2

The visual analysis of the machined grooves confirmed the vibration-based interpretation. Annealed samples consistently showed cleaner edges and lower burr formation, whereas non-annealed samples exhibited stronger plastic side flow, adhered material and pronounced top burrs. This contrast was especially evident when comparing the edge morphology of annealed and non-annealed grooves (Fig. 3), where the annealed sample had nearly clean edges while the non-annealed sample produced massive burrs extending over the groove borders. The perpendicular cutting direction on annealed samples led to visually even smaller burrs and cleaner edges than parallel cutting, despite the fact that the vibration

signal indicated a somewhat higher dynamic load in this orientation. This suggests that the layer boundaries may have promoted a more favourable chip-breaking mechanism when the material had already been stress-relieved by annealing.

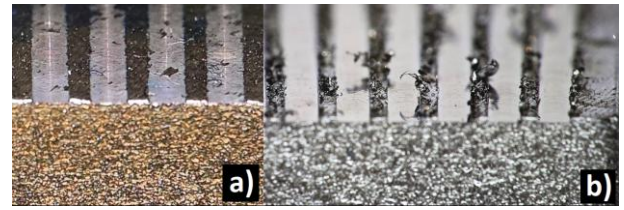


Fig. 3 Comparison of burr on annealed and non-annealed sample

The worst surface condition was observed on the non-annealed samples machined from the rough as-built surface, especially sample 4-2. In this case, very large burrs were formed and the displaced material locally overflowed across neighbouring grooves. Fig. 4 shows a visible progressive deterioration of groove quality along the cutting sequence, with a substantial increase in burr volume from the first to the twentieth groove. This behaviour supports the interpretation that the harder non-annealed material promotes faster edge degradation and leads to a progressive shift from stable cutting toward more severe plastic deformation and material dragging at the groove edges.



Fig. 4 Detailed view of burr formation at the groove edge

The profilometric measurements of burr height were consistent with the optical observations and provided quantitative confirmation of the differences between the tested conditions. The strongest contrast was found between the annealed and non-annealed material states. In the annealed sample 2-1, machined perpendicular to the layers, the burr height remained below 0.014 mm, indicating a clean and stable edge formation. In contrast, the non-annealed sample 1-2 showed markedly higher burr values, reaching 0.062 mm at the beginning of the test and up to 0.101 mm in the final stage of machining. Representative profilograms of these two conditions are presented in Fig. 5. These results confirm that annealing significantly improved edge quality and reduced plastic side flow, while burr height proved to be a suitable output parameter linking process stability with the final micro-geometry quality of the machined grooves. In combination with the vibration trends and optical observations, the profilometric results also indicate that the iTENDO² signal can be used as a practical indirect indicator of groove quality deterioration during finishing of DMLS Ti-6Al-4V ELI.

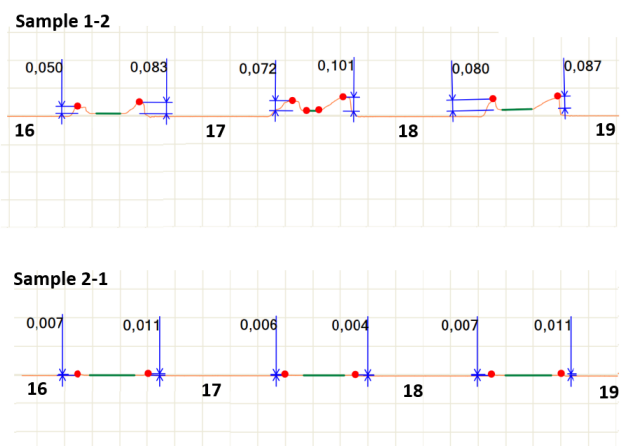


Fig. 5 Representative profilometric comparison of burr height

Overall, the results indicate that annealing is the dominant technological factor for improving the micro-milling performance of DMLS Ti-6Al-4V ELI. The most favourable conditions were obtained for annealed material, while the least favourable behaviour was observed in the non-annealed as-built state. At the same time, the cutting direction relative to the printed layers influenced the dynamic response and burr morphology in a non-trivial way: perpendicular cutting increased the kinematic resistance, but in annealed material it also contributed to cleaner edges, most likely due to more effective interruption of chip flow at the layer boundaries. From the viewpoint of process monitoring, the smart toolholder-based vibration signal proved sufficiently sensitive to distinguish between stable and critical cutting conditions, which makes this approach promising for further diagnostics of micro-milling in biomedical titanium finishing.

4. Conclusion

The presented study confirmed that heat treatment is the dominant factor affecting the micro-milling behaviour of DMLS Ti-6Al-4V ELI. Annealed samples exhibited lower vibration levels, smaller burrs and better edge integrity than the non-annealed material, while the most favourable overall performance was obtained for annealed conditions, particularly when cutting perpendicular to the printed layers. In this orientation, the layer boundaries most likely contributed to chip interruption, which improved the resulting edge quality despite the slightly higher kinematic resistance during cutting.

The results also showed that the non-annealed as-built material represents the least favourable condition for finishing by micro-milling. It generated higher initial impacts, less stable cutting behaviour and significantly larger burrs. The measured upper burr height reached up to 0.101 mm in the non-annealed material, whereas the annealed samples remained below 0.014 mm, confirming a substantial improvement in micro-geometry quality after annealing.

An important finding is that a decreasing vibration trend does not necessarily indicate an improvement of the cutting process. In the most critical non-annealed conditions, especially in sample 2-2, the drop in the chatter index after the initial grooves can be interpreted as a consequence of progressive edge degradation. In terms of micro-cutting theory, this behaviour is consistent with a shift from more effective cutting toward stronger plastic deformation and ploughing, where the worn cutting edge deforms the material instead of removing it efficiently. This transition can temporarily reduce the dynamic response of the system while simultaneously worsening groove quality.

From the viewpoint of industrial application, the results indicate that annealing should be considered not only for larger implant parts, but also for smaller DMLS titanium components that require finishing by micro-milling. The combination of lower vibration level, reduced burr formation and cleaner groove edges makes the annealed state more suitable for precision finishing of biomedical parts. At the same time, the iTENDO² smart toolholder proved to be a practically useful monitoring device capable of distinguishing between stable and critical cutting conditions during machining of additively manufactured titanium alloy.

For future research, it would be beneficial to move beyond the evaluation of the chatter index alone and analyse the raw vibration signal in greater detail. Time-domain and frequency-domain analysis of the original vibration data could provide additional information about transient events, layer-crossing effects, early edge degradation and the onset of ploughing-dominated behaviour.

Acknowledgment

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Dimensional limitations in the manufacture of tubular filter elements from flat porous powder blanks

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Abstract: Information is provided on the critical values of the ratio of the thickness of a filter element in the shape of a pipe to the radius of a cylindrical surface when it is manufactured by rolling a porous sheet blank sintered from tin-phosphorous bronze powder. An increase in the efficiency of using filter elements obtained in this way has been shown. Images of some of the developed filter products introduced into production are presented.

Keywords: TUBULAR FILTER ELEMENT, POROUS SHEET BLANK, CYLINDRICAL SURFACE RADIUS, ROLLING.

1. Introduction

Despite the increasingly widespread use of polymer and paper filters in technology [1 – 3], metal-based powder filter materials (PFM) [4 – 7] still occupy one of the important places in the implementation of filtration processes of liquid and gaseous media in mechanical engineering, power engineering, rocket, aviation, chemical, food and other industries, since in comparison with them, as well as glass, ceramic, fabric and other filter materials have a number of advantages: they are more durable and resistant to corrosion, can operate in a wide temperature range, can be machined and welded, have high thermal and electrical conductivity, and can be regenerated multiple times. One of the most widely used materials are PFMs based on tin-phosphorous bronze powders (CuSn10F1), the technology for manufacturing products from which is simple (sintering freely poured powder into a mold) and well mastered, and the powder particles spherical shape, compared to the non-spherical one, ensures PFM high permeability [6 – 8].

In practice, filter element designs based on two shapes are currently primarily used: flat (which, based on the mounting design, can also be classified as a lentils (plate-shaped) variant) and tubular (which, based on the mounting design, can also include corrugated filter elements). The need to seal a large number of joints between the “lentils” and between the elements within the lentils itself complicates the assembly of the filter device and often predetermines the choice of a tubular filter element shape. The most productive and simple technology for manufacturing tubular products from tin-phosphorous bronze powders includes sintering a flat (sheet) blanks [9], cutting to size, rolling the blanks into a pipe, welding the joint along the generatrix of the cylinder, and controlling the properties. It's known from the literature [10] that the complex stress state of a sheet blank deformed during rolling causes the appearance of two zones in the porous structure of the material: tension and compression, and when a certain value of tensile stress is reached, the magnitude of which is associated with the bending parameters (too small a rolling radius for a given thickness and material), cracks form on the outer surface of the bent sample.

The aim of the work is to determine the dimensional limitations of sheet blanks when producing tubular filter elements from them using the rolling method.

2. Experiments results and their discussion

The starting materials for the production of porous filter powder products were tin-phosphorous bronze powders of the CuSn10F1 brand with five fractional compositions: (minus 160 + 125) μm , (minus 200 + 160) μm , (minus 250 + 200) μm , (minus 315 + 250) μm and (minus 400 + 315) μm obtained by spraying the metal melt with an air jet. The sample blanks were sintered according to the technology described in [9] in the form of 200 mm long plates, the width (calculated based on the specified circumference) and thickness were determined based on the current values of the ratio of the sample thickness to its radius. The

sintering modes according to [9] ensured that the shear strength limit (at least 45 ± 1 MPa) was achieved. Rolling was performed on hand rollers of our own manufacture (Fig. 1). The rolled tubular blank is shown in Fig. 2.

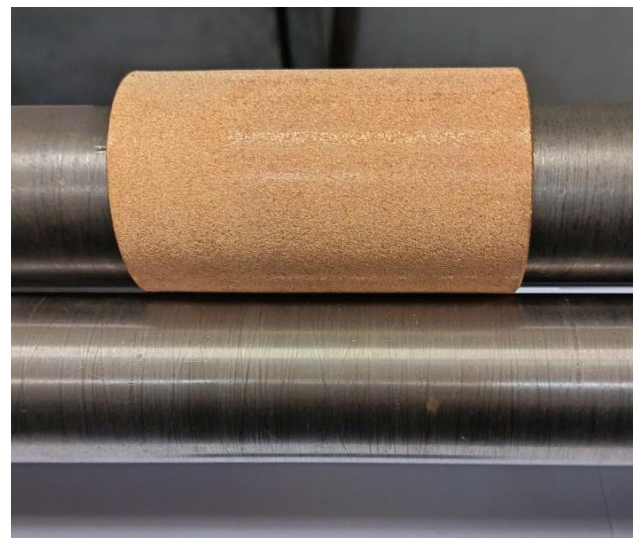


Fig. 1 The process of rolling a flat (sheet) porous blank based on tin-phosphorous bronze powder on rollers.



Fig. 2 A rolled tubular blank with a diameter of 60 mm.

The joint of the edges of the curved plate along the generatrix was sealed by welding in a protective gas (argon). On the obtained samples, the pore size [11] and the permeability coefficient [12] were measured in accordance with the recommendations, from which the efficiency parameter E_1 , proposed in equation (1) [13], was calculated:

$$E_1 = \frac{\sqrt{k}}{D}, \quad (1)$$

where:

k – is the permeability coefficient, m^2 ;
 D – average size of powder fractions used, μm .

Further on the graphs, the powder fractions used are characterized by the average particle size, determined by Anderson's formula (2) [14]:

$$D_q = (D_{\min} \cdot D_{\max}) / (0,5 \cdot (D_{\min}^2 + D_{\max}^2))^{0,5}, \quad (2)$$

where:

$D_{\max}$ – maximum size of sieve cells used to separate the powder fraction, μm ;

$D_{\min}$ – minimum size of sieve cells used to separate the powder fraction, μm .

The efficiency parameter was determined due to the fact that the appearance in the porous structure of the material during rolling of a sintered sheet blank of two zones with a smooth transition of stresses from maximum compressive to maximum tensile provides a smooth change in porosity over the cross section of the material and helps to increase the filter material efficiency parameter [15].

The research results are presented in the form of graphs in Fig. 3, which shows three dependences of the efficiency parameter (E_1) on the ratio of the sample thickness (h , mm) to the bending radius (a , mm) for three powder fractions (minus 160 + 125) μm (1), (minus 315 + 250) μm (2) and (minus 400 + 315) μm (3) and the curve (4) intersecting them on the right side of the figure, characterizing the dependence of the critical values of the ratio of sample thickness (h , mm) to bending radius (a , mm), at which the cracking process begins, on the average size of powder particles (D , μm).

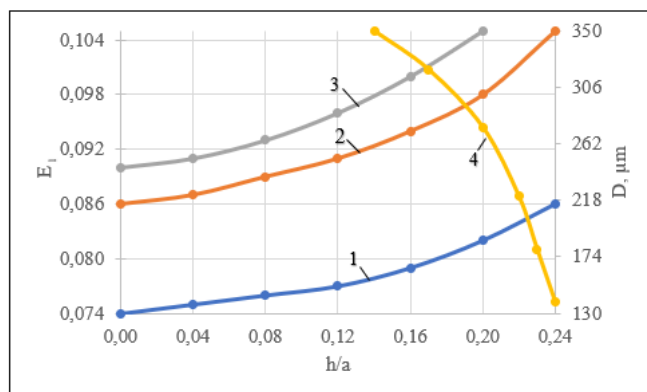


Fig. 3 Efficiency parameter dependences on the ratio of sample thickness to bending radius for three powder fractions: (minus 160 + 125) μm (1), (minus 315 + 250) μm (2) and (minus 400 + 315) μm (3) and ratio critical values of sample thickness to bending radius, at which the cracking process begins, on the powder particles average sizes (4).

The results analysis obtained shows that the process of manufacturing filter elements according to the plastic bending scheme with a ratio of plate thickness to bending radius equal to 0.15–0.24 (depending on the powder fraction) leads to an increase in the efficiency parameter by 13–26%. A further increase in this ratio leads to the occurrence of cracks and subsequently to loss of functionality and destruction. Fig. 4 shows the formation of cracks at the initial stage for one of the samples.



Fig. 4 Initial stage of crack formation on the outer surface of a curved sample.

The production of tubular powder filter elements by the rolling method significantly expands the technological capabilities in the production of products of this type. The authors' practice of using this technology included the production of filter elements with outer diameters from 40 to 500 and a length of up to 1500 mm. A slight reduction in the filtration area in the area where the edges of the products join isn't significant. Figure 5 shows, as an example, a photograph of several sintered sheet blanks and filter elements made on their basis.



Fig. 5 Sintered sheet blanks and filter elements made on their basis by rolling.

3. The results of experiment and their discussion

The studies results of dimensional limitations in the manufacture of tubular filter elements by rolling flat porous powder blanks sintered from tin-phosphorous bronze CuSn10F1 powders are presented. Critical values have been established for the ratio of the filter elements thickness to the radius of their cylindrical surface, exceeding which leads to the occurrence of cracks and subsequently to destruction. It's shown that an increase in the ratio of the plate thickness to the bending radius to values is accompanied by an efficiency parameter of the filter material increase by 13–26%. Examples of some manufactured filter products are presented.

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Tripod type parallel robots manipulators

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Abstract: Parallel robot manipulators (or parallel manipulators) feature closed kinematic chains. Compared to serial manipulators, they possess high load-carrying capacity, high positioning accuracy, and good dynamic characteristics. Most parallel manipulators with six degrees of freedom (DOF) utilize six legs and are commonly referred to as hexapods. This article focuses on the study of three-legged parallel manipulators, known as tripods. In comparison with hexapods, tripods offer larger workspaces and fewer singular configurations. The paper examines 3-PRRS and 3-PRPS tripods as examples, where P, R, and S denote prismatic, revolute, and spherical joints, respectively. Their structural synthesis was performed, their geometry investigated, and the inverse kinematics problem was solved.

Keywords: PARALLEL MANIPULATORS, TRIPODS, TRANSFORMATION MATRICES, GEOMETRY, INVERSE KINEMATICS.

1. Introduction

Parallel robot manipulators, or parallel manipulators, are manipulators formed by connecting a moving platform to a fixed platform (or base) using various types of kinematic chains. The moving platform is the working body of the parallel manipulator, executing specified motion laws. The kinematic chains connecting the moving and fixed platforms, known as the legs of parallel manipulators, form closed loops. Closed kinematic chains in parallel manipulators increase their rigidity. Therefore, compared to serial manipulators, which have open kinematic chains, parallel manipulators possess a high load-carrying capacity, high positioning accuracy, and good dynamic characteristics. The most well-known parallel manipulator is the Stewart–Gough platform [1,2], which has 6 DOF and 6 legs of the SPS or UPS type, where S, P, and U represent spherical, prismatic, and universal kinematic pairs, respectively. The DOF of the kinematic chains is determined by the Somov–Malyshev [3] or Grübler–Kutzbach [4] formulas. This platform has been widely used as a flight simulator. Parallel manipulators with 6 DOF and 6 legs are referred to as fully parallel manipulators [5]. Fully parallel manipulators typically have small workspaces and complex singular configurations. Expanding the workspace and reducing the singular configurations of fully parallel manipulators can be achieved by decreasing the number of legs connecting the moving platform to the base. Existing three-legged parallel manipulators, known as tripods, generally possess only three DOF; thus, they cannot fully provide the specified spatial motions of the moving platform. Well-known three-legged parallel manipulators include the 3-RRR spherical parallel manipulator [6,7] (where R is a revolute joint), in which the rotation axes of all six revolute joints intersect at a single point, and the Delta robot [8]. There are certain types of 6-DOF tripods in which each of the three legs consists of spatial kinematic chains such as ESR [9] (where E is a planar joint), RES [10], RRPS [11], or URS [12]. We have developed new 6-DOF tripods of the 3-PRRS, 3-PRPS, and 3-CCC types (where C is a cylindrical joint), which are protected by patents of the Republic of Kazakhstan [13, 14]. This paper presents methods for structural synthesis, geometric analysis, and solutions to the inverse kinematics problem for the 3-PRRS and 3-PRPS tripods.

2. Structural synthesis and geometry of 3-PRRS and 3-PRPS tripods

According to the developed principle for the formation of parallel manipulators [15], they are formed by connecting the moving and fixed platforms using closing kinematic chains of the active, passive, and negative types. Figures 1 and 2 illustrate 3D CAD models of the 3-PRRS and 3-PRPS type tripods.

The 3-PRRS type tripod is formed by connecting the moving platform 4 and the fixed platform 0 via three passive PRRS-type closing kinematic chains with zero DOF. Similarly, the 3-PRPS type tripod is formed by connecting the moving platform 2 and the fixed platform 1 via three passive PRPS-type closing kinematic chains with zero DOF. These passive PRRS and PRPS closing kinematic chains do not impose geometric constraints on the

motions of moving platforms 4 and 2 therefore, their 6 DOF are preserved. The input links for these tripods are selected as follows: three prismatic joints A located on the fixed platforms and three lower revolute joints B for the 3-PRRS type tripod, as well as three prismatic joints C for the 3-PRPS type tripod.

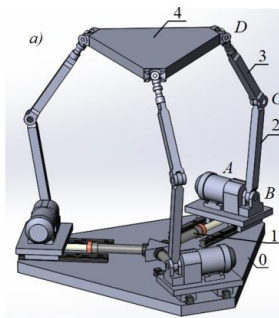


Fig. 1. 3D CAD model of the 3-PRRS type tripod.

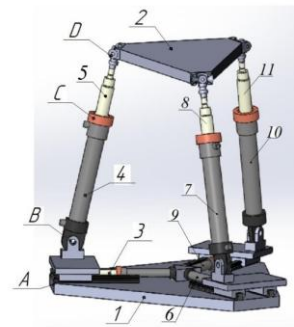


Fig.2. 3D CAD model of the 3-PRPS type tripod.

To describe the geometry and investigate the kinematics and dynamics of the 3-PRRS and 3-PRPS type tripods, UVW and XYZ coordinate systems are rigidly attached to each element of all kinematic pairs. The W and Z axes are aligned with the axes of rotation or translation of the kinematic pair elements, while the U and X axes are directed along the common perpendiculars between the W and Z axes of two adjacent kinematic pairs. The transformation matrix T_{jk} between the coordinate systems

$U_j V_j W_j$ and $X_k Y_k Z_k$ (Fig. 3) is as follows:

$$T_{jk} = T_{jk}(a_{jk}, \alpha_{jk}, b_{jk}, \beta_{jk}, c_{jk}, \gamma_{jk}) =$$

1	0	0	0
$a_{jk} \cdot c\gamma_{jk} +$ $+b_{jk} \cdot s\gamma_{jk} \cdot s\alpha_{jk}$	$c\gamma_{jk} \cdot c\beta_{jk} -$ $-s\gamma_{jk} \cdot c\alpha_{jk} \cdot s\beta_{jk}$	$-c\gamma_{jk} \cdot s\beta_{jk} -$ $-s\gamma_{jk} \cdot c\alpha_{jk} \cdot c\beta_{jk}$	$s\gamma_{jk} \cdot s\alpha_{jk}$
$a_{jk} \cdot s\gamma_{jk} -$	$s\gamma_{jk} \cdot c\beta_{jk} +$	$c\gamma_{jk} \cdot c\alpha_{jk} \cdot c\beta_{jk} -$	$-c\gamma_{jk} \cdot s\alpha_{jk}$
$-b_{jk} \cdot c\gamma_{jk} \cdot s\alpha_{jk}$	$c\gamma_{jk} \cdot c\alpha_{jk} \cdot s\beta_{jk}$	$-s\gamma_{jk} \cdot s\beta_{jk}$	$-c\gamma_{jk} \cdot s\alpha_{jk}$
$c_{jk} + b_{jk} \cdot c\alpha_{jk}$	$s\alpha_{jk} \cdot s\beta_{jk}$	$s\alpha_{jk} \cdot c\beta_{jk}$	$c\alpha_{jk}$

(1)

where a_{jk} is a distance between the W_j and Z_k axes measured in the direction of the common perpendicular t_{jk} between these axes; α_{jk} is an angle between the positive directions of the W_j and Z_k axes measured about the positive direction t_{jk} according to the right-hand rule; b_{jk} is a distance from the direction t_{jk} to the direction of the X_k axis measured along the positive Z_k axis direction; β_{jk} is an angle between the positive directions of the t_{jk} and X_k axis measured according to the right-hand rule; c_{jk} is a

As shown in Fig. 5, each leg of the 3-PRPS type tripod has the following constant parameters: $\alpha_{13} = 90^\circ$, $c_{13} = O_1O_3$, γ_{13} , $a_{34} = O_3O_4$, a_{34} , $\alpha_{34} = -90^\circ$ and the following variable parameters: $c_{33} = O_3O_3' = s_3$, $a_{42} = O_4O_2 = s_5$, $\gamma_{44} = \theta_4$, of which s_3 and s_5 are input parameters, and θ_4 is an output parameter. Then, the link geometry and kinematic pair matrices take the following form:

$$\mathbf{G}_{13} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \gamma_{13} & 0 & \sin \gamma_{13} \\ 0 & \sin \gamma_{13} & 0 & -\cos \gamma_{13} \\ c_{13} & 0 & 1 & 0 \end{bmatrix}, \quad (9)$$

$$\mathbf{P}_3^P = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ s_3 & 0 & 0 & 1 \end{bmatrix}, \quad (10)$$

$$\mathbf{G}_{34} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ a_{34} & 0 & 0 & -1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \end{bmatrix}, \quad (11)$$

$$\mathbf{P}_4^P = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \theta_4 & -\sin \theta_4 & 0 \\ 0 & \sin \theta_4 & \cos \theta_4 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (12)$$

$$\mathbf{P}_5^P = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ s_5 & 0 & 0 & 1 \end{bmatrix}, \quad (13)$$

3. Inverse kinematics of 3-PRRS and 3-PRPS type tripods

In inverse kinematics, the pose (position and orientation) of the coordinate system $PX_p Y_p Z_p$, attached to the moving platform, is given. It is necessary to determine the input parameters of the tripods. The solution to the inverse kinematics problem for parallel robots is crucial, as the obtained input parameter values are used to control the robot's motion.

Let us consider the solution to the inverse kinematics problem for the 3-PRRS type tripod. To do this, we determine the coordinates of the spherical joints $O_{4,i}$ of the moving platform in the absolute coordinate system $OU_o V_o W_o$ through the specified coordinates of the $PX_p Y_p Z_p$ coordinate system using the following equation:

$$[1, U_{O_{4,i}}, V_{O_{4,i}}, W_{O_{4,i}}]^T = \mathbf{T}_{OP} \mathbf{G}_{P4} [1, 0, 0, 0]^T \quad (14)$$

and through the $ABCD$ legs by the equation

$$[1, U_{O_{4,i}}, V_{O_{4,i}}, W_{O_{4,i}}]^T = \mathbf{G}_{01} \mathbf{P}_{1i}^P \mathbf{G}_{12} \mathbf{P}_{2i}^R \mathbf{G}_{23} \mathbf{P}_{3i}^R \mathbf{G}_{34} [1, 0, 0, 0]^T. \quad (15)$$

Expanding Eq. (15) and substituting the values of the spherical joint coordinates from Eq. (14), we obtain:

$$\left. \begin{aligned} U_{O_{4,i}} &= -b_i c \gamma_i + s_i s \gamma_i - f_i s \gamma_i s \theta_{2,i} - g_i s \gamma_i s \theta_{23,i} \\ V_{O_{4,i}} &= -b_i s \gamma_i - s_i c \gamma_i + f_i c \gamma_i s \theta_{2,i} + g_i c \gamma_i s \theta_{23,i} \\ W_{O_{4,i}} &= c_i + a_i + f_i c \theta_{2,i} + g_i c \theta_{23,i} \end{aligned} \right\}, \quad (16)$$

where $\theta_{23,i} = \theta_{2,i} + \theta_{3,i}$.

An analysis of the system of Eq. (16) shows that the first two equations are linearly dependent. We transform the first and third equations of system (16) into the following form:

$$A_i s^2 \theta_{2,i} - B_i s \theta_{2,i} + C_i = 0, \quad (17)$$

where A_i, B_i , and C_i are known parameters

$$A_i = (s_i - K_i)^2 + M_i^2, \quad B_i = 2(f + g c \theta_{3,i})(s_i - K_i), \quad (18)$$

$$C_i = (f + g c \theta_{3,i})^2 - M_i^2, \quad K_i = \frac{U_{O_{4,i}} + b c \gamma_i}{s \gamma_i}, \quad M_i = W_{O_{4,i}} - c - a.$$

From Eq. (17), and also from the first and third equations of system (16), two possible values of the parameters $\theta_{2,i}$ and $\theta_{3,i}$ can be determined:

$$\left. \begin{aligned} \theta_{2,i} &= s^{-1} \frac{B_i \pm \sqrt{B_i^2 - 4A_i C_i}}{2A_i}, \quad \theta_{2,i} = \pi - s^{-1} \frac{B_i \pm \sqrt{B_i^2 - 4A_i C_i}}{2A_i}, \\ \theta_{3,i} &= \pm c^{-1} \frac{(s_i - K_i)^2 + M_i^2 - f^2 - g^2}{2fg}. \end{aligned} \right\} \quad (19)$$

which correspond to two assembly configurations of each tripod leg.

Let us consider the solution to the inverse kinematics problem of a 3-PRPS type tripod. We shall determine the coordinates of the spherical joints D of the moving platform in the absolute coordinate system $OU_o V_o W_o$ in terms of the given coordinates of the

$PX_p Y_p Z_p$ coordinate system using the equation:

$$[1, U_D, V_D, W_D]^T = \mathbf{T}_{OP} \mathbf{G}_{PO_5} [1, 0, 0, 0]^T. \quad (20)$$

and via the $OABCD$ legs using the equation

$$[1, U_D, V_D, W_D]^T = \mathbf{G}_{13} \mathbf{P}_1^P \mathbf{G}_{34} \mathbf{P}_4^R \mathbf{P}_5^P [1, 0, 0, 0]^T, \quad (21)$$

By expanding Eq. (21) and substituting the values for the coordinates of joints D from Eq. (20), we obtain:

$$\left. \begin{aligned} s_3 \cdot s \gamma_{13} - s_5 \cdot s \gamma_{13} \cdot s \theta_4 &= U_D \\ -s_3 \cdot c \gamma_{13} + s_5 \cdot c \gamma_{13} \cdot s \theta_4 &= V_D \\ c_{13} + a_{34} + s_5 \cdot c \theta_4 &= W_D \end{aligned} \right\}. \quad (22)$$

An analysis of the system of equations (22) shows that the first two equations are linearly dependent. Therefore, the parameter s_3 can be chosen free.

After transforming the first and the third equations of system (22), we obtain

$$\left. \begin{aligned} s_5 \cdot s \theta_4 &= s_3 - F \\ s_5 \cdot c \theta_4 &= K \end{aligned} \right\}, \quad (23)$$

where $F = \frac{U_D}{s \gamma_{13}}$, $K = W_D - c_{13} - a_{34}$.

From the system of equations (22) we obtain the parameters s_5 and θ_4

$$s_5 = \sqrt{(s_3 - F)^2 + K^2}, \quad (24)$$

$$\theta_4 = c^{-1} \left(\frac{M \pm \sqrt{2 - M^2}}{2} \right), \quad (25)$$

where $M = \frac{s_3 - F + K}{s_5}$.

4. Conclusions

The article outlines the fundamental concepts of parallel manipulators and their advantages over serial manipulators, such as high load-carrying capacity, high positioning accuracy, and good dynamic characteristics due to the presence of closed kinematic chains. A comparison is conducted between two types of parallel manipulators, hexapods and tripods demonstrating that tripods possess larger workspaces and fewer singular configurations compared to hexapods. Structural synthesis was performed, the geometry was studied, and the inverse kinematics problems were solved for 3-PRRS and 3-PRPS type tripods. These tripods are formed by connecting the moving and fixed platforms via passive closing kinematic chains of the PRRS and PRPS types with zero DOF. To investigate geometry and kinematics, a generalized transformation matrix with six parameters was formulated, serving as the basis for obtaining the geometry matrices of the links and kinematic pairs of the tripods under consideration. Using these transformation matrices, the inverse kinematics problems for the 3-PRRS and 3-PRPS type tripods were solved.

5. Acknowledgment

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A Comparative Analysis of the Main Methods of 3D Steganography

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Abstract: The report examines three main groups of approaches: geometric methods, topological techniques, and transformation-based methods. Their robustness, data hiding capacity, visual imperceptibility, and computational complexity are evaluated through analysis. The results show that geometric methods offer high capacity but are more vulnerable to attacks such as smoothing and model simplification. Topological techniques provide greater robustness but have limited capacity. Transformation-based methods achieve a good balance between robustness and quality, albeit at the cost of higher computational expense. The report emphasizes that the choice of approach depends on the specific application, such as copyright protection or secure communication, and provides guidance for selecting the optimal method according to security and performance requirements.

Keywords: 3D STEGANOGRAPHY, TWO-STATE, LSB DOMAIN, PERMUTATION AND TRANSFORM

1. Introduction

3D steganography hides information inside the geometry, topology, or mathematical representation of a 3D object. Unlike 2D steganography images, 3D models contain richer data structures like vertices, edges, faces, normals, textures, which provide more places to embed information. Three-dimensional (3D) models have become ubiquitous in digital communication, gaming, medicine, and engineering. As the use of 3D data increases, so does the need for secure data hiding within such media. This paper presents a comparative analysis of the principal methods employed in 3D steganography, organized according to a four-domain taxonomy: two-state domain, Least Significant Bit (LSB) domain, permutation domain and transform domain. Each method is evaluated against key criteria including embedding capacity, imperceptibility, robustness against attacks, reversibility, and computational complexity. The analysis reveals that LSB-based methods in the geometric domain currently represent the best overall trade-off between capacity, imperceptibility, and ease of implementation, while transform-domain methods offer superior robustness at the cost of capacity.

Early work on data hiding in 3D models was largely motivated by digital watermarking where they need to assert copyright ownership [1], [2]. Over time, the field evolved toward general purpose steganography focused on covert communication with higher payload capacity. Foundational surveys, such as that of [3], organized 3D steganography techniques into geometrical, topological, and representation domains. More recent work by [4] proposed a refined four-category taxonomy-two-state, LSB, permutation, and transform domains, which has become widely adopted. In its latest iteration, 3D steganography transcends traditional boundaries leveraging the complexity of three-dimensional structures to hide data in plain sight [6]. In [8] provides a taxonomy of 3D steganography methods across geometric, topological, and representation domains, including challenges and attack models.

Current challenges in the 3D field include problems presented in fig.1.

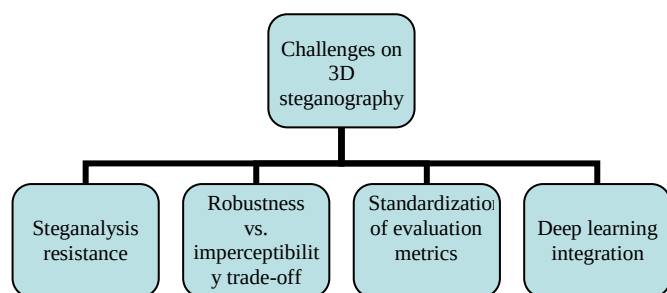


Fig. 1 Challenges on 3D steganography

For steganalysis resistance we can say that many 3D steganographic methods remain detectable by modern statistical

steganalysis tools. Robust embedding typically requires larger vertex modifications, harming visual quality. For standardization of evaluation metrics can say unlike PSNR in 2D, 3D quality metrics such as Hausdorff Distance (HD) are less universally applied. According to [5] deep learning integration (DLI) means that 3D mesh steganography remains dominated by non-AI methods, leaving room for geometric deep learning innovations.

In [7] is presented the novel approach for non-destructive steganography by predetermination. In [8] provides a taxonomy of 3D steganography methods across geometric, topological, and representation domains, including challenges and attack models.

2. Materials for Production of Prototype Parts

Modelling of realistic 3D image is a challenging problem in computer graphics. Realistic 3D images have a wide range of potential applications, including visualization and design for research and educational purposes, computer animation and games, and more than that, information encryption in the 3D scenes [12], [13]. In [10] reviews problematic aspects of the digital transposition of a real learning s.

Cybersecurity is one of the most commented areas in IT nowadays [15]. In the stage of Industri 4.0, a certain opportunity arises for humans to implement their own strategies with the capabilities of machines [9] to achieve the most effective way of data processing [14].

3D image steganography uses a 3D image as cover image which has points or vertices in the 3D geometry which are manipulated for hiding a secret message. Embedding capacity of 3D image steganography is measured in terms of number of bits embedded per vertex of cover image. If we compare 3D image steganography techniques with 2D we can be seen more payload carrying capacity than 2D image steganography techniques.

In terms of 3D image steganalysers, they are designed taking into account the statistical changes that might have crept in cover mesh model because of embedding of secret message inside it. [11] tell us that secret message inside the cover model may be imperceptible to the human eye but disturbs the natural statistics of the cover model.

Given the complexity and flexibility of 3D data structures, this field offers great potential but requires the development of highly contextual and domain-aware steganographic techniques. Future research challenges include optimizing adaptive embedding, defending against universal steganalysis, and integrating with multimodal system [5].

Comparative Analysis of Steganographic Methods

The table 1 presents a systematic comparison of four steganographic methods which are: Two-State, LSB Domain, Permutation and Transform. They are evaluated across six key performance criteria. *Capacity* refers to the amount of data that can

be concealed within a carrier medium, measured in bits per vertex (bpv), *imperceptibility* denotes visual and geometric quality of the stego-model, *robustness* measures the ability of the embedded message to survive unintended modifications, such as compression, noise, or format conversion, *reversibility* indicates whether the original cover medium can be fully restored after the extraction of the hidden message.

Table 1. Criteria for Comparison

Method Criteria	Two- State	LSB Domain	Permutation	Transform
Capacity	Low ~1 bpv	High 2-5 bpv	High 2-5 bpv	Low-Mod 0.5-2 bpv
Imperceptibility	High	High	Perfect	Moderate
Robustness	Low	Low	None	High
Reversible	Yes	Achievable	Yes(lossless)	No(lossy)
Blind	Yes	Yes	Partial	Some
Cost	Low	Low	Moderate	High
Steganalysis Resistance	Moderate	Low-Mod	Moderate	High

The diagram (fig. 2) shows the overall “profile” of each method. The larger and more symmetrical the figure is the more balanced the method. Transform (blue) is clearly drawn to robustness and steganalysis resistance, while LSB Domain (green) and permutation (red) are strong in capacity, imperceptibility and reversibility.

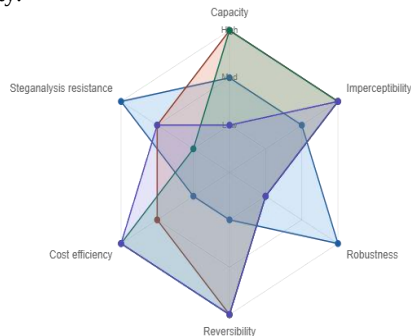


Fig.2. Performance evaluation by criterion

Types of Attacks on 3D Steganography.

Types of attacks against 3D steganography could be systematized according to several criteria:

- Affine transformations: translation, rotation, uniform scaling
- Vertex reordering: changing the traversal order of vertices
- Noise addition: random perturbation of vertex coordinates
- Mesh smoothing: Laplacian or Taubin smoothing
- Mesh simplification: reducing vertex count via decimation
- Mesh cropping: partial removal of mesh regions

When we are comparing methods for resistance to attacks, we can see their assessment according to five criteria in a table 2, where X robust and ✓ fragile.

Table 2. Criteria for comparison for resistance to attacks

Attack	Two- State	LSB	Permuta- tion	Transform
Affine transformation	X	X	✓	✓
Vertex reordering	X	X	X	✓
Noise addition	X	X	✓	✓
Mesh smoothing	X	X	✓	✓
Mesh simplification	X	X	✓	Partial

Conclusion:

Throughout this study, we have demonstrated the compare of embedding data within 3D objects in a manner that is both imperceptible and does not compromise the object's structural integrity or aesthetic value. This paper has surveyed and compared the four principal categories of 3D mesh steganography: two-state, LSB, permutation, and transform domain methods. Each category represents a distinct trade-off across the evaluated criteria. Adaptive LSB-based geometric domain methods currently offer the best balance of capacity, imperceptibility, and practical utility for covert communication applications. Transform-domain spectral methods remain the method of choice when robustness against geometric attacks is paramount. The field is evolving rapidly, with deep learning offering promising avenues for closing the remaining performance gaps

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Automatic quality control of blanked parts based on segmentation of shear and fracture zones using a convolutional neural network

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Abstract: A method for automatic quality control of blanked parts based on the ratio of the plastic deformation (shear) zone to the brittle fracture (rupture) zone on the cut surface is presented. Unlike known approaches that require strictly controlled shooting conditions, the proposed convolutional AI model (R-CNN) demonstrates robustness to a wide range of illumination: variations in brightness and light incidence angle reduce segmentation accuracy by no more than 3%. This is achieved through the use of local texture features that are invariant to brightness scale. The system takes into account the material grade — reference ratios of the zones are defined for each steel grade. Experiments were carried out on samples of three grades (AISI 1010, S235JR, AISI 1066). The classification accuracy of acceptable and defective parts was 98% relative to expert assessment.

KEYWORDS: SHEET METAL STAMPING, BLANKING, QUALITY CONTROL, CUT SURFACE, PLASTIC DEFORMATION ZONE, FRACTURE ZONE, BURR, MACHINE VISION, CONVOLUTIONAL NEURAL NETWORK

1. Introduction

Sheet metal stamping occupies one of the leading positions among metal forming technologies due to its high productivity, low material consumption, and the ability to produce complex-shaped parts in a short time. The blanking operation is used to separate a sheet workpiece along a closed contour and is the basis for manufacturing many products — from car body elements to precision instrument components.

The quality of blanked parts is primarily determined by the condition of the cut surface. When stamping with clearances not exceeding 5–10% of the sheet thickness, characteristic zones are formed on the edge: the rollover (indentation zone), the smooth shiny zone of plastic shear, the rough zone of brittle fracture, and the burr on the lower face [1].

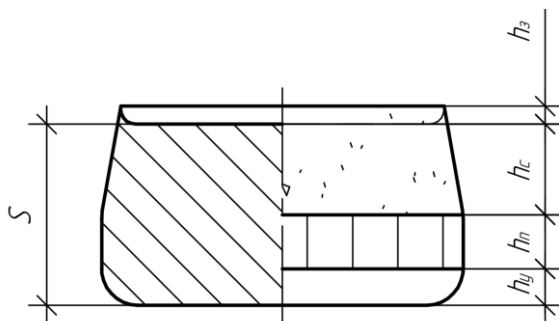


Fig. 1. Scheme of the separation zone on a blanked part
 S – thickness; h_r – rollover zone; h_n – plastic deformation zone; h_c – fracture zone; h_b – burr.

The ratio between the plastic deformation zone and the fracture zone is a sensitive diagnostic parameter reflecting the clearance between punch and die, the degree of tool wear, and the plastic properties of the workpiece material. Therefore, quality control of blanked parts is a mandatory stage of the production process [2].

The first and most common method is visual and instrumental inspection. The inspector examines the edge of the part and measures the burr height with a feeler gauge or microscope. This method is simple and does not require expensive equipment, but it is subjective, labor-intensive, and practically unsuitable for 100% inspection on automatic lines with a cycle time of 1–2 seconds.

The second method is destructive testing involving the preparation of micro-sections. The sample is cut, ground, etched, and examined under a microscope. This allows accurate measurement of all cut zones, but the method is time-consuming, unsuitable for inspecting every part, and requires highly qualified personnel. Its domain is selective batch inspection or process qualification during die setup.

The third method is non-contact laser inspection. Laser triangulation sensors and optical profilometers allow constructing a 3D model of the edge with micron accuracy. Disadvantages include high cost, complex setup, and, most importantly, low productivity. Processing a single profile takes seconds, which becomes a "bottleneck" on an automatic line with a cycle time of 0.5–1 second.

The fourth method is machine vision systems with machine learning algorithms. A camera captures an image of the edge, and algorithms detect the presence of defects. This method is productive (up to 10–20 parts per second) and relatively cheap. However, existing implementations impose strict requirements on shooting conditions: illumination, part position, and orientation must be tightly controlled. In real production, this is difficult to achieve — lamps age, flare and shadows from neighboring equipment appear, and the part surface may be contaminated with lubricant. As a result, the high accuracy of algorithms achieved in the laboratory degrades on the production line.

Thus, modern methods for quality control of blanked parts are either insufficiently productive, or subjective, or too sensitive to external conditions. There is a need for a method that is simultaneously fast, objective, and robust to variations in shooting conditions [3].

In this work, propose an approach based on a convolutional artificial intelligence model for automatic segmentation of plastic deformation and fracture zones on the cut surface of parts obtained by sheet metal blanking operations. The key feature of the method is robustness to a wide range of illumination conditions, achieved by training the neural network on local texture features rather than on absolute brightness values. Additionally, the system takes into account the mechanical characteristics of the material, allowing different reference zone ratios to be used for ductile and brittle steels. The paper describes the experimental methodology, neural network architecture, obtained results, and their comparison with expert assessment.

2. Preparation of the experiment

2.1. Materials and Methods

For the experiment, a simple-action blanking die was designed and manufactured, allowing round blanks with a diameter of 30 mm to be cut from sheet metal with a thickness of 1.5 mm. The round shape was chosen due to the absence of corner stress concentration zones, which simplifies the analysis of the cut surface.

Sheets of three steel grades were used as the material: AISI 1010, S235JR, AISI 1066, which differ significantly in their shear strength (σ_s). This made it possible to evaluate the influence of the plastic properties of the material on the shear-to-fracture zone ratio.



Fig. 2. Blanked part

2.2. Sample Formation

At the initial stage, the die was equipped with sharply sharpened punch and die with a radial clearance of 10% of the sheet thickness (0.15 mm). This clearance provides a high-quality cut with minimal burr and clear deformation and fracture zones. The obtained blanks were used as reference (acceptable) parts.

To artificially create defects, the punch was replaced with a tool of smaller diameter, which increased the clearance. The clearance was sequentially increased in steps of 1% of the sheet thickness. The maximum investigated clearance was 20% (0.30 mm), leading to a pronounced burr and predominance of the fracture zone over the shear zone. For each clearance value (from 10% to 20%), at least 20 blanks were manufactured.

3. Image Acquisition

The blanks were photographed using an ESP32-CAM board (OV2640 camera, 2 MP). The key condition was the simulation of real production conditions:

- Shooting was performed under various lighting conditions (daylight, overhead workshop lighting, local illumination, darkened conditions) — the "as is" principle, without professional light sources.
- The images were not subjected to any retouching, color correction, or sharpening.



Fig. 3. Parts photographed at different angles

Shooting was carried out at different angles with a deviation of -30° to $+30^\circ$ relative to the normal, simulating variations in part position. The total dataset size was 220 images. For each image, an expert performed manual annotation of the shear and fracture zones for training and validation of the neural network.

4. Neural Network Model Training

After image acquisition and dataset formation, data preparation for training was performed. Manual annotation of images was carried out using specialized software. At the first stage, the cut surface region was outlined — thus defining the region of interest (ROI), which allowed training the model to focus specifically on the edge of the part, ignoring the background and end surfaces.

At the second stage, within the selected cut zone, pixel-wise segmentation of two types of areas was performed: the plastic deformation zone (smooth shiny area) and the fracture zone (rough matte area).

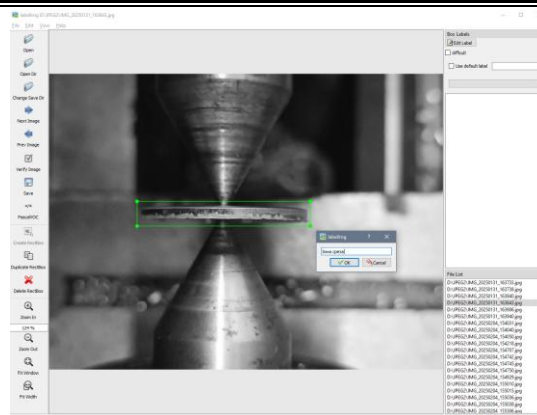


Fig. 4. Image labeling process

The annotated images formed the training dataset. The artificial intelligence model was implemented in Python using the TensorFlow framework. Training was conducted for 12 epochs. The final accuracy of the model on the validation set was 94.25%. The loss value during training decreased to 2.12%, indicating stable convergence and the absence of obvious overfitting.

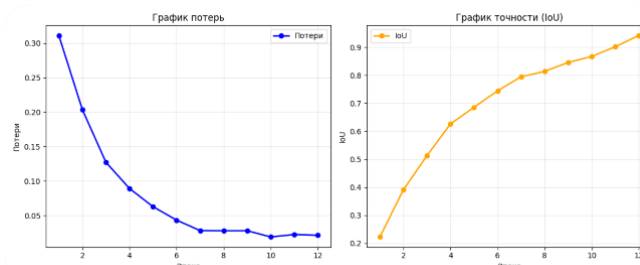


Fig. 5. AI model accuracy metrics vs. training epochs

Upon completion of training, the model is capable of automatically segmenting the shear and fracture zones on new images obtained under various lighting conditions without additional tuning.

5. Experimental Validation Results

At the final stage, the trained model was evaluated on a test set that was not used during training. The test set consisted of 100 images of cut surfaces obtained from different material grades (AISI 1010, S235JR, AISI 1066). Half of the images corresponded to blanks manufactured with increased clearance (11–20%), which exhibited pronounced burrs of various heights. The other half corresponded to reference blanks (clearance 10%) with a high-quality cut and no burr.



Fig. 6. Example of model operation in cut zone detection

The experiments confirmed that the trained model correctly recognizes the plastic deformation and fracture zones and also detects defects in the form of burrs. The decision on the presence of a defect was made automatically based on the deviation of the measured zone ratio from the reference value specified individually for each material grade.

On the test set, burr defects were detected in 98% of cases. This result confirms the high efficiency of the proposed approach and its suitability for automatic quality control of blanked parts under conditions close to real production.

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Thermal and acoustic insulation studies of composite lime and lime-cement plasters based on foam glass granules and thermally treated rice husks

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Abstract: This paper presents the results of studies on the thermophysical and sound-insulating properties of new composite materials intended for interior and exterior plasters in construction. The materials were developed on the basis of foam glass granules and thermally treated rice husks using a specialized methodology. The guarded hot plate method was used to investigate the thermal insulation properties of the composite plasters. Tests for determining the acoustic insulation characteristics were carried out under laboratory conditions using the two-chamber method. The results show that the newly developed composite plasters exhibit better thermal and acoustic insulation properties than the standard plaster compositions traditionally used in construction.

Keywords: COMPOSITE PLASTERS, FOAM GLASS GRANULES, RICE HUSKS, THERMAL CONDUCTIVITY COEFFICIENT, SOUND INSULATION COEFFICIENT

1. Introduction

The optimization of the thermal and acoustic insulation properties of construction materials is of key importance for improving energy efficiency and comfort in buildings. Traditional plasters often suffer from limited insulating properties and insufficient resistance to external influences. In this context, new composite plasters based on foam glass granules and thermally treated rice husks represent an innovative solution combining environmentally friendly characteristics with improved physical and mechanical properties.

A number of researchers have investigated the possibilities for the application of composite materials based on foam glass granules [1,2,3]. In Bulgaria, a production facility for their production has been developed and put into operation [4].

Rice is one of the leading cereal crops worldwide and generates significant amounts of agricultural waste. The final product obtained from thermally treated rice husks, containing amorphous silicon dioxide, finds application not only in the ceramic industry [4], but also in other industrial fields, including plasters, due to its high reactivity.

The present study aims to present the results of experimental investigations on the thermophysical and sound-insulating properties of interior and exterior composite lime and lime-cement plasters incorporating these innovative additives. The tests were carried out using methods compliant with international standards, and the results were compared with data for traditional materials.

2. Experimental Part

2.1. Materials

The subject of the investigation consists of dried plaster-type samples with dimensions of (0.3×0.3) m and different thicknesses, composed of lime and lime-cement composite materials intended for interior and exterior applications.

The samples were obtained by adding foam glass granules and thermally treated rice husks, which replace part of the quartz sand in the plasters and improve a number of physicochemical properties. The foam glass granules had particle sizes below 3 mm and a bulk density of approximately 130 kg/m^3 .

Following the thermal treatment of the rice husks, ash containing amorphous silicon dioxide was obtained. The role of the active amorphous silicon dioxide is associated with a "cementing" effect, contributing to the strengthening and improvement of the plaster properties. In the investigated samples, rice husks thermally

treated at 650°C and ground into powder with a sedimentation size below $10 \mu\text{m}$ were used.

The inert fraction in the white dry lime interior plasters consisted of sand : foam glass granules : thermally treated rice husks in a volume ratio of 1 : 1.5 : 0.5. For the gray exterior plasters containing cement, the ratio was 1 : 1.5 : 0.4, while the volume fraction of cement was 0.1.

Table 1 presents the main characteristics of the samples, while Figure 1 shows the plaster plates.

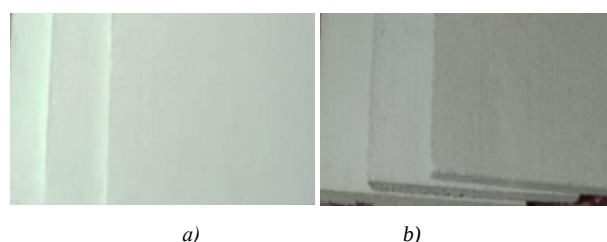


Fig.1. Appearance of plaster samples: a) lime interior plasters; b) lime-cement exterior plasters.

Table 1: Material characteristics of composite plasters

N	Code	Dimensions, m	Density, kg/m^3
	Composite lime interior plaster		
1	B-13-Int	$0.3 \times 0.3 \times 0.013$	675
2	B-20-Int	$0.3 \times 0.3 \times 0.02$	910
3	B-30-Int	$0.3 \times 0.3 \times 0.03$	1295
	Composite lime-cement exterior plaster		
4	S-13-Ext	$0.3 \times 0.3 \times 0.013$	671
5	S-20-Ext	$0.3 \times 0.3 \times 0.02$	859
6	S-30-Ext	$0.3 \times 0.3 \times 0.03$	1278

2.2. Methodology for Determining the Thermal Conductivity Coefficient of the Plasters

The investigation of the thermal insulation properties of the composite materials was carried out using a steady-state temperature method, in which the temperature gradient remains constant over time. The measurements were based on the passage of heat flow through parallel layers, taking into account the temperature difference between the two opposite sides of a sample of known thickness.

For the measurements, the Guarded Hot Plate method was used, employing a plate of reference material with a known thermal conductivity coefficient [6].

The tests were conducted in a thermal chamber with dimensions of $0.7 \text{ m} \times 0.7 \text{ m}$, insulated with mineral wool and aluminum foil. The square plates were placed horizontally inside the chamber, tightly fitted and without gaps, with the heater positioned on the lower side. A schematic representation of the experimental setup for determining the thermal conductivity coefficient of the plasters is shown in Figure 2.

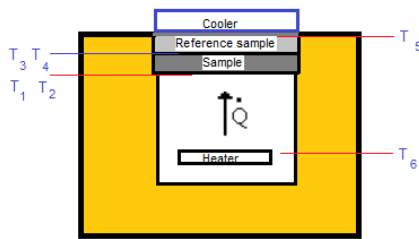


Fig.2. Scheme of the experimental setup – thermal chamber

The heat flow passing through the tested sample was assumed to be equal to that passing through the reference plate, which allowed the unknown thermal conductivity to be calculated through the ratio between temperature differences and layer thicknesses.

$$Q_x = Q_R \quad (1)$$

$$\lambda_x \Delta T_x \frac{A_x}{d_x} = \lambda_R \Delta T_R \frac{A_R}{d_R} \quad (2)$$

Where the subscript x denotes the tested plate, while the subscript R denotes the reference plate.

The area of the sample (A_x) was equal to the area of the reference plate (A_R).

The thicknesses of the sample plate and the reference specimen are denoted by d_x and d_R , respectively.

Eight thermocouples connected to an eight-channel temperature recorder with computer data acquisition capability were used for temperature measurements. Two thermocouples were positioned on the heated side of the sample and two on the opposite, non-heated side. A cooler was placed on the reference plate to ensure a controlled temperature difference.

The thermal conductivity coefficient λ_x of the investigated samples was calculated according to the following equation:

$$\lambda_x = \lambda_R \frac{T_{34} - T_5}{T_{12} - T_{34}} \frac{d_x}{d_R} \quad (3)$$

Where:

λ_R is the thermal conductivity of the reference plate ($\lambda_R = 0.036 \text{ W/mK}$),

T_{12} is the average temperature on the heated side of the sample,

T_{34} is the average temperature on the non-heated side of the sample,

T_5 is the temperature of the outer surface of the reference plate,

d_x и d_R are the thicknesses of the investigated sample and the reference plate..

The test specimens were placed in the thermal chamber and subjected to heating until a steady-state condition was reached, which required approximately 2 hours. The measurements then continued for an additional 5 hours to achieve higher accuracy.

2.3. Methodology for Acoustic Investigations

The sound insulation properties of the composite plasters were determined in accordance with the international standards EN ISO 10140-1, EN ISO 10140-2, EN ISO 10140-5, and EN ISO 717-1.

For this purpose, the two-chamber method was applied, in which the tested sample was placed between two chambers. The

measurements were performed using specialized equipment consisting of two acoustically isolated rooms: a reverberation chamber with dimensions $700 \times 600 \times 600 \text{ mm}$ and a receiving (“anechoic”) chamber with dimensions $700 \times 600 \times 500 \text{ mm}$ [5].

The reverberation chamber was constructed from multilayer materials such as gypsum board, particle board, mineral wool, and glass, and contained two broadband loudspeakers generating white noise in the frequency range 20–20000 Hz.

The receiving chamber was insulated with two layers of polyurethane foam and pyramid-type sound-absorbing foam, minimizing external noise. The equipment used for the acoustic investigations is described in greater detail in [5].

Sound pressure measurements were carried out using ECM999 microphones positioned in both chambers and processed using a dual-channel Real Time Acoustic Analyzer VT RTA-168 and MultiInstrument 3.9 Professional software.

By emitting white noise and recording the sound pressure before and after the sample, the difference in sound levels was determined and used to calculate the sound insulation coefficient R according to the equation:

$$R = L_{p1} - L_{p2} + 10(S/A) \quad (4)$$

Where:

L_{p1} is the average sound pressure level in the source room, dB,

L_{p2} is the average sound pressure level in the receiving room, dB,

S is the surface area of the tested partition sample, equal to the area of the test opening, m^2 ,

A is the sound absorption of the receiving room, m^2 .

The measurements were repeated four times, and the average values were taken to represent the acoustic characteristics of the plasters.

3. Results and Discussion

Thermal Insulation Properties

Figures 3 and 4 present the temperature variations over time during the experimental measurements of thermal conductivity for the white interior lime plaster and the gray exterior lime-cement plaster with different thicknesses (13 and 30 mm).

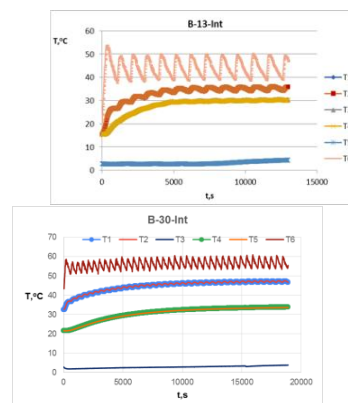


Fig.3. Temperature changes during the testing of the interior lime plasters with thicknesses of 13 and 30 mm

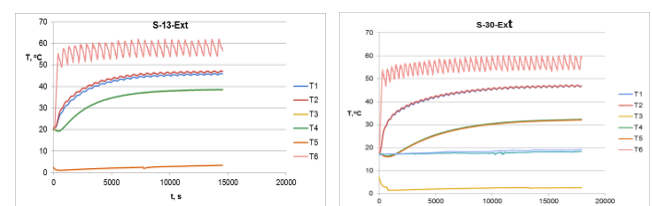


Fig.4. Temperature changes during the testing of the external lime-cement plasters with thicknesses of 13 and 30 mm.

The measured temperatures T_1 and T_2 were recorded on the heated side of the plates, while T_3 and T_4 represent the values measured on the non-heated side. T_5 and T_6 correspond to the temperatures measured on the reference plate and the heater, respectively.

The calculated thermal conductivity coefficients for the investigated samples, presented in Table 2, range from 0.067 to 0.08 W/mK. These values are significantly lower than the typical values reported in the literature for standard cement plasters, which vary between 0.9 and 1.4 W/mK.

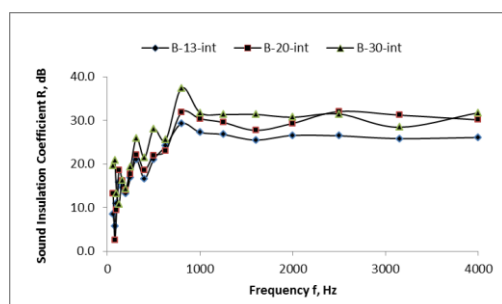
Table 2: Thermal conductivity coefficients of composite plasters

No	Code	Thermal conductivity λ_x , W/(m.K)	Uncertainty
1	B-13-Int	0.080	0.000503
2	B-20-Int	0.079	0.001115
3	B-30-Int	0.08	0.001097
4	S-13-Ext	0.069	0.039853
5	S-20-Ext	0.076	0.00158
6	S-30-Ext	0.067	0.001464

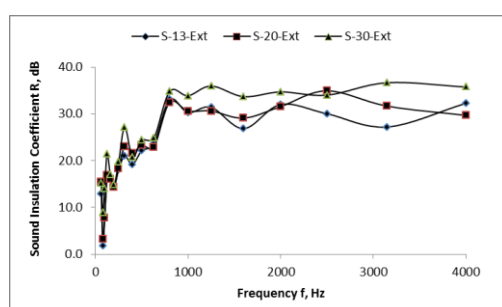
The low thermal conductivity coefficients indicate the high thermal insulation potential of the composite plasters, surpassing traditional materials in terms of energy efficiency.

Sound Insulation Properties

The results of the acoustic measurements presented in Fig. 5 show the variation of the sound insulation coefficients R as a function of frequency up to 4 kHz for the interior and exterior plasters, respectively.



a)



b)

Fig.5. Sound insulation coefficients of the composite plasters
a) lime interior plasters; b) lime-cement exterior plasters.

According to the EN ISO 717 standard, the weighted sound reduction index R_w for airborne noise was calculated for each sample and is presented in Table 3.

Table 3. Weighted Sound Reduction Index R_w

No	Code	Weighted Sound Reduction Index R_w , dB
1	B-13-Int	26
2	B-20-Int	26
3	B-30-Int	26
4	S-13-Ext	28
5	S-20-Ext	28
6	S-30-Ext	28

The obtained indices confirm that the developed composite plasters provide good acoustic protection, while the exterior lime-cement plasters exhibit slightly higher sound insulation values.

This is due to the use of cement and their denser structure, which contributes to more effective attenuation of sound waves. The achieved values are competitive with those of traditional materials and demonstrate the applicability of the composite plasters in buildings with increased sound insulation requirements.

4. Conclusion

The present paper reports the results of investigations on the thermophysical and sound-insulating properties of newly developed composite lime and lime-cement plasters incorporating foam glass granules and thermally treated rice husks as innovative additives.

The conducted investigations demonstrate that the newly developed composite plasters possess significantly better thermal and acoustic insulation properties compared to standard cement plasters. In addition, the acoustic tests show improved sound insulation performance of the new materials, with weighted sound reduction index R_w values reaching up to 28 dB for the exterior plasters.

These results demonstrate the potential of the investigated composite plasters for application in construction aimed at improving energy efficiency and acoustic comfort.

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Advanced metal additive manufacturing using xBeam 3D metal printing technology: processing, microstructure, mechanical performance and emerging applications

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Abstract: xBeam 3D metal printing is an advanced wire-feed electron-beam DED technology based on a unique coaxial "hollow conical electron beam–wire" configuration. This review summarizes the relationships between process design, microstructure evolution, mechanical properties, and engineering applications.

The technology utilizes a low-voltage (<20 kV) gas-discharge electron gun operating in medium vacuum (10^{-1} – 10^{-2} mbar), improving process efficiency, reducing alloying-element losses, and extending cathode lifetime. Studies show that xBeam processing promotes a columnar-to-equiaxed transition of primary β grains in Ti–6Al–4V, producing weakly textured equiaxed structures without grain refiners. After heat treatment, tensile strengths of 950–1020 MPa and elongations of 12–15% are achieved.

Recent developments include titanium-based cored wires for in-situ fabrication of Ti–6Al–4V + 40%TiC composites and functionally graded materials. Ballistic studies demonstrate enhanced energy dissipation in layered titanium structures, while successful copper–stainless steel bimetallic fabrication confirms the ability to minimize brittle interfacial layers.

Overall, xBeam has evolved from a manufacturing technique into a versatile platform for microstructure engineering, advanced material development, and multimaterial additive manufacturing..

Keywords: XBEAM 3D METAL PRINTING; ELECTRON BEAM ADDITIVE MANUFACTURING; DIRECTED ENERGY DEPOSITION; TI–6AL–4V; COLUMNAR-TO-EQUIAXED TRANSITION; METAL MATRIX COMPOSITES; FUNCTIONALLY GRADED MATERIALS; BALLISTIC MATERIALS; MULTIMATERIAL MANUFACTURING.

Introduction.

The current stage of development of metal additive manufacturing (AM) is characterized by a gradual transition from the fabrication of geometrically complex components toward the deliberate engineering of material microstructure and performance directly during processing. This evolution reflects a broader shift in manufacturing philosophy, where additive technologies are increasingly regarded not only as shaping methods but also as tools for microstructure design and materials-by-design manufacturing.

Among the various additive manufacturing technologies, directed energy deposition (DED) processes occupy a unique position owing to their high deposition rates, scalability, and suitability for large structural components. Within this family, electron-beam directed energy deposition (EB-DED) offers additional advantages associated with high energy efficiency, deep penetration capability, and operation under vacuum conditions. These characteristics make electron-beam technologies particularly attractive for the processing of titanium alloys, refractory metals, and advanced aerospace materials [1,6].

Despite these advantages, conventional EB-DED systems employing lateral wire feeding suffer from several inherent limitations. The asymmetric interaction between the electron beam, feedstock wire, and melt pool often leads to non-uniform heat distribution, directional solidification, and strong dependence of process stability on deposition trajectory. As a consequence, large columnar prior- β grains and pronounced anisotropy of microstructure and mechanical properties frequently develop during fabrication [22–25].

To overcome these limitations, a novel coaxial electron-beam additive manufacturing approach, known as xBeam 3D Metal Printing, was developed and industrially implemented [3,4]. The technology is based on the generation of profile electron beams using low-voltage gas-discharge electron guns with cold cathodes [1,3]. The combination of a hollow conical electron beam and axial wire feeding creates a highly symmetric thermal field around the deposition zone, enabling stable liquid-bridge metal transfer and improved control of melt-pool dynamics.

The resulting thermal conditions significantly modify solidification behavior and grain-growth mechanisms, creating opportunities for microstructure engineering during fabrication. As demonstrated by recent investigations, the technology enables the formation of fine equiaxed β -grain structures in Ti–6Al–4V alloys, substantially reducing crystallographic texture and improving

isotropy of mechanical properties [9–12]. Furthermore, the adaptation of advanced titanium-based cored wires has enabled the fabrication of metal matrix composites, functionally graded materials, layered ballistic structures, and multimaterial systems, thereby extending the capabilities of electron-beam additive manufacturing beyond conventional structural applications [17–20].

The objective of this review is to provide a comprehensive analysis of the technological principles, thermal phenomena, microstructure evolution, mechanical performance, and emerging applications of xBeam additive manufacturing. Particular attention is devoted to the relationships between process parameters, solidification conditions, phase transformations, and resulting material properties. The review further discusses recent advances in metal matrix composites, functionally graded materials, ballistic structures, and multimaterial manufacturing, and future directions of xBeam 3D metal printing.

1 Fundamentals of xBeam 3D metal printing technology and process architecture.

1.1 Process architecture

The xBeam 3D metal printing represents a fundamentally different implementation of wire-feed electron-beam additive manufacturing compared with conventional electron-beam directed energy deposition systems. The key distinguishing feature of the process is the complete coaxial alignment of the energy source and feedstock material along a common geometric axis [3,4].

The process is enabled by a specially designed low-voltage gas-discharge electron gun (xGun) equipped with a ring-shaped cold cathode. Unlike conventional thermionic electron guns, the xGun generates a stationary electron beam in the form of an inverted hollow cone. The apex of the conical beam is focused directly onto the substrate surface, where a rotationally symmetric melt pool is formed [3,7].

The feedstock material, either a solid metallic wire or a powder-filled cored wire, is supplied vertically through a central channel integrated into the electron gun assembly. Consequently, the electron beam uniformly surrounds the wire circumference immediately before its interaction with the melt pool, creating highly symmetric thermal conditions within the deposition zone [4,10]. The general architecture of the xBeam process is illustrated in **Fig. 1**, which presents the coaxial arrangement of the electron beam, feedstock wire, and melt pool.

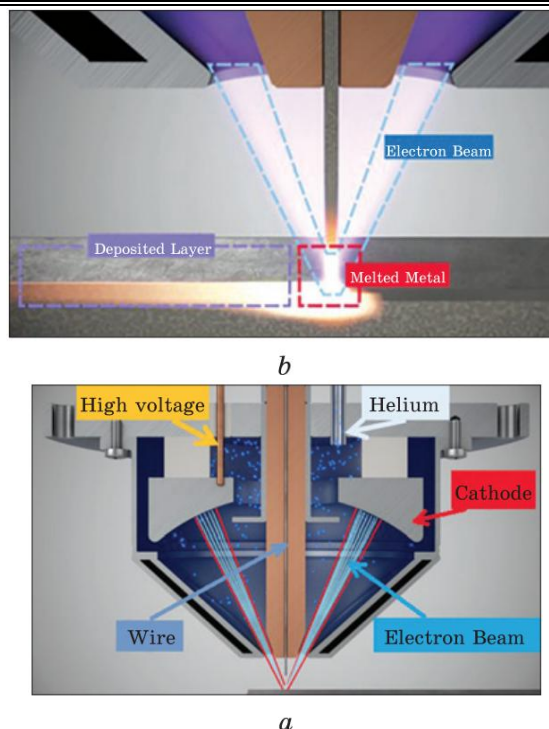


Fig. 1. Principle of xBeam additive manufacturing: (a) schematic arrangement of the coaxial wire-feed deposition process and (b) design of the xGun gas-discharge electron gun generating a hollow conical electron beam [14].

1.2 Hollow conical electron beam

The hollow conical electron beam constitutes the defining technological feature of xBeam manufacturing. In contrast to conventional Gaussian or ribbon-shaped electron beams, the annular energy distribution generated by the xGun produces a highly symmetric heat source around the feedstock wire.

Such beam geometry provides several important technological advantages. First, thermal energy is distributed uniformly around the wire, resulting in homogeneous heating conditions independent of deposition direction. Second, the resulting melt pool exhibits improved geometric stability compared with systems employing lateral wire feeding. Third, the symmetric thermal field significantly reduces directional solidification effects and contributes to more uniform microstructure development during deposition.

These characteristics ultimately influence the solidification behavior and grain-growth mechanisms discussed in the following sections.

1.3 Liquid-bridge metal transfer

One of the most important consequences of the coaxial process configuration is the formation of a stable liquid bridge between the wire tip and the melt pool.

Unlike the conventional wire-feed additive manufacturing systems, where metal transfer often occurs through droplet formation and detachment, xBeam processing promotes continuous transfer of molten material through a liquid-metal bridge maintained by surface-tension forces. As a result, the deposition process becomes highly stable and less sensitive to local perturbations.

The liquid-bridge transfer mechanism substantially suppresses spatter formation, minimizes fluctuations in bead geometry, and reduces the tendency for porosity formation within deposited material [4,10]. Furthermore, the continuous interaction between the molten wire tip and the melt pool improves metallurgical bonding between adjacent layers, promoting the formation of dense and defect-minimized structures.

1.4 Medium-vacuum operation

A further distinguishing feature of xBeam 3D metal printing is its operation under medium-vacuum conditions, typically within the range of 10^{-1} – 10^{-2} mbar [3,4].

The use of accelerating voltages below 20 kV significantly differentiates the technology from conventional high-voltage electron-beam systems. Lower accelerating voltages reduce the generation of high-energy bremsstrahlung radiation and consequently decrease shielding requirements, simplifying equipment design and improving industrial applicability [1,8].

The medium-vacuum environment also provides metallurgical benefits. The residual gas atmosphere generates a dynamic counter-pressure that suppresses excessive evaporation of volatile alloying elements, particularly aluminum in Ti–6Al–4V alloys. Consequently, the chemical composition of the deposited material can be maintained more effectively during prolonged manufacturing operations [3,5].

1.5 Advanced electron-beam sources

Recent developments of gas-discharge electron-beam technology have expanded the capabilities of the xBeam platform through the development of electron guns capable of generating ribbon-shaped electron beams [20]. Numerical and analytical investigations of cathode thermal behavior enabled optimization of cathode geometry and operating conditions, resulting in improved thermal balance and enhanced service life of industrial electron-beam systems.

The thermal regime of the cathode assembly was analyzed using arithmetic-logical relationships and locus-function approaches, allowing optimization of cathode dimensions and operating parameters with a thermal-balance accuracy of approximately 5–10% [20]. Such studies demonstrate that further progress in xBeam 3D metal printing depends not only on metallurgical aspects of additive manufacturing but also on continuous improvement of electron-beam source design and process stability.

The development of advanced beam-forming systems provides opportunities for more precise control of energy distribution, melt-pool dynamics, and thermal gradients during deposition. Consequently, future generations of xBeam equipment may enable even greater control over microstructure formation and process repeatability.

2 Thermal processes, solidification kinetics and grain structure control.

The microstructure of titanium alloys produced by additive manufacturing is primarily governed by the thermal conditions that develop during solidification. In conventional wire-feed and powder-based additive manufacturing systems, the combination of concentrated energy input and predominantly vertical heat extraction promotes epitaxial grain growth through multiple deposited layers. Consequently, large columnar prior- β grains extending across several build layers are commonly observed in Ti–6Al–4V components produced by conventional DED and EBAM technologies [22–25].

One of the most important metallurgical advantages of xBeam 3D metal printing is its capability to modify solidification conditions and promote a columnar-to-equiaxed transition (CET) without the use of chemical grain refiners [9,12].

The mechanisms governing grain morphology are commonly described using the classical solidification criteria developed by Hunt [21] and further extended through microstructure maps proposed by Gäumann et al. [22] and Kobryn and Semiatin [23]. These approaches demonstrate that grain morphology is controlled primarily by the ratio between the thermal gradient at the solidification front (G) and the solidification rate (R). High G/R values favor directional columnar growth, whereas lower G/R ratios promote constitutional undercooling and the formation of equiaxed grains.

The relationship between thermal gradient, solidification rate, and grain morphology in Ti–6Al–4V alloys is illustrated in Fig. 2, which presents the solidification map and the CET boundary proposed for coaxial electron-beam additive manufacturing.

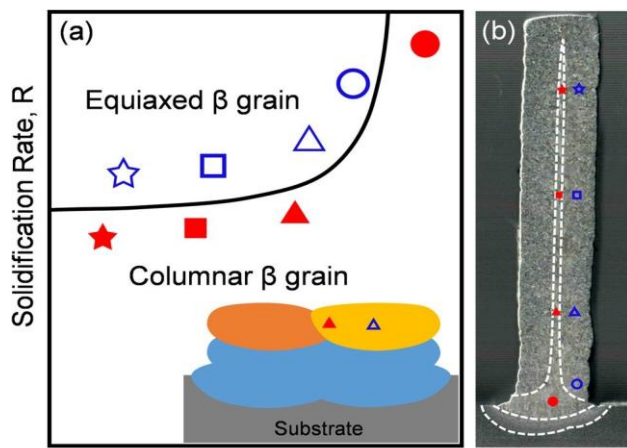


Fig. 2. Ti-6Al-4V solidification map showing the relationship between thermal gradient (G), solidification rate (R), and grain morphology, including the columnar-to-equiaxed transition (CET) boundary [9].

The unique thermal conditions generated by the xBeam process significantly influence these parameters. Owing to the circular geometry of the hollow conical electron beam, heat is distributed more uniformly around the melt pool perimeter compared with conventional side-fed wire systems. As a result, the melt pool becomes wider and its bottom surface less pronounced, while the heat-flow pattern changes from a predominantly vertical direction to a combined radial-axial configuration [7].

This redistribution of thermal energy reduces the thermal gradient at the solidification front while maintaining relatively high solidification rates [9]. Under such conditions, constitutional undercooling develops ahead of the advancing solidification front, enabling heterogeneous nucleation of new crystals within the liquid metal [12]. Consequently, grain growth is no longer dominated by epitaxial extension of existing grains, and an extensive region of fine equiaxed prior- β grains can be formed.

Experimental investigations conducted by Zhang et al. [9] and Davis et al. [12] demonstrated the formation of fine equiaxed prior- β grains with characteristic dimensions of approximately 100–150 μm in Ti-6Al-4V alloys manufactured using coaxial electron-beam wire deposition. The resulting microstructures exhibited significantly reduced texture intensity compared with conventional electron-beam additive manufacturing and contributed to a substantial reduction in microstructural and mechanical anisotropy.

The ability to control grain morphology through manipulation of thermal conditions represents one of the most significant scientific achievements associated with xBeam 3D metal printing and forms the foundation for subsequent control of phase transformations and mechanical properties discussed in the following sections.

3 Phase transformations and optimization of mechanical properties by heat treatment.

The microstructure of Ti-6Al-4V alloys produced by electron-beam additive manufacturing is strongly influenced by the high cooling rates typically associated with the process, which may range from approximately 10^2 to 10^4 K/s depending on local thermal conditions and deposition parameters [5]. As a consequence, the as-built material exhibits a non-equilibrium microstructure consisting of acicular α' martensite and ultrafine $\alpha+\beta$ lamellar constituents formed during rapid solidification and subsequent cooling [5].

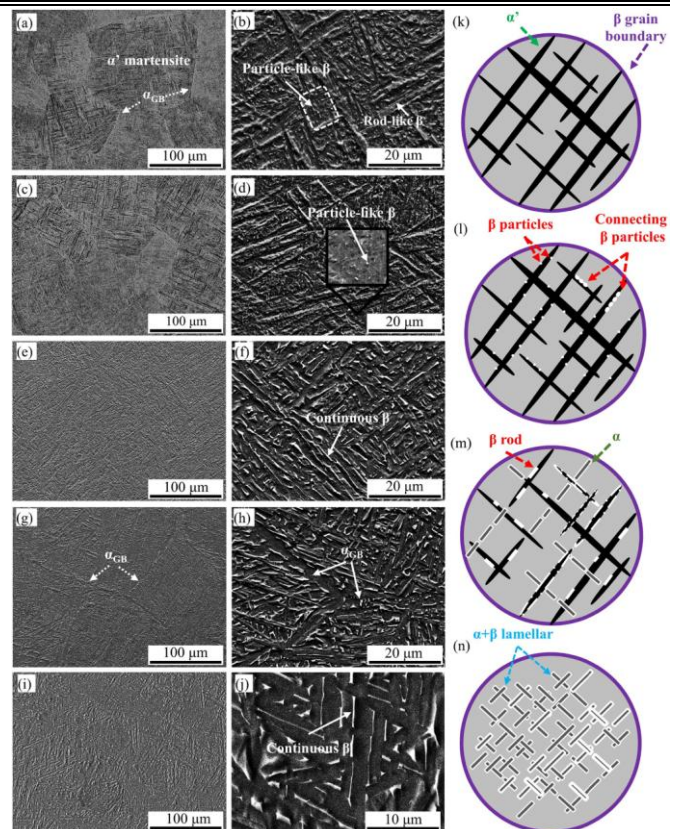


Fig. 3. SEM images of samples annealed at (a, b) 690°C/2 h/FC (HT1), (c, d) 750°C/2 h/FC (HT2), (e, f) 810°C/2 h/FC (HT3), (g, h) 870°C/2 h/FC (HT4), and (i, j) 900°C/2 h/FC (HT5). The α phase is dark, β phase is bright. (k–n) Schematic diagrams of β phase precipitation during decomposition of α' martensite at different temperatures. (k) Original α' martensite in prior β grain; (l) formation of β particles at α' boundary when heated at low temperature; (m) formation of β rods and α phase on heat treatment at higher temperature; (n) formation of $\alpha + \beta$ lamellar structure with α' completely decomposed. [11].

While the grain morphology is primarily established during solidification, the final mechanical performance of Ti-6Al-4V components is largely governed by subsequent phase transformations occurring within the prior- β grains. In addition to rapid cooling, layer-by-layer manufacturing is accompanied by repeated interpass thermal cycling. These thermal cycles act as an intrinsic *in-situ* tempering treatment, promoting partial decomposition of metastable phases and gradual evolution of the microstructure during deposition [9,10].

To achieve an optimal balance between strength and ductility, post-build heat treatment within the $\alpha+\beta$ phase field is commonly employed [11]. The evolution of the intragranular microstructure during annealing is illustrated in Fig. 3, which presents SEM images of Ti-6Al-4V specimens subjected to different heat-treatment temperatures.

Detailed investigations performed by Hu, Zhang, and co-workers [11] demonstrated that subtransus annealing at 690–750°C initiates diffusion-controlled decomposition of α' martensite accompanied by the formation of fine β precipitates along martensite interfaces. Increasing the annealing temperature to 810–900°C promotes nearly complete decomposition of the martensitic morphology and the formation of a stable basket-weave (Widmanstätten) $\alpha+\beta$ microstructure containing continuous β lamellae.

Simultaneously, the α lamellae undergo gradual coarsening through diffusion-controlled growth processes, resulting in reduced internal stresses and improved microstructural stability [10,11]. Heat-treatment schedules involving solution treatment and aging (STA) at temperatures of approximately 940–960°C further modify the microstructure through fragmentation of primary α plates,

disruption of continuous grain-boundary α networks, and precipitation of fine secondary α particles, thereby providing additional precipitation strengthening [11].

The elimination of continuous brittle grain-boundary constituents, combined with the formation of refined equiaxed prior- β grains, results in an attractive combination of strength and ductility. Representative mechanical properties reported for xBeam-manufactured Ti-6Al-4V alloys are summarized in **Table 1** and demonstrate excellent agreement with aerospace and additive-manufacturing standards.

The combination of a refined equiaxed prior- β grain structure and a thermally optimized $\alpha+\beta$ lamellar microstructure enables tensile strengths of 950–1020 MPa and elongations of 12–15%, while maintaining relatively low anisotropy between horizontal and vertical build directions.

Table 1. Mechanical properties of Ti-6Al-4V alloy produced by xBeam 3D metal printing compared with ASTM F2924 and AMS 4928 requirements [5, 7, 10].

Sample cutting direction	Tensile strength σ_B , MPa	Yield strength $\sigma_{0.2}$, MPa	Elongation δ , %
Horizontal (X/Y)	980...1020	880...920	13,3...15,5
Vertical (Z)	950...990	860...890	12,0...14,0
Standard ASTM F2924 (AM)	≥ 930	≥ 860	$\geq 10,0$
Standard AMS 4928 (Forging)	≥ 895	≥ 825	$\geq 10,0$

Collectively, these results demonstrate that the combination of controlled solidification, grain-structure refinement, and optimized post-build heat treatment enables xBeam-manufactured Ti-6Al-4V alloys to achieve an attractive balance of strength, ductility, and microstructural isotropy, meeting or exceeding the requirements specified for aerospace-grade wrought and additively manufactured materials.

4 Advanced materials systems and emerging applications

4.1 Metal matrix composites based on titanium cored wires

The coaxial architecture of xBeam 3D metal printing has enabled successful adaptation of the process for the fabrication of advanced metal matrix composites (MMCs) using innovative titanium-based cored wires developed in collaboration with the E.O. Paton Electric Welding Institute and the I.M. Frantsevich Institute for Problems of Materials Science [16,17]. These feedstock materials consist of a thin-walled titanium sheath filled with a pre-engineered powder mixture containing titanium carbide (TiC) particles [17].

To prevent powder dispersion under vacuum conditions caused by direct interaction of the electron beam with the cored wire, a so-called *immersed melting* approach was implemented. In this configuration, the energy of the hollow conical electron beam is concentrated primarily on the substrate, producing a deep molten pool into which the cored wire is continuously submerged during deposition [17].

During fabrication of Ti-6Al-4V + 40%TiC composites, intensive Marangoni-driven convection promotes efficient dissolution and redistribution of carbon within the molten pool [17]. Subsequent solidification proceeds according to the Ti-C phase diagram, resulting in a basket-weave titanium matrix reinforced by uniformly distributed endogenous TiC particles with characteristic sizes below approximately 4 μm [17].

The resulting microstructure is illustrated in **Fig. 4**, which presents SEM observations of endogenous carbide particles together with the corresponding phase analysis.

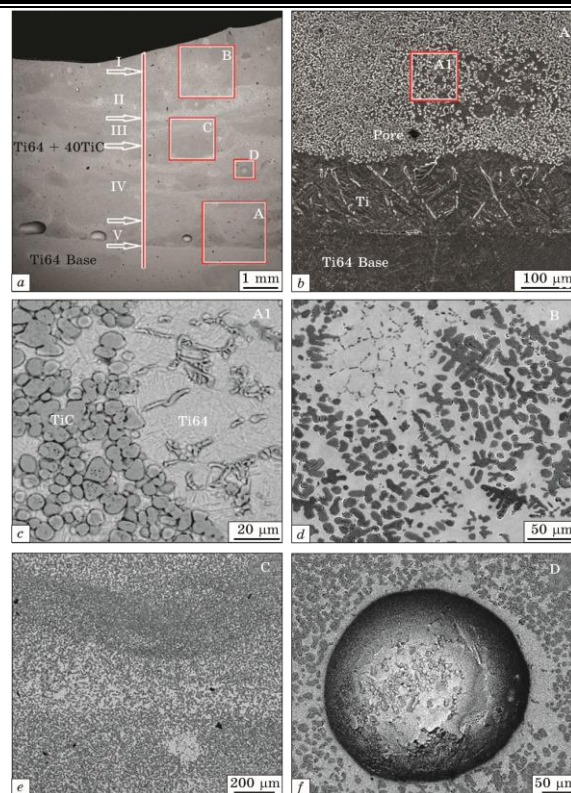


Fig. 4. SEM micrographs showing the morphology and distribution of endogenous TiC particles formed during fabrication of Ti-6Al-4V + 40%TiC metal matrix composites using cored-wire xBeam deposition: (a) General view of Ti-6Al-4V-40%TiC MMC at Ti-6Al-4V base plate with indicated line where hardness was measured and locations of detailed microstructural analysis: (b) zone (A) inside non-uniform layer of low-alloyed titanium between base substrate and MMC; (c) zone (A1) with non-uniform distribution of TiC, (d) dendritic type of TiC inside zone (B), (e) zone (C), and (f) pore inside zone (D) with fine TiC particles on its inner surface and around. SEM, BSE [17].

Optimized processing conditions enabled the formation of a nearly isotropic composite microstructure with microhardness values ranging from 490 to 615 HV, demonstrating significant potential for wear-resistant and high-performance engineering applications [17]. Similar processing strategies have also been successfully applied to advanced metastable β -titanium alloys, including Ti-55511 and Ti-55541.5, as well as the biomedical low-modulus alloy Ti-13Zr-13Nb [16].

4.2 Layered titanium armour systems and ballistic performance

The high hardness and wear resistance of xBeam-fabricated titanium-based composites have been further exploited in the development of advanced layered ballistic materials [13,15,18]. Using combinations of solid and cored wires, both bilayer (MMC/Ti alloy) and multilayer titanium-based armour systems were fabricated through layer-by-layer deposition and subsequently integrated with powder-metallurgy components [13,18].

Ballistic testing (Fig.5) using 7.62×51 mm armour-piercing projectiles containing hardened steel cores (~ 870 HV) demonstrated complete resistance to perforation under NATO-standard testing conditions [18]. The hard MMC front layer (~ 500 HV) effectively deforms and blunts the projectile core, while impact energy is dissipated through the formation of adiabatic shear bands and fracture of TiC reinforcement particles [18].

The observed ballistic performance confirms the feasibility of combining additive manufacturing and powder-metallurgy routes for the fabrication of lightweight protective structures.

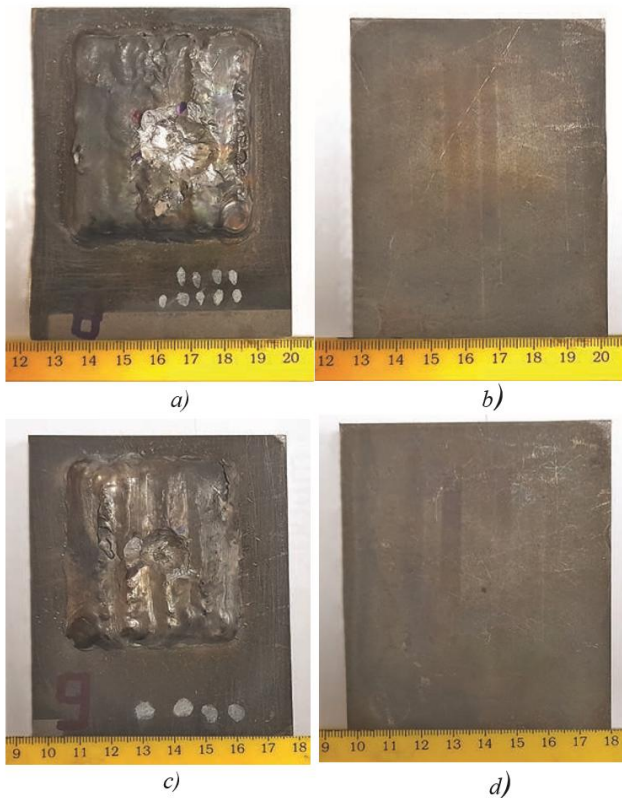


Fig. 5. Appearance of layered titanium-based armour specimens after ballistic testing: front (a,c) and rear (b,d) surfaces of impacted samples [17].

The ductile titanium-alloy or commercially pure titanium backing layers absorb residual impact energy and prevent catastrophic failure of the armour system [13]. Furthermore, the characteristic wave-shaped interface generated during xBeam deposition acts as a shock-wave attenuation and deflection boundary, redistributing stress waves and significantly reducing the likelihood of spall formation during impact loading [18,24].

4.3 Multimaterial manufacturing of bimetallic systems

One of the most remarkable achievements of xBeam 3D metal printing is its capability to produce metallurgically bonded structures from materials exhibiting substantially different thermophysical properties. A representative example is the successful fabrication of copper–stainless steel bimetallic components combining pure copper (M1) and austenitic stainless steel 316L [19].

The microstructure of the dissimilar-metal interface is shown in Fig. 6.

During deposition of copper onto stainless steel, the hollow conical electron beam generates extremely short melt-pool lifetimes, typically on the order of milliseconds [19]. The resulting rapid solidification effectively suppresses extensive interdiffusion and limits the interfacial reaction zone to only a few micrometres in thickness. Consequently, the formation of thick brittle intermetallic layers is avoided, preserving both structural integrity and functional performance [19].

The process enabled production of copper deposits with relative densities approaching 99.1% and electrical conductivities reaching approximately 99.2% IACS. Helium leak testing confirmed vacuum-tight joints with no measurable leakage at pressures down to 10^{-8} Torr, demonstrating the suitability of these bimetallic structures for demanding applications such as particle accelerators, vacuum systems, and advanced heat exchangers [19].

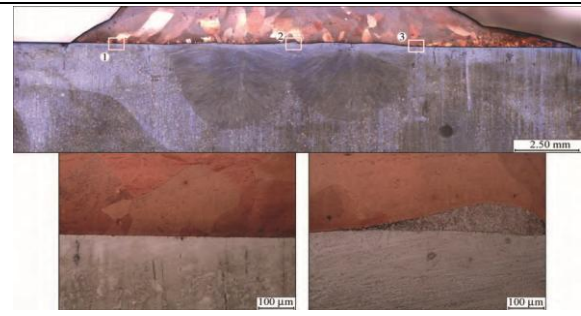


Fig. 6. (upper) Macrograph of etched copper/stainless steel interface demonstrating heat affected zone in stainless steel as well as variable grain size distribution in the substrate/copper interface. (bottom-left) Micrograph of copper/substrate interface at region 1 highlighted above, demonstrating sharp boundary between copper and stainless. (bottom-right) Micrograph of interface region 2, demonstrating copper infiltration into porous stainless steel bump above interface [19]

The studies reviewed in this section demonstrate that xBeam 3D metal printing has evolved beyond a manufacturing process for titanium alloys and has become a versatile platform for advanced materials engineering. The successful fabrication of metal matrix composites, layered ballistic structures, and multimaterial systems highlights the capability of the technology to tailor microstructure, phase composition, and functional performance simultaneously. These developments represent an important transition from geometry-driven additive manufacturing toward materials-by-design approaches, where process parameters are deliberately used to engineer material architecture across multiple length scales.

5 Challenges and Future Perspectives.

Despite the significant scientific and technological progress achieved in the development of xBeam 3D metal printing, several important challenges remain to be addressed before its broader industrial implementation and certification can be fully realized.

One of the key scientific challenges concerns the quantitative understanding of thermal phenomena governing melt-pool evolution and solidification behavior. Although the unique coaxial architecture of xBeam 3D metal printing has demonstrated its capability to promote columnar-to-equiaxed transition (CET) and grain-structure refinement in titanium alloys, the relationships between process parameters, thermal gradients, constitutional undercooling, and resulting microstructure require further investigation. Additional experimental and numerical studies are needed to establish predictive processing–structure–property relationships for different classes of materials.

Another important challenge is associated with process repeatability and quality assurance. Most currently available studies have focused on microstructural characterization and mechanical testing of deposited materials, whereas comparatively limited attention has been devoted to systematic investigation of process stability during long-duration manufacturing. Future research should therefore focus on the development of reliable methodologies for monitoring melt-pool behavior, thermal history, and defect formation during deposition.

The fabrication of advanced material systems introduces additional complexities. In particular, metal matrix composites, layered ballistic structures, and multimaterial components exhibit heterogeneous microstructures and compositionally complex interfaces that require detailed investigation. Further studies are necessary to evaluate long-term mechanical reliability, fatigue resistance, fracture behavior, and environmental stability of such materials under service conditions.

The successful fabrication of Ti–6Al–4V + TiC metal matrix composites has demonstrated the effectiveness of cored-wire feedstocks for in-situ synthesis of reinforcing phases during deposition. Nevertheless, optimization of powder composition, particle morphology, reinforcement distribution, and interface characteristics remains an important area for future research.

Similar challenges apply to the development of functionally graded materials, where precise control of local composition and microstructure is required to achieve predictable property gradients.

Multimaterial manufacturing represents another promising direction for future development. The successful production of copper–stainless steel structures has demonstrated the capability of xBeam 3D metal printing to create metallurgically bonded interfaces between dissimilar materials with substantially different thermophysical properties. Future studies should expand this approach toward other technologically important material combinations and investigate the mechanisms governing interfacial reactions, residual stress formation, and long-term service performance.

From an equipment-development perspective, further improvement of gas-discharge electron guns remains an important objective. Optimization of cathode geometry, beam-shaping systems, energy distribution, and process stability may further enhance manufacturing efficiency and expand the range of processable materials. The development of advanced beam-forming systems capable of generating tailored energy distributions may provide additional opportunities for microstructure control and materials engineering.

Overall, the reviewed studies indicate that the future evolution of xBeam 3D metal printing is likely to be associated with the transition from conventional additive manufacturing toward deliberate engineering of material architecture. The demonstrated capability to control grain morphology, phase composition, reinforcement formation, and interfacial phenomena suggests that xBeam 3D metal printing should be regarded not only as a manufacturing method but also as a versatile platform for advanced materials design. Future developments are therefore expected to focus on metal matrix composites, functionally graded materials, layered protective structures, and multimaterial systems with application-specific combinations of mechanical and functional properties.

Conclusions.

The analysis presented in this review demonstrates that xBeam 3D Metal Printing has evolved into a mature and versatile electron-beam directed energy deposition technology capable of addressing several limitations traditionally associated with wire-feed additive manufacturing.

The unique combination of a hollow conical electron beam and coaxial wire feeding provides highly symmetric thermal conditions during deposition, promoting stable liquid-bridge metal transfer and reducing the directional effects commonly observed in conventional electron-beam and wire-feed DED systems. Operation under medium-vacuum conditions further contributes to improved process efficiency and reduced evaporation losses of volatile alloying elements, thereby supporting chemical stability during fabrication.

One of the most important metallurgical features demonstrated for xBeam 3D metal printing is its demonstrated capability to modify solidification behavior and promote a columnar-to-equiaxed transition (CET) in Ti–6Al–4V alloys without the use of chemical grain refiners. The resulting refinement of prior- β grain structure, combined with the effects of interpass thermal cycling and optimized post-build heat treatment, enables the formation of stable α + β microstructures exhibiting an attractive balance of strength, ductility, and reduced anisotropy. Mechanical properties reported for xBeam-manufactured Ti–6Al–4V alloys satisfy, and in some cases exceed, the requirements specified for aerospace-grade wrought and additively manufactured materials.

The reviewed studies further demonstrate that xBeam 3D metal printing has progressed beyond conventional monomaterial fabrication. The successful implementation of titanium-based core wires enables the in-situ synthesis of Ti–6Al–4V–TiC metal matrix composites with enhanced hardness and wear resistance. In addition, the technology has proven effective for the fabrication of layered ballistic structures, functionally graded architectures, and multimaterial systems involving dissimilar materials such as copper and stainless steel. These developments highlight the capability of

xBeam 3D metal printing to simultaneously control composition, microstructure, and functional performance during manufacturing. Overall, the available experimental evidence indicates that xBeam 3D metal printing should be regarded not only as an additive manufacturing process but also as a platform for advanced materials engineering. Its demonstrated capability to control grain morphology, phase transformations, reinforcement formation, and interfacial phenomena provides new opportunities for the design of next-generation structural and functional materials. Future developments are expected to further expand the application of xBeam 3D metal printing in metal matrix composites, graded materials, multilayer protective systems, and multimaterial manufacturing, reinforcing its role within the broader framework of materials-by-design approaches.

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Antimicrobial activity of aqueous-alcoholic extracts of waste materials from red sweet pepper, red hot pepper and eggplant against pathogenic microorganisms. Part I

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Abstract: Pepper and eggplant processing generates significant amounts of waste raw materials, such as peels, seeds, stems and residual pulp. These waste products are rich in bioactive components, such as phenolic acids, flavonoids, anthocyanins, capsaicinoids and glycoalkaloids, which determine their antimicrobial and antioxidant activities. Therefore, waste raw materials from peppers and eggplants represent a potential for industrial application. The aim of the present study was to determine the phenolic acid content in aqueous-alcoholic extracts of red sweet peppers, red hot peppers and eggplants as well as their antimicrobial activity against pathogenic microorganisms, causing food-borne toxicoinfections and toxicoses. Aqueous-alcoholic (20%, 40%, 70%) extracts of waste raw materials of red sweet peppers, red hot peppers and eggplants were used in the present study. Phenolic acids were determined by HPLC, and the antimicrobial activity - by agar diffusion method with wells. The minimum inhibitory concentration (MIC) was determined by the serial dilution method. The aqueous-alcoholic extracts from waste raw materials of red sweet peppers, red hot peppers and eggplants exhibited bactericidal activity against the pathogenic bacteria *Escherichia coli* ATCC 25922, *Staphylococcus aureus* ATCC 25293, *Salmonella enteritidis* ATCC 13076, *Salmonella abony* NTCC 6017, *Listeria monocytogenes* ATCC 19111, *Pseudomonas aeruginosa* NBIMCC 1390, *Enterococcus faecalis* ATCC 19433, with inhibition zones of 9 mm to 20 mm and MIC ranging from 60 ppm to 600 ppm. The relationship between the antimicrobial activity of the aqueous-alcoholic extracts and the presence of bioactive components with an inhibitory effect in them has been revealed. Their water-alcoholic extracts are rich in phenolic acids, which also determine their antimicrobial activity against pathogenic and saprophytic microorganisms. The flours obtained from them are carriers of bioactive components and have antimicrobial action. This makes them suitable for use in the food industry.

Keywords: ANTIMICROBIAL ACTIVITY, MINIMUM INHIBITORY CONCENTRATION, HPLC, ANTIOXIDANT ACTIVITIES, MICROSTRUCTURE

1. Introduction

In today's context of rapid growth in the food industry, there has been a significant increase in the volume of agro-industrial waste, posing serious environmental and economic challenges. At the same time, these waste materials are viewed as a valuable resource, rich in bioactive compounds with potential for application in various industries [1–6]. Among widely cultivated vegetable species, the genera *Capsicum* (pepper) and *Solanum*, including the species *Solanum melongena* (eggplant), play an important role in both the human diet and the agricultural sector. Studies show that extracts from various parts of the pepper plant, particularly seeds and placental tissue, exhibit an inhibitory effect against a broad spectrum of microorganisms, including Gram-positive bacteria such as *Staphylococcus aureus* and *Bacillus subtilis*, as well as Gram-negative bacteria such as *Escherichia coli* and *Salmonella enterica* [7–9]. This effect is mainly due to the presence of capsaicinoids and phenolic compounds, which interact with the cellular structures of microorganisms.

The aim of the present study was to determine the antibacterial activity of extracts from waste materials of red sweet peppers, red hot peppers, and eggplant on the growth of Gram-positive and Gram-negative pathogenic bacteria.

2. Materials and Methods

For the experiments, water-alcohol extracts (20%, 40%, 70%) from waste materials of red sweet peppers, red hot peppers, and eggplant, provided by the company "Bulcons" Ltd., Pervomai, were used.

Microorganisms

Test microorganisms: pathogenic bacteria were used as test microorganisms during the experimental work – *Escherichia coli* ATCC 25922, *Staphylococcus aureus* ATCC 25293, *Salmonella enteritidis* ATCC 13076, *Salmonella abony* NTCC 6017, *Listeria*

monocytogenes ATCC 19111, *Pseudomonas aeruginosa* NBIMCC 1390, *Enterococcus faecalis* ATCC 19433.

Determination of Antimicrobial Activity – Agar Diffusion Method With Wells

Each test microorganism (10^7 CFU/cm³) was inoculated into Petri dishes containing agar medium; after the agar has solidified, wells (7 mm) were prepared. Sixty microliters of the respective extract or its dilutions were pipetted into the wells, and the plates were incubated at 4°C for 1 hour to allow diffusion into the agar. The Petri dishes containing the test microorganisms were incubated at 37 °C for 24 to 48 h, after which the inhibition zones in mm were measured.

Analytical methods

Determination of the minimum inhibitory concentration (MIC) of extracts from red sweet pepper, red hot pepper and eggplant waste materials against pathogenic microorganisms.

The antimicrobial activity of extracts from pepper and eggplant waste materials was determined using the serial dilution method [10].

Data analysis

The data from the triplicate experiments were analyzed using MS Office Excel 2010, employing statistical functions to determine the standard deviation and the maximum error of estimation at a significance level of $\alpha < 0.05$.

3. Results and Discussion

In a series of experiments, the inhibitory effect of water-alcohol extracts from waste materials generated during the processing of red sweet peppers, red hot peppers, and eggplant was determined. The results of the experimental studies on the antimicrobial activity of

water-alcohol extracts (20%, 40%, and 70% ethanol) are presented in Table 1, Table 2 and Table 3. Depending on the percentage of the alcohol content, the type and amount of bioactive substances in the extracts with antimicrobial effect varied. The water-alcohol extracts of pepper waste materials contained significant amounts of sinapic acid and gallic acid with inhibitory activity. Ferulic acid, gallic acid, 3,4-dihydroxybenzoic acid, rosmarinic acid, chicoric acid, caffeic acid, cinnamic acid, and others were not detected in these extracts (Table 1).

The highest antimicrobial activity against pathogenic microorganisms was observed in the methanol extracts from waste materials derived from red sweet peppers and red hot peppers, where inhibition zones ranging from 15.0 to 19.0 mm were measured, with a MIC < 6 ppm (Table 2). A high degree of inhibition was observed in the 40% water-ethanol extracts from waste materials of red sweet peppers, red hot peppers, and eggplant.

The increase in the alcohol content (up to 70%) in the extracts had little effect on the growth of pathogenic bacteria. Larger zones of inhibition were observed for Gram-positive pathogens compared to Gram-negative ones. They inhibited the growth of pathogenic microorganisms causing gastrointestinal diseases. The method used to assess the antimicrobial activity, as well as the selection of test microorganisms, varies across different publications. The permeability of bacterial membranes, the presence of porin proteins in Gram-negative bacteria, and the intracellular distribution of plant extract components are key factors influencing the diffusion and action of the extracts within the cell. In the majority of the literature, Gram-positive organisms appear to be more sensitive to plant extracts compared to Gram-negative ones. However, other studies do not confirm this observation, as it has been found that Gram-positive bacteria are less sensitive or equally sensitive to Gram-negative bacteria [11, 12].

Table 1: Phenolic acid content in water-alcohol extracts from waste materials derived from red sweet peppers, red hot peppers, and eggplant (Phenolic acid, $\mu\text{g/g}$)

	Sinapic acid	3,4-dihydroxy benzoic acid	Caffeic Acid	p-Coumaric acid	Ferulic acid	Gallic acid	Rosmarinic acid	Cinnamic Acid
20% ethanol; red sweet pepper stems	369,33	-	-	-	-	-	-	-
40% ethanol; red sweet pepper stems	78,19	-	-	-	-	-	-	-
70% ethanol; red sweet pepper stems	72,28	-	-	-	-	-	-	-
20% ethanol; red hot peppers	130,60	-	-	-	-	78,06	-	-
40% ethanol; red hot peppers	22,89	-	-	-	-	-	-	-
70% ethanol; red hot peppers	98,88	-	-	-	-	-	-	-
20% ethanol; eggplant stems	32,17	-	-	-	-	-	-	-
40% ethanol; eggplant stems	31,52	-	-	-	-	-	-	-
70% ethanol; eggplant stems	36,11	-	-	-	-	-	-	-
40% methanol; red sweet pepper stems	66,81	-	-	-	-	74,85	-	-
40% methanol; red hot pepper stems	27,24	-	-	-	-	-	-	-
40% methanol; eggplant stems	29,33	-	-	-	-	-	-	-

Table 2: Antimicrobial activity and Minimum Inhibitory Concentration (MIC) of plant extracts against Gram (-) pathogenic microorganisms. Inhibition Zones (IZ) are in mm $d_{\text{disk}} = 6 \text{ mm}$.

Test-microorganism	E. coli ATCC 25922 1,2 *10 ¹² cfu/cm ³		Salmonella abony NTCC 6017 4,1*10 ¹⁰ cfu/cm ³		L. monocytogenes ATCC 1911 3,1*10 ¹⁰ cfu/cm ³		Ps. aeruginosa 2,34*10 ¹⁰ cfu/cm ³	
	IZ, mm	MIC, ppm	IZ, mm	MIC, ppm	IZ, mm	MIC, ppm	IZ, mm	MIC, ppm
Sample								
20% ethanol; red sweet pepper stems	9,0±0,0	< 600	9,0±0,0	< 600	10,0±0,0	< 600	9,0±0,0	< 600
40% ethanol; red sweet pepper stems	10,0±0,0	60	10,10	< 600	10,0±0,0	< 60	9,0±0,0	< 600
70% ethanol; red sweet pepper stems	1010±0,0	<600	10,10	< 600	9,0±0,0	< 600	10,0±0,0	< 60
20% ethanol; red hot peppers	-	-	-	-	-	-	9,0±0,0	< 600
40% ethanol; red hot peppers	9,5±0,5	<600	9,0±0,0	< 600	-	-	9,0±0,0	< 600
70% ethanol; red hot peppers	10,0±0,0	<600	10,0±0,0	< 60	-	-	10,0±0,0	< 60
20% ethanol; eggplant stems	10,0±0,0	<600	9,0±0,0	< 600	-	-	10,0±0,0	< 600
40% ethanol; eggplant stems	18,0±0,0	<60	9,0±0,0	< 600	10,0±0,0	< 60	9,0±0,0	< 600
70% ethanol; eggplant stems	10,0±0,0	<600	9,0±0,0	< 600	9,0±0,0	< 600	9,0±0,0	< 600
40% methanol; red sweet pepper stems	9,0±0,0	<600	9,0±0,0	< 600	10,0±0,0	< 600	12,0±0,0	< 60
40% methanol; red hot pepper stems	15,0±0,5	<60	11±0,0	< 60	14,5±0,5	< 60	15,0±0,0	< 60
40% methanol; eggplant stems	14,5±0,5	<60	-	-	-	-	-	-
Control K1: 20% ethanol	-	-	-	-	-	-	-	-
Control K2: 40% ethanol	-	-	-	-	-	-	-	-
Control K3: 70% ethanol	-	-	-	-	-	-	-	-
Control K4: 40% methanol	-	-	-	-	-	-	-	-

Table 3: Antimicrobial activity and Minimum Inhibitory Concentration (MIC) of plant extracts against Gram (+) pathogenic microorganisms. Inhibition zones (IZ) are in mm $d_{disc} = 6$ mm.

Sample	Test-microorganism		<i>St. aureus</i> ATCC 25923 1,1*10 ¹⁰ cfu/cm ³		<i>L. monocytogenes</i> ATCC 1911 3,1*10 ¹⁰ cfu/cm ³		<i>Ent. faecalis</i> 1,0*10 ¹² cfu/cm ³	
	IZ, mm	MIC, ppm	IZ, mm	MIC, ppm	IZ, mm	MIC, ppm	IZ, mm	MIC, ppm
20% ethanol; red sweet pepper stems	10,0±0,0	< 600	10,0±0,0	< 600	10,0±0,0	< 600	10,0±0,0	< 600
40% ethanol; red sweet pepper stems	10,0±0,0	< 600	10,0±0,0	< 60	11,0±1,0	< 60	10,0±0,0	< 60
70% ethanol; red sweet pepper stems	11±0,0	< 60	9,0±0,0	< 600	10,0±0,0	< 60	10,0±0,0	< 60
20% ethanol; red hot peppers	-	-	-	-	-	-	-	-
40% ethanol; red hot peppers	-	-	-	-	9,0±0,0	-	-	-
70% ethanol; red hot peppers	9,0±0,0	< 600	-	-	9,0±0,0	< 600	9,0±0,0	< 600
20% ethanol; eggplant stems	10,0±0,0	< 600	-	-	10,0±0,0	< 60	10,0±0,0	< 60
40% ethanol; eggplant stems	14,5±0,5	< 60	10,0±0,0	< 60	18,0±0,0	< 60	18,0±0,0	< 60
70% ethanol; eggplant stems	10,0±0,0	< 600	9,0±0,0	< 600	13,0±1,0	< 60	13,0±1,0	< 60
40% methanol; red sweet pepper stems	19,0±1,0	< 6	10,0±0,0	< 600	10,0±0,0	< 600	10,0±0,0	< 600
40% methanol; red hot pepper stems	17±0,0	< 6	14,5±0,5	< 60	9,0±0,0	< 600	9,0±0,0	< 600
40% methanol; eggplant stems	15,0±0,0	< 60	-	-	16,0±1,0	< 60	16,0±1,0	< 60
Control K1: 20% ethanol	-	-	-	-	-	-	-	-
Control K2: 40% ethanol	-	-	-	-	-	-	-	-
Control K3: 70% ethanol	-	-	-	-	-	-	-	-
Control K4: 40% methanol	-	-	-	-	-	-	-	-

Plant extracts derived from waste materials from red sweet peppers, red hot peppers, and eggplant inhibit the growth of pathogenic microorganisms that cause gastrointestinal diseases. The method used to assess the antimicrobial activity, as well as the selection of test-microorganisms, varies across different publications. The permeability of bacterial membranes, the presence of porin proteins in Gram-negative bacteria, and the intracellular distribution of plant extract components are key factors influencing the diffusion and action of the extracts within the cell. In the majority of the literature, Gram-positive organisms appear to be more sensitive to plant extracts compared to Gram-negative ones. However, other studies do not confirm this observation, as it has been found that Gram-positive bacteria are less sensitive or equally sensitive to Gram-negative bacteria [11]. In this study, Gram-positive bacteria were more sensitive to the extracts (inhibition zones between 9.5 and 19 mm), and the minimum inhibitory concentration was below 600 ppm. The tested Gram-negative bacteria were less sensitive (inhibition zones between 9 and 11 mm), with a minimum bactericidal concentration below 60 ppm. This was due to the difference in the structure and composition of the cell walls of the two groups of bacteria. The presence of an outer membrane in Gram-negative bacteria impedes the diffusion of the extracts through the membrane into the cell protoplasm, making them more resistant to the effects of the tested extracts.

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Antimicrobial activity of aqueous-alcoholic extracts of waste materials from red sweet pepper, red hot pepper and eggplant against spoilage microorganisms. Part 2

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Abstract: The industrial processing of peppers and eggplants yields substantial quantities of byproduct materials, including peels, seeds, and stems. These secondary raw materials are concentrated sources of bioactive compounds, notably phenolic acids and flavonoids, which possess significant potential for repurposing due to their inherent biological activities. This study aimed to quantify the phenolic acid profiles of aqueous-alcoholic extracts derived from red sweet pepper, red hot pepper, and eggplant waste, and to evaluate their inhibitory efficacy specifically against saprophytic microorganisms responsible for food spoilage. Extracts were prepared using varying concentrations of ethanol (20%, 40%, and 70%). High-Performance Liquid Chromatography (HPLC) was employed for the identification of phenolic acids. The antimicrobial potential was assessed using the agar well diffusion method, while the Minimum Inhibitory Concentration (MIC) was established via serial dilutions. The extracts demonstrated robust antifungal and anti-yeast activity against key spoilage organisms, including *Saccharomyces cerevisiae*, *Candida utilis*, *Aspergillus niger*, *Penicillium chrysogenum*, and *Fusarium moniliforme*. Inhibition zones ranged from 9 mm to 20 mm, with MIC values spanning 60 ppm to 600 ppm. A direct correlation was observed between the concentration of specific bioactive phenolics and the degree of microbial suppression. Given their high phenolic content and proven effectiveness in inhibiting common spoilage fungi and yeasts, these materials—and the flours derived from them—offer a viable, bioactive alternative for extending shelf life in food industry applications.

Keywords: ANTIMICROBIAL ACTIVITY, MINIMUM INHIBITORY CONCENTRATION, HPLC, ANTIOXIDANT ACTIVITIES, MICROSTRUCTURE, SPOILAGE ORGANISMS

1. Introduction

The industrial processing of peppers and eggplants generates significant amounts of waste materials, such as peels, seeds, stems, and residual pulp. These byproducts are often treated as waste, even though they contain high concentrations of bioactive compounds, including phenolic acids, flavonoids, anthocyanins, capsaicinoids, and glycoalkaloids [1–4]. Accumulated scientific data indicate that these compounds possess pronounced antioxidant and antimicrobial properties, making them the subject of increased scientific interest [5–8].

Eggplant waste materials, especially the peel, are also characterized by high antimicrobial activity due to their content of chlorogenic acid, anthocyanins (nasunin), and glycoalkaloids (solasanone and solamargine) [9, 10, 3]. These compounds exhibit inhibitory effect against both bacteria and fungi, including *Candida albicans* and *Aspergillus niger* [10, 11]. Of particular importance is the ability of glycoalkaloids to interact with the cell membranes of microorganisms and to cause their destabilization [9].

The antimicrobial activity of these extracts is mediated by complex mechanisms, including disruption of the cell membrane, inhibition of enzymatic activity, induction of oxidative stress, and suppression of biofilm formation [12, 13, 14]. Additionally, certain phenolic compounds can influence gene expression and cellular signaling in microorganisms, including quorum sensing processes [15]. The synergistic interaction between different groups of bioactive compounds further enhances their effect and broadens their spectrum of action.

In this context, the study of the antimicrobial activity of waste materials from peppers and eggplants represents a timely and significant scientific task. Assessing their potential as a source of natural antimicrobial agents could contribute to the development of new functional products, natural preservatives, and sustainable technologies for the utilization of plant waste [16, 17, 18].

The aim of this study was to investigate the antimicrobial activity of water-alcohol extracts from waste materials of red sweet peppers, red hot peppers, and eggplant against spoilage microorganisms.

2. Materials and Methods

The following were used to conduct the experiments: Water-alcohol (20%, 40%, 70%) extracts from waste materials of red sweet peppers, red hot peppers, and eggplant, provided by the company “Bulcons” EOOD, Parvomai.

Microorganisms

Test microorganisms:

Saprophytic microorganisms: *Bacillus subtilis*, *Bacillus cereus* ATCC 14579, *Candida utilis* ATCC 42402, *Saccharomyces cerevisiae* ATCC 9763, *Aspergillus niger* ATCC 1015, *Penicillium chrysogenum* ATCC 28089, *Fusarium moniliforme* ATCC 38932.

Determination of antimicrobial activity – agar diffusion method using wells

Each of the test microorganisms (10^7 cfu/cm³) was inoculated into Petri dishes containing agar medium, and after the agar has solidified, wells (7 mm) were prepared. Sixty microliters of the respective extract and its dilutions were added to the wells, and the plates were incubated at 4°C for 1 hour to allow diffusion into the agar. The Petri dishes containing the test microorganisms were incubated at 30 °C for 24 to 48 h, after which the inhibition zones in mm were measured.

Analytical Methods

Determination of the minimum inhibitory concentration (MIC) of extracts from red sweet pepper, red hot pepper and eggplant waste materials against spoilage microorganisms

The antimicrobial activity of the extracts from red sweet pepper, red hot pepper and eggplant waste materials was determined using the serial dilution method [19].

Data Analysis

The data from the triplicate experiments were analyzed using MS Office Excel 2010, employing statistical functions to determine the standard deviation and the maximum estimation error at a significance level of $\alpha < 0.05$.

3. Results and Discussion

In a series of experiments, the inhibitory effect of water-alcohol extracts from waste materials generated during the processing of red sweet peppers, red hot peppers, and eggplant on the growth of spoilage microorganisms was examined. The results of these studies are presented in Table 1 and Table 2. The chemical composition of the antimicrobial compounds in the water-alcohol extracts (20%, 40%, and 70% ethanol) was determined. Ferulic acid, gallic acid, 3,4-dihydroxybenzoic acid, rosmarinic acid, chicoric acid, caffeic acid, cinnamic acid, and others were not detected in the obtained extracts. All extracts contained significant amounts of sinapic acid,

the concentration of which ranged from 27.24 µg/g to 369.33 µg/g depending on the type of raw material and the extractant used to obtain them. Gallic acid was detected only in extracts from red hot pepper stems obtained with 20% ethanol and 40% methanol.

The antimicrobial activity of water-alcohol extracts from waste materials of red sweet peppers, red hot peppers, and eggplant against the growth of spoilage and spore-forming bacteria and yeasts was weak (Table 1). An exception was observed in the water-alcohol extracts (20% and 40%) of red sweet peppers, which inhibited the growth and development of the yeast *Saccharomyces cerevisiae* ATCC 9763, where inhibition zones of 15–17 mm were determined. Clear antimicrobial activity of the water-alcohol extracts from waste materials of red sweet peppers, red hot peppers, and eggplant against spoilage bacteria and yeasts was observed at an alcohol content of 70% in the extract, at which MIC <600 ppm

was determined. 70% water-alcohol extracts from waste materials of red sweet peppers, red hot peppers, and eggplant also inhibited the growth of the yeast *Candida utilis* ATCC 42402.

A similar trend was observed when determining the inhibitory effect of water-alcohol extracts from waste materials of red sweet peppers, red hot peppers, and eggplant against fungi (Table 2). Water-alcohol extracts from waste materials of red sweet peppers, red hot peppers, and eggplant containing 20% and 40% alcohol did not affect the growth and development of fungi from the genera *Penicillium*, *Fusarium*, and *Aspergillus*. The growth of the three fungal strains was affected by the water-alcohol extracts from waste materials of red sweet peppers, red hot peppers, and eggplant with 70% alcohol content (Table 2), for which small zones of inhibition and a low MIC (around 600 ppm) were determined.

Table 1: Antimicrobial activity of plant extracts derived from waste materials from the canning industry against spoilage microorganisms: spore-forming bacteria and yeasts. Inhibition zones (IZ) were measured in mm, with a disc diameter of 6 mm.

Sample	Test microorganisms		<i>B.subtilis</i> ATCC 6633 1,0 *10 ⁹ cfu/cm ³		<i>B.cereus</i> ATCC 14579 1,6*10 ⁹ cfu/cm ³		<i>C.utilis</i> ATCC 42402 2,7*10 ¹⁰ cfu/cm ³		<i>Saccharomyces cerevisiae</i> ATCC 9763 1,4*10 ¹⁰ cfu/cm ³	
	IZ, mm	MIC, ppm	IZ, mm	MIC, ppm	IZ, mm	MIC, ppm	IZ, mm	MIC, ppm	IZ, mm	MIC, ppm
20% ethanol; red sweet pepper stems	-	-	-	-	-	-	-	-	15,0±0,0	< 600
40% ethanol; red sweet pepper stems	-	-	10,0±0,0	< 600	-	-	-	-	17,0±0,0	< 600
70% ethanol; red sweet pepper stems	10±0,0	<600	10,0±0,0	< 600	10±0,0	< 600	-	-	9,0±0,0	< 600
20% ethanol; red hot peppers	-	-	-	-	-	-	-	-	-	-
40% ethanol; red hot peppers	-	-	-	-	-	-	-	-	-	-
70% ethanol; red hot peppers peppers	9,0±0,0	<600	10,0±0,0	< 600	-	-	-	-	9,0±0,0	< 600
20% ethanol; eggplant stems	-	-	-	-	-	-	-	-	-	-
40% ethanol; eggplant stems	-	-	9,0±0,0	< 600	-	-	-	-	-	-
70% ethanol; eggplant stems	9,0±0,0	<600	9,0±0,0	< 600	-	-	-	-	9,0±0,0	< 600
40% methanol; red sweet pepper stems	-	-	10,0±0,0	< 600	9,0±0,0	< 600	-	-	-	-
40% methanol; red hot pepper stems	-	-	-	-	-	-	-	-	-	-
40% methanol; eggplant stems	-	-	-	-	-	-	-	-	-	-
Control K1: 20% ethanol	-	-	-	-	-	-	-	-	-	-
Control K2: 40% ethanol	-	-	-	-	-	-	-	-	-	-
Control K3: 70% ethanol	-	-	-	-	-	-	-	-	-	-
Control K4: 40% methanol	-	-	-	-	-	-	-	-	-	-

Table 2: Antimicrobial activity of plant extracts derived from waste materials from the canning industry against saprophytic microorganisms: fungi. The inhibition zones (IZ) were measured in mm, with a disc diameter of 6 mm.

Sample	Test microorganisms		<i>Penicillium chrysogenum</i> ATCC 28089 5,0 *10 ⁷ cfu/cm ³		<i>Fusarium moniliforme</i> ATCC 38932 8,0*10 ⁶ cfu/cm ³		<i>Aspergillus niger</i> ATCC 1015 2,9*10 ⁷ cfu/cm ³	
	IZ, mm	MIC, ppm	IZ, mm	MIC, ppm	IZ, mm	MIC, ppm	IZ, mm	MIC, ppm
20% ethanol; red sweet pepper stems	-	-	-	-	-	-	-	-
40% ethanol; red sweet pepper stems	-	-	-	-	-	-	-	-
70% ethanol; red sweet pepper stems	10±0,0	<600	9,0±0,0	< 600	9,0±0,0	< 600	9,0±0,0	< 600
20% ethanol; red hot peppers	-	-	-	-	9,0±0,0	< 600	-	-
40% ethanol; red hot peppers	9,5±0,5	<600	-	-	-	-	-	-
70% ethanol; red hot peppers peppers	9,0±0,0	<600	10,0±0,0	< 600	10,0±0,0	< 600	10,0±0,0	< 600
20% ethanol; eggplant stems	-	-	-	-	-	-	-	-
40% ethanol; eggplant stems	9,0±0,0	<600	9,0±0,0	< 600	9,0±0,0	< 600	9,0±0,0	< 600
70% ethanol; eggplant stems	9,5±0,5	<600	9,0±0,0	< 600	-	-	-	-
40% methanol; red sweet pepper stems	-	-	-	-	-	-	-	-
40% methanol; red hot pepper stems	-	-	-	-	-	-	-	-
40% methanol; eggplant stems	-	-	-	-	-	-	-	-
Control K1: 20% ethanol	-	-	-	-	-	-	-	-
Control K2: 40% ethanol	-	-	-	-	-	-	-	-
Control K3: 70% ethanol	-	-	-	-	-	-	-	-
Control K4: 40% methanol	-	-	-	-	-	-	-	-

Plant extracts derived from waste materials of red sweet peppers, red hot peppers, and eggplant inhibited the growth of spoilage microorganisms. Furthermore, these microorganisms produced and released various types of toxins into food. Water-alcohol extracts from waste materials of red sweet peppers, red hot peppers, and eggplant exhibited varying antimicrobial activity against all tested microorganisms. This was due to differences in the chemical composition of the individual extracts. The experimental results supported the targeted utilization of waste from the agricultural and processing industries as an alternative source of

natural antimicrobial agents applicable in the food industry, as a substitute for chemically synthesized preservatives. In conclusion, it can be summarized that future research should focus on standardizing methods for the extraction and characterization of bioactive compounds, as well as on evaluating their efficacy in real food systems and safety during prolonged use. In this context, phenolic acids extracted from plant waste emerge as promising candidates for the development of innovative functional ingredients with antimicrobial activity.

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Design, Implementation, and Performance Analysis of a Single-Pole Dual-Axis Solar Tracking System for Photovoltaic Energy Improvement

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Abstract: The increasing demand for electrical energy, the reduction of fossil fuel reserves, and growing concerns about environmental pollution have driven the development of technologies for energy production from renewable sources, particularly solar energy. The efficiency of photovoltaic systems depends on the angle of incidence of solar radiation on photovoltaic panels. Static systems cannot maintain the optimal orientation toward the sun throughout the day, resulting in reduced electricity generation. For this reason, mechanisms for automatic solar trajectory tracking have been developed, significantly improving the performance of photovoltaic systems. This paper addresses the design, development, monitoring, and operation of a single-pole dual-axis mechanism for solar trajectory tracking of the SM44M3V15P type, integrated with photovoltaic modules. The system was developed as a prototype and later implemented near the Mechatronics Laboratory at the Faculty of Mechanical Engineering, University of Prishtina. The mechanism enables continuous tracking of the sun's trajectory through two independent axes: the azimuth axis and the elevation axis. The system includes linear actuators, a mechanical structure, electronic components, and software for automatic monitoring and control. The study includes experimental analyses and simulations to compare the performance between a fixed photovoltaic system and a dual-axis tracking system. The results show that the dual-axis mechanism significantly improves electrical energy production compared to static and single-axis systems. Annual energy production increased from 4156.13 kWh in the fixed system to 5487.42 kWh in the dual-axis tracking system. The findings demonstrate that dual-axis solar tracking systems represent an efficient and sustainable solution for improving the performance of photovoltaic installations in modern engineering applications.

Keywords: PHOTOVOLTAIC SYSTEMS, DUAL-AXIS TRACKING, RENEWABLE ENERGY, ENERGY EFFICIENCY, SOLAR TRACKING

1. Introduction

The increasing global demand for electrical energy, the depletion of fossil fuel resources, and growing environmental concerns have accelerated the development of renewable energy technologies, particularly solar energy systems [1], [2]. Among renewable energy sources, solar energy is considered one of the most promising due to its abundance, sustainability, and minimal environmental impact during operation [3].

Photovoltaic systems (PV) convert solar radiation directly into electrical energy; however, their efficiency strongly depends on the angle of incidence between incoming solar radiation and the surface of the PV modules. Fixed photovoltaic systems operate at constant tilt and azimuth angles, which leads to suboptimal alignment with the sun throughout the day and across seasonal variations, resulting in significant energy losses [4]. To overcome this limitation, solar tracking systems have been developed to continuously adjust the orientation of photovoltaic panels toward the sun, thereby enhancing energy harvesting efficiency [5].

Solar tracking systems are generally classified into single-axis and dual-axis configurations (Figure 1.b and Figure 1.c). Single-axis trackers follow the apparent motion of the sun along one rotational axis, typically from east to west, whereas dual-axis trackers enable adjustments in both azimuth and elevation angles, allowing more precise alignment with solar radiation throughout the year [6]. Numerous studies have demonstrated that dual-axis tracking systems can increase annual energy production by approximately 20%–40% compared to fixed systems (Figure 1.a), depending on geographical location, climatic conditions, and system configuration [7].

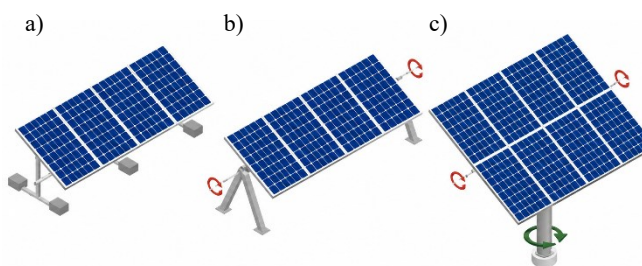


Fig. 1 Types of solar module installations: a) static (fixed) configurations; b) single-axis configurations and c) dual-axis configuration.

The development of solar tracking systems involves the integration of mechanical design, electronic components, sensors,

and control algorithms. Modern implementations commonly utilize linear actuators, light-dependent resistors (LDRs), microcontroller-based control units, and feedback control mechanisms to ensure accurate and autonomous tracking of the sun's trajectory [8]. Advances in mechatronics and control engineering have significantly improved the reliability, precision, and practical feasibility of such systems for real-world applications.

Recent research conducted in Kosovo has also highlighted the strong potential of renewable energy sources within the region. Studies on solar and wind energy resources in the urban area of Prishtina have confirmed favorable conditions for the exploitation of renewable energy systems [9]. Furthermore, investigations into small-scale wind energy systems have demonstrated their potential contribution to reducing environmental pollution and improving overall energy sustainability [10], [11]. In addition, previous research on mechanical and mechatronic systems, including micro-hydro turbines and structural dynamic systems, emphasizes the importance of integrated design, numerical simulation, and experimental validation in improving system performance and efficiency [12].

Motivated by these findings, this study presents the design, implementation, and performance analysis of a single-pole dual-axis solar tracking system integrated with photovoltaic modules [13]. The proposed system is developed as a laboratory prototype and subsequently implemented under real environmental conditions near the Mechatronics Laboratory at the Faculty of Mechanical Engineering, University of Prishtina. The system integrates a mechanical structure, linear actuators, sensor-based feedback, and an automated control system to continuously orient photovoltaic panels toward the sun, with the objective of maximizing energy production efficiency and improving overall photovoltaic system performance.

2. System Design and Methodology

The proposed solar tracking system is composed of four main subsystems: a mechanical structure, a sensing subsystem, an actuation subsystem, and a control unit. The coordinated integration of these components enables continuous two-axis alignment of the photovoltaic module with the sun's position. The overall architecture of the system is presented in Figure 2, which illustrates the interaction between sensors, actuators, and the control unit.

As illustrated in Fig. 2, the proposed system consists of four integrated subsystems.

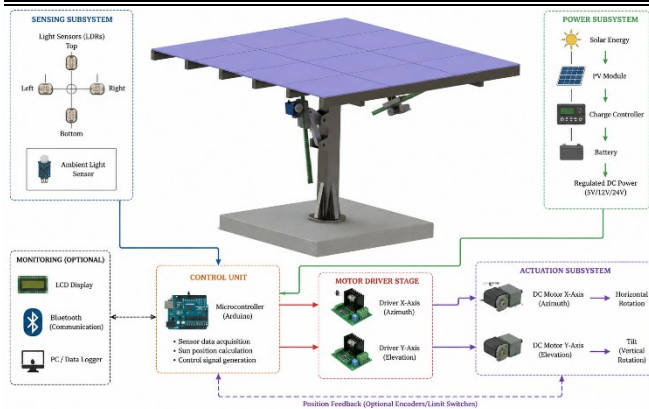


Fig. 2 Overall system architecture of the dual-axis solar tracker

The system operates in a closed-loop control configuration, where real-time sensor feedback is continuously processed by the control unit to regulate actuator motion. The control objective is to minimize the angular error between the panel orientation and the sun's position, ensuring optimal alignment and maximizing solar energy capture efficiency.

2.1. Mechanical Design and 3D Modeling

The mechanical structure of the prototype was developed using SolidWorks CAD software to ensure structural integrity and operational feasibility. The final 3D model is shown in Figure 3.



Fig. 3 3D CAD model of the single-pole dual-axis tracking system

The system consists of a vertical steel column, a rotational base for azimuth movement, and a tilt mechanism for elevation adjustment. The mechanical assembly decomposition is shown in Figure 4, where the main components are highlighted, including the base, support frame, and PV mounting structure.

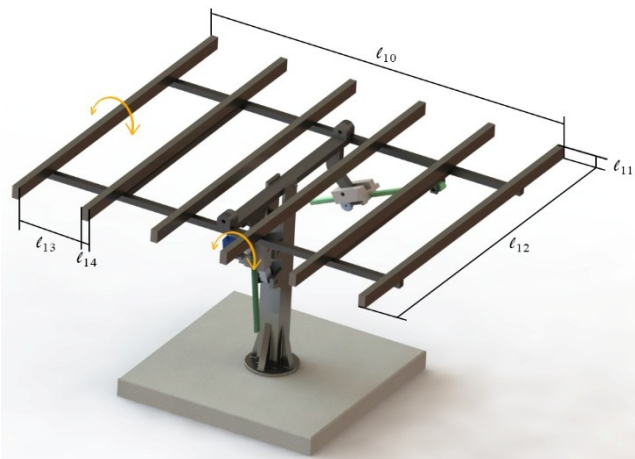


Fig. 4 Mechanical assembly decomposition of the tracking system

2.2. Rack-and-Pinion Actuation System

Linear motion required for panel adjustment is achieved using a rack-and-pinion mechanism, which converts rotary motion into linear displacement. The mechanism is illustrated in Figure 5.

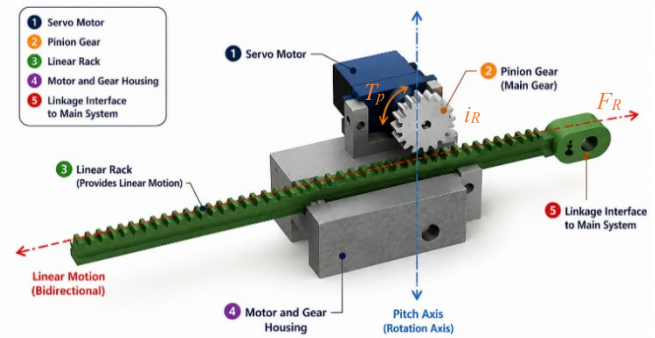


Fig. 5 Rack-and-pinion actuation mechanism driven by a Servo Motor

The gear ratio of rack and pinion is defined as:

$$i_R = \frac{z_r}{z_p} = \frac{55}{16} = 3.43 \quad (1)$$

This configuration ensures sufficient torque amplification for panel positioning.

The required force (F_r) acting on the rack is modelled as:

$$F_r = m \cdot (g + a) + F_c \quad (2)$$

The torque at the pinion (T_p) is expressed as:

$$T_p = F_r \cdot r_p \quad (3)$$

where:

z_r – rack teeth

z_p – pinion teeth

m [kg] – moving mass, which includes the load and any component of the system that moves

g [m/s²] – gravitational acceleration (9.81 m/s²)

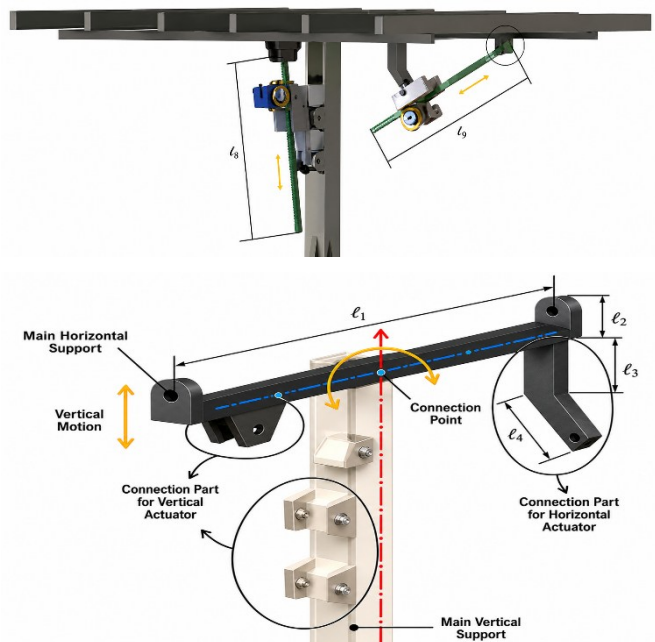
a [m/s²] – acceleration to which the system is subjected

F_c [N] – compressive force

r_p [mm] – pinion radius

2.3. Mechanism for Tracking System for Photovoltaic

Based on the movement of the Sun, a mechanism has been developed that enables continuous tracking of sun trajectory at any time, as shown in Figure 6.



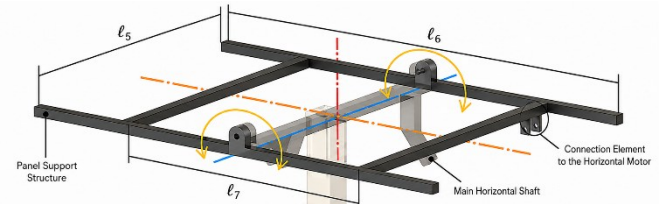


Fig. 6 Mechanism for single-pole dual-axis tracking system

The main objective of this mechanism is to maintain maximum perpendicularity between the incoming solar rays and the PV panel surface, thereby maximizing photovoltaic power output.

The system enables two-axis rotation: vertical and horizontal, allowing solar tracking from east to west (azimuth) during the day and from south to north (elevation) to accommodate seasonal variations.

2.4. Control System and Sensor Configuration

The tracking system utilizes four LDR sensors positioned at the corners of the PV panel. These sensors detect differential light intensity to determine solar direction. The system operates by minimizing the difference between sensor outputs, ensuring continuous alignment of the PV panel with the Sun's position. The

LDR sensor signals are processed by an Arduino microcontroller, which serves as the central control unit, converting analog inputs into digital data and generating control signals for the actuators, Figure 7.

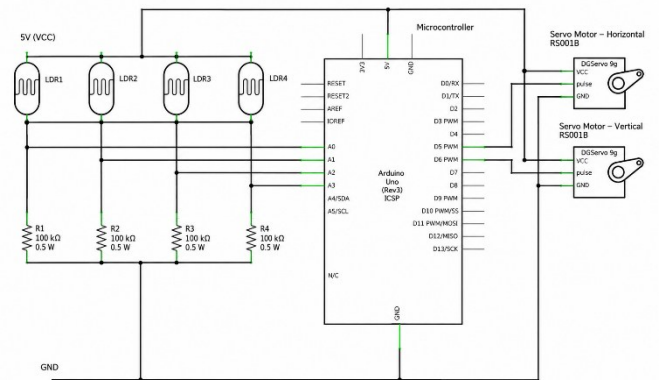


Fig. 7 Circuit diagram of the Arduino-based dual-axis solar tracking system using LDR sensors and servo motors

The control logic is implemented in the Arduino program, which coordinates system operation based on real-time sensor feedback.

For implementation, all components are interconnected according to the control algorithm. The mechanism is precisely Figure 7 presents the complete circuit diagram illustrating the connections between the Arduino board, sensors, and actuators.

As shown, four LDR sensors are used for two-axis tracking, with each pair responsible for one axis. The measured light intensities are compared, and based on these differences, control signals are sent to the motors, which adjust the system to follow the Sun's position.

The system operates by minimizing the difference in sensor outputs, ensuring continuous alignment with the sun's position.

3. Structural Simulation and Finite Element Analysis

3.1. Boundary Conditions and Loading

Structural validation was performed using SolidWorks Simulation. The system was constrained at the base, as shown in Figure 8, while a load of 8 kgf was applied to the PV mounting frame, as illustrated in Figure 9.

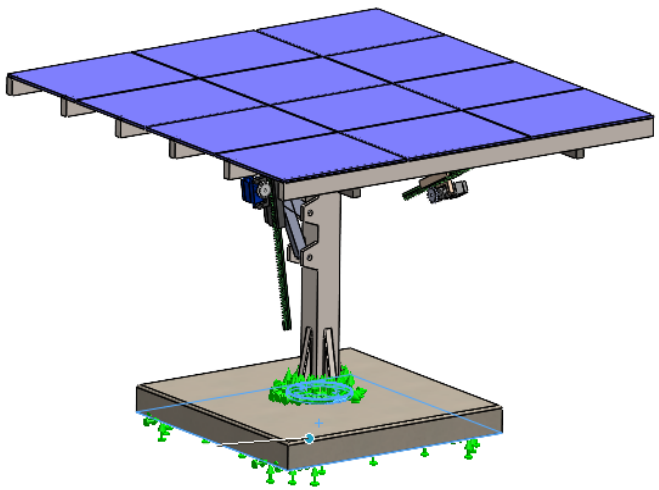


Fig. 8 Fixed boundary conditions of the structure

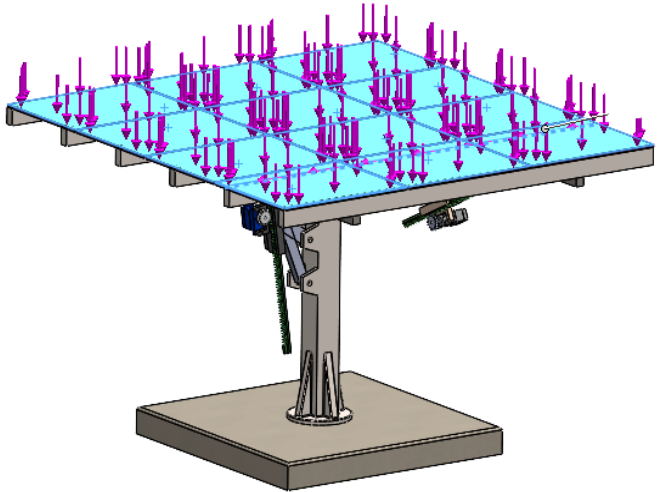


Fig. 9 Applied load distribution

3.2. Mesh Generation

Finite element discretization of the model is shown in Figure 10, where the mesh ensures numerical stability and accurate stress distribution results.

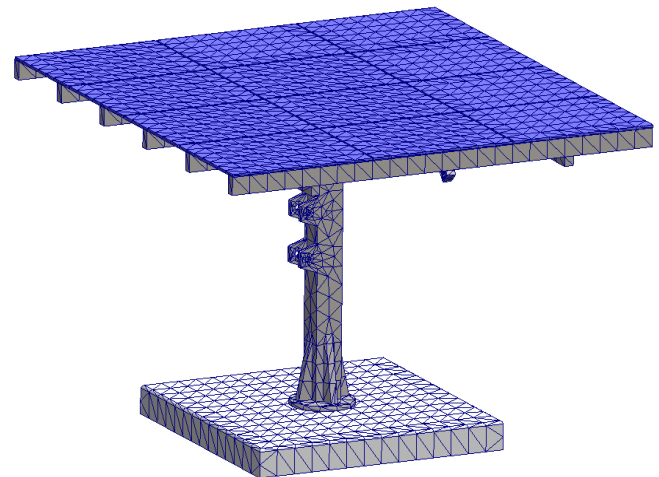


Fig. 10 Finite element mesh model

3.3. Simulation Results

Stress distribution results are presented in Figure 11, showing that maximum stress values remain within safe material limits.

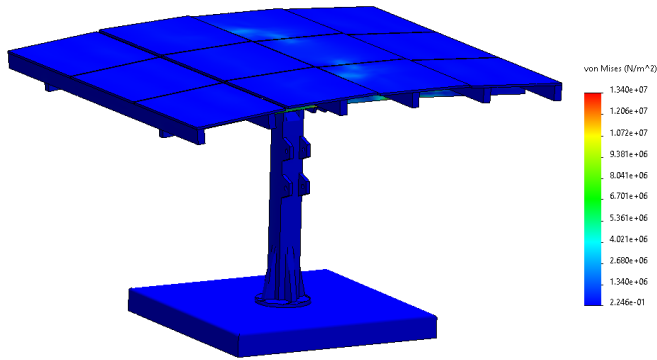


Fig. 11 Von Mises stress distribution

Structural displacement is illustrated in Figure 12, indicating minimal deformation under applied loads.

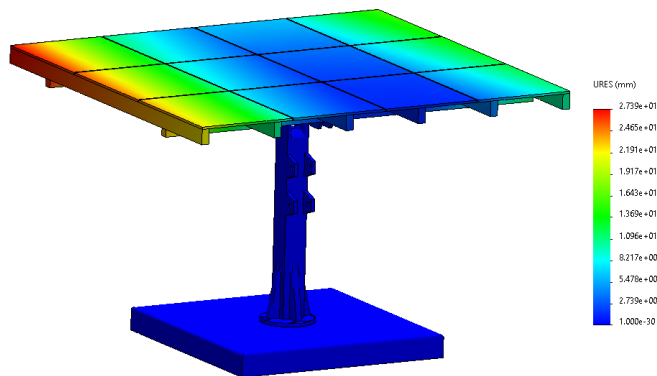


Fig. 12 Displacement contour results

Strain distribution is shown in Figure 13, confirming structural stability under operational conditions.

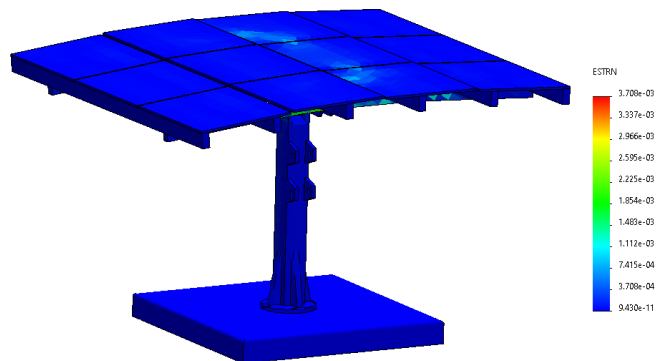


Fig. 13 Equivalent strain analysis

4. Experimental Implementation

A Single-Pole Dual-Axis Solar Tracking System was installed at the Faculty of Mechanical Engineering, University of Prishtina, as shown in Figure 14.

Table 1 summarizes the main mechanical specifications of the proposed dual-axis solar tracking system. The structure is designed to support up to fifteen photovoltaic modules with a total active surface area of approximately 25 m². Two linear actuators (SM4S900M3) provide independent motion along the azimuth and elevation axes, enabling continuous solar tracking throughout the day. The supporting structure consists of square steel profiles to ensure adequate stiffness and structural stability under operational loading conditions.



Fig. 14 Installation site at University of Prishtina

Table 1: Mechanical specifications of the dual-axis solar tracking system

Parameter	Specification
Tracking configuration	Dual-axis
Azimuth rotation range	100°
Elevation angle range	15°–90°
Azimuth actuator	Linear actuator SM4S900M3, stroke length 900 mm
Elevation actuator	Linear actuator SM4S900M3, stroke length 900 mm
Azimuth beam	Square steel tube 140 × 140 mm
Support frame dimensions	5 m × 5 m
Panel support fastening system	Serrated scissor clamps (60 units)
Mounting pole	Square steel tube 200 × 200 mm, height 3500 mm
Maximum PV array capacity	15 photovoltaic modules
PV module dimensions	0.99 m × 1.67 m per module
Total PV surface area	Approximately 25 m ²
Maximum PV array weight	345 kg (15 × 23 kg)
Service life	20–25 years*

* Depending on operating conditions and maintenance schedule.

The installation process included foundation preparation, vertical column mounting, frame assembly, and PV panel integration, as shown in Figure 15–17.



Fig. 15 Concrete foundation and installing vertical steel pole



Fig. 16 Structural frame assembly

The completed system is shown in Figure 17, demonstrating full operational capability under real environmental conditions.



Fig. 17 Final dual-axis solar tracking system

5. Energy Performance Analysis

5.1. Fixed PV System

The annual energy production values were obtained using PVGIS simulations for the geographical coordinates of Prishtina (42.648°N, 21.166°E). Simulation parameters for fixed PV system are summarized in Table 2.

Table 2: Simulation parameters for PVGIS analysis

Parameter	Specification
Location	42.648°N, 21.166°E
Installed power	15 modules x 216 W = 3240 Wp
System losses	14%

The monthly energy production of the fixed system is shown in Figure 18, while solar irradiance distribution is illustrated in Figure 19.

Figure 18 illustrates the monthly electrical energy output of the photovoltaic system with fixed system. Energy production increases steadily from January to July, reaching a peak of approximately 495 kWh, followed by a gradual decrease toward the end of the year. This seasonal trend is mainly influenced by variations in solar irradiance, daylight hours, and weather conditions, highlighting the strong effect of climate on photovoltaic system performance.

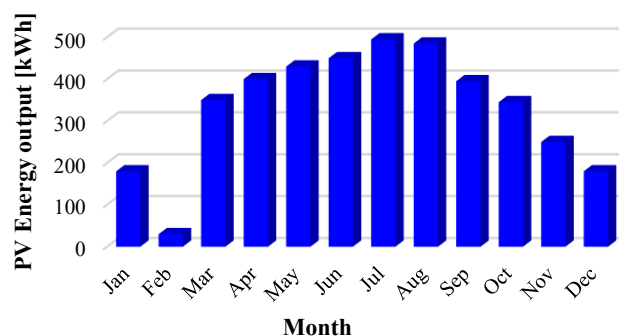


Fig. 18 Monthly energy production (fixed system) from 3240 Wp

As shown in Figure 19, the monthly in-plane solar irradiation exhibits a clear seasonal trend, peaking in July at approximately 205 kWh/m² and reaching its minimum during winter, thereby directly affecting the photovoltaic system's energy output.

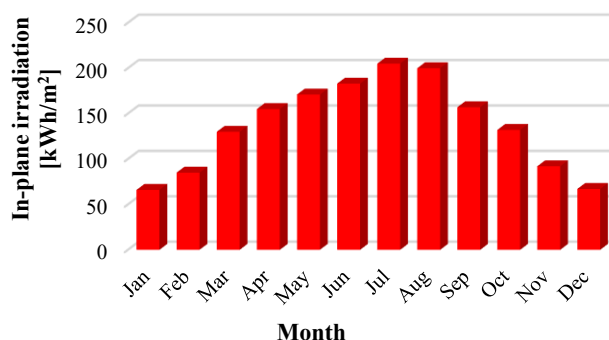


Fig. 19 Monthly in-plane solar irradiation incident on the photovoltaic array (fixed system)

The annual energy yield is given in Table 3.

Table 3: Fixed system performance

Parameter	Specification
Annual energy	4156.13 [kWh]
Irradiance	1646.02 [kWh/m²]

5.2. Dual-Axis Tracking System

The tracking system performance is shown in Figure 20–22, illustrating improved energy distribution throughout the year.

Figure 20 presents the monthly electrical energy output of the photovoltaic system equipped with a dual-axis tracking mechanism. Energy production increases steadily from January to July, reaching a maximum of approximately 640 kWh, and then gradually declines through December. This seasonal variation is mainly driven by changes in solar irradiance, daylight duration, and weather conditions, highlighting the significant influence of environmental factors on photovoltaic system performance and energy yield.

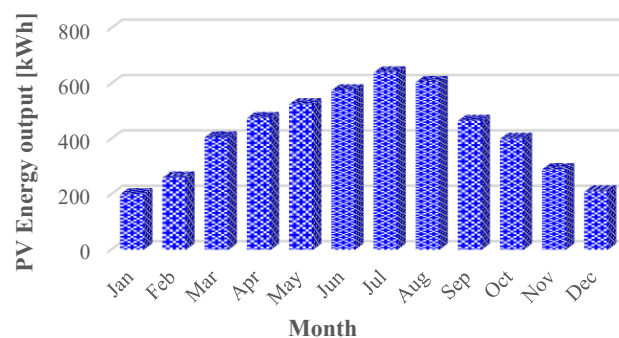


Fig. 20 Monthly energy production (dual-axis tracking system) from 3240 Wp

Figure 21 illustrates the monthly in-plane solar irradiation received by the photovoltaic system equipped with a dual-axis tracking mechanism. Solar irradiation increases gradually from January to July, reaching a peak of approximately 290 kWh/m², before declining toward the winter months. This seasonal variation is mainly influenced by changes in solar elevation, daylight duration, and weather conditions, confirming the strong relationship between solar irradiation and photovoltaic energy production throughout the year.

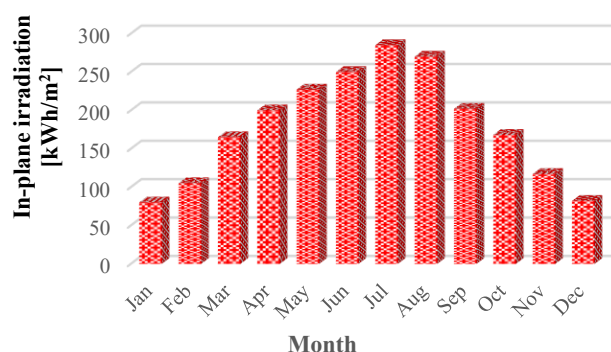


Fig. 21 Monthly in-plane solar irradiation incident on the photovoltaic array (dual-axis tracking system)

The corresponding performance are summarized in Table 4.

Table 4: Dual-axis tracking system performance

Parameter	Specification
Annual energy	5487.42 [kWh]
Irradiance	2161.83 [kWh/m ²]

5.3. Comparative Analysis

Figure 22 presents a comparison between fixed and dual-axis tracking photovoltaic systems. Both systems follow a similar seasonal trend, with maximum energy production during summer and minimum production during winter. However, the dual-axis tracking system consistently achieves higher energy output, reaching approximately 640 kWh in July compared to 495 kWh for the fixed system, demonstrating the benefit of solar tracking in improving photovoltaic performance.

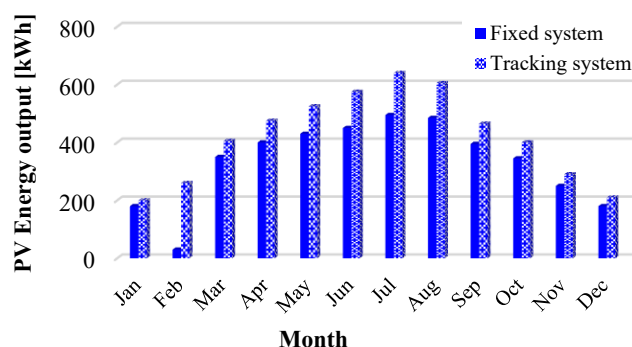


Fig. 22 Energy production comparison between fixed and tracking system

These results demonstrate that solar tracking significantly enhances energy yield by optimizing the orientation of PV modules toward the Sun throughout the year. Comparison between fixed vs Dual-Axis tracking system is summarized in Table 5.

Table 5: Comparative performance of PV systems

Parameter	Fixed	Dual-axis	Increase
Annual energy	4156.13 [kWh]	5487.42 [kWh]	32.03%
Irradiance	1646.02 [kWh/m ²]	2161.83 [kWh/m ²]	31.34%

Although the dual-axis tracking system increases installation complexity and investment cost, the observed annual energy gain of approximately 32% can significantly reduce the payback period of photovoltaic installations.

6. Results and Discussion

The obtained results clearly demonstrate that dual-axis solar tracking significantly enhances photovoltaic energy harvesting. The improvement observed in Table 3 and Table 4 is primarily attributed to: continuous optimization of solar incidence angle; reduction of cosine losses and seasonal adjustment of elevation angle.

Compared to fixed systems (Fig. 18–19), the tracking system (Fig. 20–21) maintains higher irradiance capture throughout the year.

These findings are consistent with previous studies reporting 20–40% improvement in dual-axis systems [6–8], confirming the validity of the proposed design.

7. Conclusion

This study presented the design, implementation, and experimental validation of a single-pole dual-axis solar tracking system. The system integrates mechanical, electronic, and control components into a compact and efficient architecture.

Experimental results demonstrated an increase in annual energy production from 4156.13 kWh to 5487.42 kWh, corresponding to a 32% improvement. The proposed system provides a cost-effective and scalable solution for enhancing photovoltaic system performance.

The results are based on the climatic conditions of Prishtina and may vary depending on geographical and meteorological conditions.

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Features of modeling complex twist deformation for obtaining multilayer metal cord structures

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Abstract: Features of modeling multilayer metal cord structures are shown. Data on the parameters of the numerical model of metal cord twisting and stretching are given. The dependences of the magnitude of stresses during the destruction of metal cord on the diameter of wires for various metal cord structures are determined. It is shown that symmetrical steel cord structures are less susceptible to a decrease in aggregate strength. The difference between the breaking forces of a multilayer symmetric metal cord with a core is about 10%. It is shown that with an increase in the wire diameter, there is no significant increase in the fracture stresses.

Keywords: STEEL CORD, MODELING, PROPERTIES, STRESSES

1. Introduction

The metal cord is a twisted product in the form of a three-dimensional spiral. In the process of twisting the metal cord, the wire is subjected to torsional and bending stresses. This, combined with the stress-strain state of the wire during drawing and twisting, as well as the level of internal residual stresses that occur in the wire after drawing, makes it impossible to predict changes in the properties of the wire and cord using known computational methods. For the correct calculation of the metal cord twist, an accurate forecast of the level of internal residual stresses that occur during drawing is required.

Uneven distribution of residual stresses in the wire after drawing, as well as a high value of residual stresses after twisting the metal cord, can worsen the properties of the metal cord.

The development of an adequate computer model for twisting metal cord from thin wire, assessing the level of residual stresses in the metal cord, is a promising area of study of metal cord from thin wire. The simulation itself allows you to save time and material resources necessary for laboratory tests. However, in order to use the numerical model correctly, it is necessary to check its adequacy and, if necessary, introduce correction factors.

The main method of studying the magnitude of residual stresses is the method of numerical modeling. Using this method, based on the finite element method, allows us to obtain a general picture of the stresses and deformations of the wire in the straightening device with high calculation accuracy. The main requirements in numerical modeling are the correct construction of the model in terms of geometry, the choice of initial and boundary conditions, as well as the choice of the optimal type of finite element grid. The accuracy and duration of calculations, as well as the adequacy of the constructed model, will depend on the selected type of final element and its geometric shape.

Numerical modeling, unlike analytical methods, shows with sufficient accuracy the picture of stresses and deformations not only in the elastic, but also in the plastic deformation zone. This is the main advantage over analytical calculations.

Verification of the results of numerical modeling is carried out by comparing the results of analytical calculations with the simulation results.

Verifying the adequacy of a computer model is a complex complex task. To verify the adequacy or bring the model to an adequate one, it is necessary to use a direct check of the desired values. This means that it is necessary to match the value of the same parameter obtained in a different way to a certain value of the output parameter of the model. The difference in values is unavoidable and is an error. The errors are estimated using relative values. If the difference between the value obtained in the model and the value obtained by another method is significant, then it is necessary to enter a correlation coefficient or dependence to be able to translate the model values. The difference in the values of the output parameters of the model is due to simplifications and idealization of some parameters of the model.

After twisting, the stress-strain equivalent state of the metal cord is nonequilibrium. The equilibrium stress-strain state of the metal cord means that the level of internal residual stresses is equal

to or close to zero. At this level of residual internal stresses, relaxation will be minimal. This means that the finished metal cord will have high technological properties.

In the process of twisting a metal cord, tensile, torsional and bending stresses and deformations act on the wire. The equivalent deformation is the reduced deformation to assess the total deformation effect on the wire when winding in a rope machine. Areas of large wire deformations are provided along the twisting path compared to other areas of the cable car. In such zones, the stages of twisting wires into a metal cord are carried out, the deformation of individual wires can be carried out in different directions. However, in absolute terms, the total equivalent deformation always increases. The diameter of the metal cord, the aggregate strength, and the strength of adhesion to rubber depend on the wires and their location in the metal cord.

The non-twisting of the metal cord is ensured by additional twisting of the strand in the torsion device to achieve deformation of the wires in the plastic region. After additional twisting, the pitch of the metal cord increases slightly and then unwinds in the opposite direction in the area of elastic deformations. The amount of additional twisting of the metal cord is created by the rotational speed of the torsion device.

In multilayer symmetrical structures of metal cord with a core, there is a feature associated with the pattern of contact interaction. From the point of view of modeling, it is necessary to take into account the initial stress level in the wires, as well as the contact interaction between the wires.

The main property of multilayer metal cord is its aggregate strength. This property shows how much the actual strength of the metal cord corresponds to the theoretical strength. Due to the complex twisted structure, the metal cord does not collapse simultaneously during stretching, but gradually: first one wire collapses, then the next, etc. Ideally, all the wires of the metal cord should be destroyed at the same time. However, this is not happening. Modeling the process of twisting and stretching the metal cord will allow us to determine the dependencies and understand the mechanism of behavior of wires in the metal cord structure during stretching and fracture.

The finite element method and numerical modeling were used to study twisting and fracture. Numerical models of twisting of multilayer metal cord structures based on five wires are constructed: 1+4x0. 25HT; 1+4x0. 30HT; 1+4x0. 35HT. Numerical models take into account the contact interaction of wires in the structure. The wire material model takes into account the features of plastic deformation during twisting, mechanical properties of thin wire, taking into account the processes of fine drawing, and also contains a Johnson-Cook damage model[1].

The simulation was performed with the following parameters:

The total number of grid elements is 370 thousand elements on average.

The type of finite element grid is tetrahedral.

The tension of the wires when twisting is 40 N.

The rotor speed is 3000 rpm.

The twist pitch is 15 mm.

Material-Steel 80.

The parameters of the twist are close to the current parameters of the twist in the actual production of metal cord. Twisting of wires is made on two steps of a metal cord. The results of twisting are shown in Figure 1.

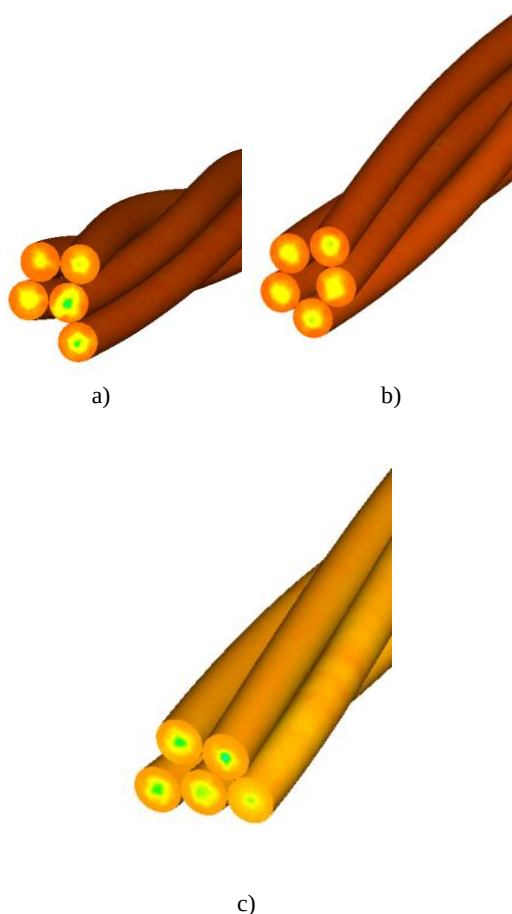


Fig. 1 Results of twisting metal cords:
a) 1+4x0. 25HT; b) 1+4x0. 30HT; c) 1+4x0. 35HT

According to the results of modeling the twist, it can be seen that a larger wire diameter allows for smaller wire displacements in the metal cord structure during the twist due to the greater rigidity of the wire rod. However, even though the wires are displaced, the structure remains tight when twisted. At the length corresponding to about 35% of the twist pitch, there is a transition from a symmetrical section to an unbalanced one, which shifts the center of gravity of the section by an average of 28%. This can affect the distribution of the mass of the metal cord in the rubber web during its reinforcement, as well as the processes of twisting the metal cord itself. With such an unbalanced arrangement of wires, an excessive tension force will be exerted on the core.

A model is constructed to simulate the stretching of a metal cord to complete rupture of the entire metal cord structure. The destruction of the material obeys the classical laws of plastic flow of the material. The results of modeling the breakage of metal cord are shown in Figure 2.



Fig. 2 Results of modeling of metal cord breakage

As can be seen from the model, the fracture obeys the classical principles of plastic deformation of the material. Because of the small iteration step, the simulation shows the formation of a neck and the moment of rupture, which is simulated by dividing the finite element grid. At a stretching rate of 1 mm/s, the formation and destruction of the neck takes an average of 0.2 seconds.

Similar models of metal cord stretching were constructed, but using a different law of material damage – Cocroft-Latham and Lemaitre [2, 3]. The results of material destruction in these models show inadequate behavior of the wire under tension, showing a relative elongation of the wire in the range of 4.5-5%, which is approximately 1.85 times higher than the actual mechanical properties of steel 80.

The stretching diagram of a multilayer metal cord is shown in Figure 3.

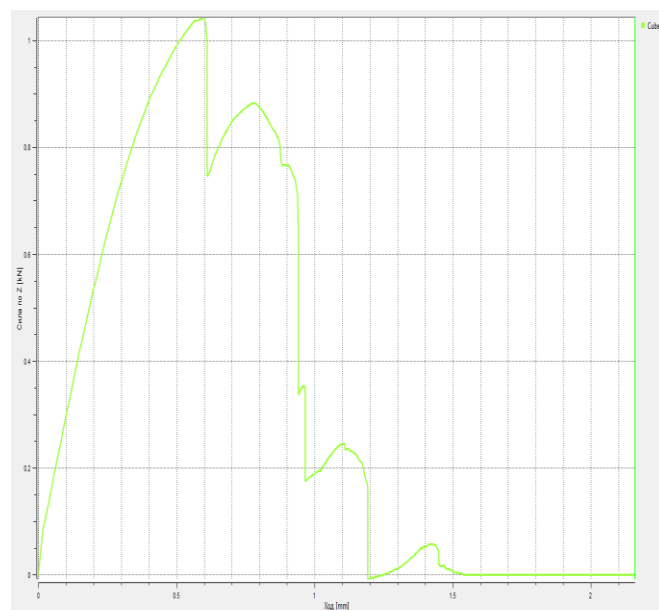


Fig. 3 Metal cord stretching diagram

The tensile diagram of a multi-layer metal cord shows the zones of increasing the breaking force during the destruction of wires.

This is due to the redistribution of loads on the wires in the structure due to the transverse displacement of the wires. First of all, the wire farthest from the center of mass of the cross-section of the metal cord is torn. The remaining wires continue to resist plastic deformation during a significant movement (0.5-0.6 mm). Subsequently, the break occurs almost simultaneously for the remaining wires. Last of all, the wire of the first layer breaks due to a smaller torsional deformation during twisting. In general, the aggregate strength of the studied metal cord is 8-10% less than the tensile strength of wires.

When the diameter of the wires increases, the stiffness of the wire rods is higher. As a result, more stable contact points of wires in the metal cord structure are formed during twisting. When such a structure is deformed, the destruction pattern is more predictable and uniform. Breaks are formed in approximately one zone, which is no more than 10% of the metal cord pitch.

Thus, a possible way to increase the aggregate strength of the metal cord can be to twist the metal cord with a large number of wires of the second layer and a core of one wire, as well as increase the diameter of the wires for more stable contact of the wires in the metal cord structure.

In addition, numerical models of stranding of multilayer types of metal cord of the following structures are constructed: 1+3x0. 25 HT, 1+3x0. 30 HT, 1+3x0. 35 HT, 1+4x0. 25 HT, 1+4x0. 30 HT, 1+4x0. 35 HT, 1+5x0. 25 HT, 1+5x0. 30 HT, 1+5x0. 35 HT. The basic parameters of the model are similar to a single-layer metal cord. The number of finite elements for each wire is at least 80,000. After modeling the twist and obtaining the initial level of wire position in the structure, as well as the initial level of equivalent residual stresses, the corresponding models of metal cord rupture were constructed.

As a result of numerical tests, the values of stresses and deformations for the moments of wire destruction in the metal cord structure up to complete destruction are determined. The results are shown in Figure 4 as a diagram.

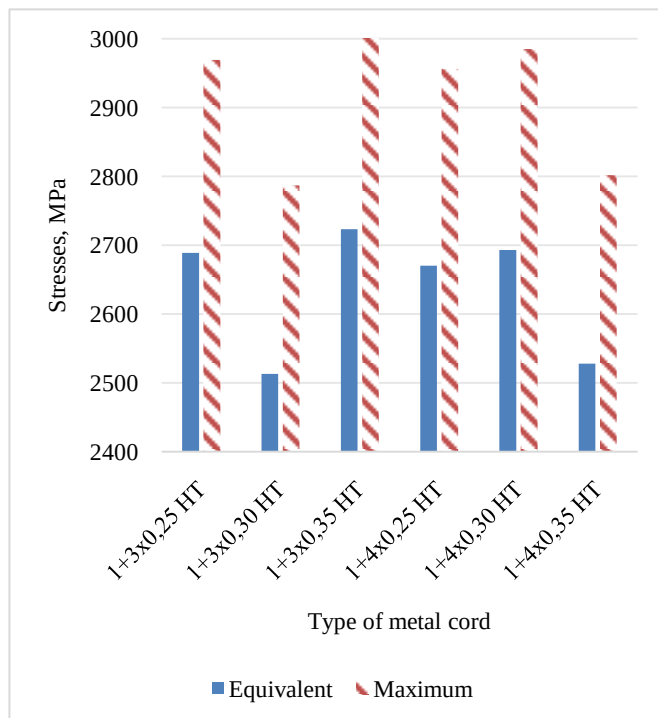


Fig. 4 Metal cord break stresses

Based on the simulation results, the dependences of the stress value during the destruction of the metal cord on the wire diameter for various metal cord structures are obtained.

For a metal cord of the 1+3 construction, the dependency looks like this:

$$\sigma = 77200d^2 - 45980d + 9359 \quad (1)$$

For a metal cord of the 1+4 construction, the dependency looks like this:

$$\sigma = -37600d^2 + 21140d - 265 \quad (2)$$

where σ – equivalent stresses at the moment of wire break, MPa;
 d – wire diameter.

The analysis shows that with an increase in the diameter of the wires, there is no significant increase in the fracture stresses. These stresses correspond to the strength class of the metal cord. The exception is metal cords of the 1+4x0. 35 HT and 1+3x0. 30 HT designs, in which the twisting process led to a shift of the wires to a non-equilibrium state with a distortion of the shape of the bulk spiral. Such defects in the twist can be prevented by increasing the tension during the twist. The pattern of contact interaction of the wires of the second layer in such a design shows restrictions on the movement of the wires in the tangential direction, which leads to increased (by 12-15%) torsional deformation. At the same time, the equivalent deformation remains unchanged for such a structure. The difference between the maximum voltage and the equivalent voltage at which the metal cord wires break was on average 10%.

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Biogas production from alcoholic stillage

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Abstract: Biogas is produced during the process of anaerobic digestion of organic waste. It is an important element of the purpose to minimize the dependence of natural gas, as well as to contribute to less pollution of the environment. The best way to achieve such goals, is to utilize every organic waste and produce valuable product. Alcoholic industry is a large sector and produces huge amounts of alcoholic beverages. Like any other food industry, there are organic wastes during and after the production process. One such organic waste is the stillage. It is a liquid waste material, produced after distillation. Stillage contains various nutrition elements, which could be used as feeding material for biogas production. As it is a way to utilize organic waste, there is a scientific interest to research the possibility to utilize it in an anaerobic digestion bioreactor to produce biogas. For that purpose, the stillage is mixed with cattle manure. The accumulated biogas could be used for heating, auxiliary electrical power (powering CNG generators) and as an alternative fuel for vehicles.

Keywords: BIOGAS, ANAEROBIC DIGESTION, BIOMASS, STILLAGE MATERIAL, ORGANIC WASTE, BIOREACTOR

1. Introduction

Biofuels represent a great share of the energy carriers of the modern developed society. They are considered an alternative to the traditional energy sources such as oil, coal and nature gas. Biofuels stands for ethanol, produced from plants, biodiesel, produced from nature lipids and biogas, produced through anaerobic digestion of plant and animal waste. Current worldwide oil consumption reached around 100 million b/d (barrels per day) in 2022. [1] One barrel is 159 liters. That is a gigantic consumption, and of course coal and nature gas were still used. All these basic fossil fuels gave the possibility of humans to achieve technological and economic progress, as wells as demographical (world population reached 8 billion around 2020) [2]. Of course there was a negative side – and that was pollution. Large scale pollution, which affects the whole planet, mainly by changing the climate. The main reason was the release of all the carbon trapped in the fossil fuels for millions of years. That caused the greenhouse effect (or more precisely intensified) it. Acid rains, land erosion, extremely high temperatures (during heat waves) and extreme rains, thunderstorms, tornados and hurricanes became more frequent and more violent [3]. Of course, our economy can't exist without consumption, but it should be made in a such way, as to cause minimum or even zero (where possible) harm to the nature. It could be achieved by using energy efficient machines and devices, highly effective waste management and by adopting carbon neutral technologies. One way to cut pollution is by research and development of new technologies, such as solar power, wind power, tide power, geothermal power, nuclear power, hydrogen, biomass and biofuels. Development of these technologies could be a possible solution to lower fossil fuel consumption and therefore environmental pollution. As a result, from oil crises during XXth century, biofuels have been considered as an alternative to conventional fuels. Today in EU every gasoline or diesel contains some quantity of ethanol (E10) or biodiesel (B7) [4]. From laboratory experiment to wide use throughout the world. Biogas is widely used fuel in economically developed countries, as well as in the countries from 3rd world. It has many applications. Among the most important ones are as fuel for both thermal power plants, national gas grid systems, as well as a fuel in various types of vehicles, including passenger cars, trucks, small and midsize boats and aircrafts. It can be injected into the national gas grid system and carried much easier.

Biogas is widely used fuel in economically developed countries, as well as in the countries from 3rd world. It has many applications. Among the most important ones are as fuel for thermal power plants; in small scale back up power systems producing electricity by running CNG generators; as alternative to nature gas injected into the national gas grid system and as a fuel in various types of vehicles, including passenger cars, trucks, small and midsize boats and aircrafts (in research state). It is also possible to produce

hydrogen from biogas. The main source to produce biogas is manure. It has been used since the beginning of XX century. Some of the disadvantages of producing biogas from manure only, are the low content of methane (50 ~ 60%), as well as the presence of sulfuric compounds. In the current case, our aim is to investigate the possibilities of optimizing the methods and conditions for biogas production from industrial waste. One such method is to mix cattle manure with alcoholic stillage. In the manufacture of distilled spirits, stillage refers to the residue remaining after fermentation and distillation of mash or other substances. The stillage usually contains water, solids, unfermented residues and other organic components. These solids can be separated using mechanical separation technology, concentrated and thus optimally pre-dewatered before thermal drying (source: <https://www.flottweg.com/applications/beverages/stillage/>).

Series of periodic experiments on biogas production from alcoholic waste have been carried out in the Institute of Chemical Engineering (BAS). Two different alcoholic stillages were used: untreated and treated. The treatment involved the removal of sulfide ions and their oxidation to sulfate ions. The procedure was carried out by our colleague Stefan Stefanov.

The aim of experiments was to investigate the possibility to produce biogas from such waste material, as well as to check the influence of treatment. After that, the stillage and the organic waste were mixed. Then the mixture was poured in air insulated glass vessels (called bioreactors). The vessels were installed in water bath, where the temperature was kept at around 35 °C. Heating was provided by aquarium heaters. Bioreactors were connected by silicon hoses with glass cylinders, in which the accumulated biogas was collected. The cylinders were filled with water and all connections were sealed. Biogas yields were checked and samples for analyze were taken daily.

The following photo shows a view from the experimental setup.



Fig. 1 Outlook of the small scale bioreactor

2. Results and Discussion

During the first part of the project, it was investigated the possibility to produce biogas by using different waste materials, which include treated and untreated stillage and kept in defined conditions (temperature – 35 °C). The materials used were mainly from alcoholic industry, stillage is a liquid waste, left after distillation process. Manure is an organic waste from cattle farms. The treatment of the stillage included techniques for Sulphur removing. According to theoretical data, removing the Sulphur should make the material more accessible for the methanogenic bacteria (and less toxic).

Table 1: Biogas yield per sample.

	Untreated stillage, mL	Treated stillage, mL
Sample 1	135	435
Sample 2	120	200
Sample 3	100	120
Sample 4	90	80
Sample 5	80	50
Sample 6	110	35
Sample 7	100	35
Sample 8	95	35
Sample 9	100	35
Sample 10	100	45
Sample 11	110	35
Sample 12	0	50
Total volume	1140	1155

In the conducted experiments, we have found out that, the treatment of the waste material leads to improvement in the ingredients of produced biogas, expressed mainly in a slightly higher biogas volume (reaching 1155 ml of total accumulated biogas).

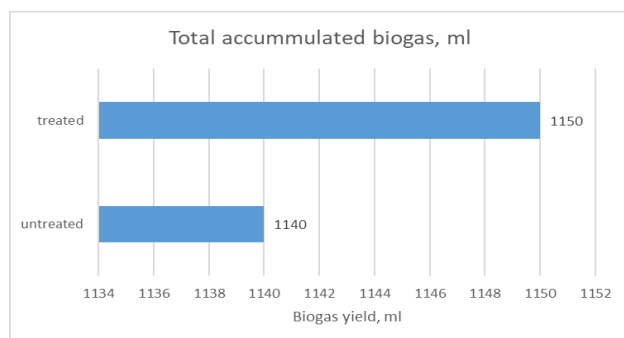


Fig.2 Total biogas yield comparison

Fig. 2 shows the combined results for both alcoholic stillages. As it can be seen from the figure, the treated stillage gave slightly more biogas, then the untreated. The result showed, that the removal of the sulphuric content improved the anaerobic digestion. Sulphuric elements are toxic to methanogenic bacteria, so their removal is beneficial for the anaerobic digestion. The less toxic feeding material gives the bacteria more time to consume the organic matter.

Fig. 3 and Fig. 4 show the corresponding biogas results for each experiment. It can be noticed that in the first experiment, the process went in a streamline way. It started with 135 ml/sample and reached 110 ml/sample at the end of the experiment.

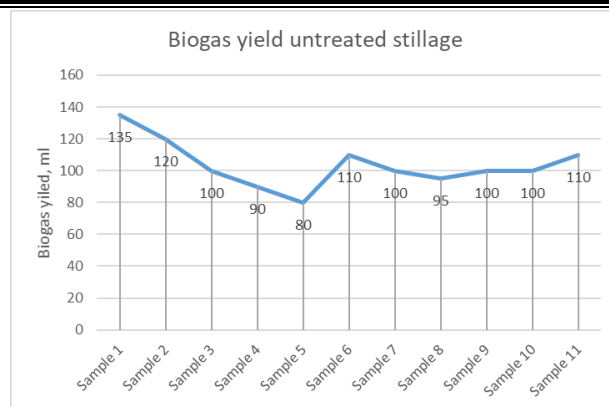


Fig.3 Biogas yield Experiment 1 untreated stillage

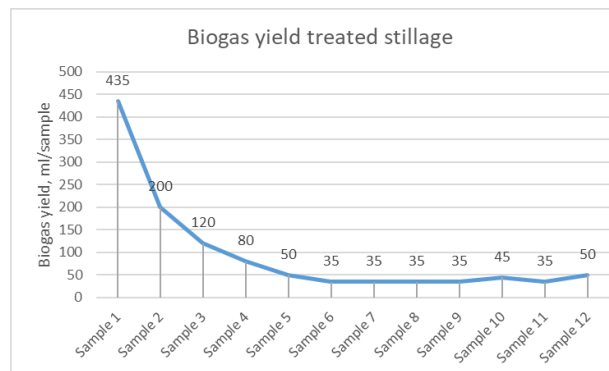


Fig.4 Biogas yield Experiment 2 treated stillage

In a contrast, the process in the second experiment Fig.4 started with rapid biogas production, reaching 450 ml/sample and then slowing down to 35 – 45 ml/sample. The total accumulated biogas was 1155 ml of volume. The graphic shows rapid consumption of organic matter in the beginning of the process, followed by slight decline. Despite that, it continued to produce biogas, but at lower rate.

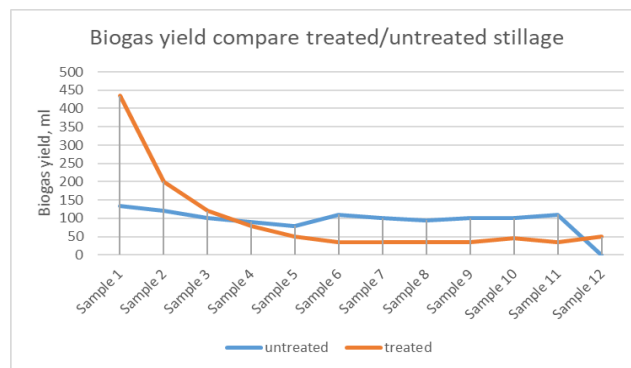


Fig.5 Biogas yield comparison between untreated and treated stillage

As it can be observed from the figure, the process in the treated stillage was slightly shifted in the beginning of the fermentation process. It showed us, that the methanogenic bacteria rapidly consumed the organic matter in the beginning, leading to a faster process. After some time, when the amount of the organic matter become low, the process started to slow down. Despite the higher rate of the organic matter consumption, the treated alcoholic stillage managed to produce higher quantity of biogas. It is clear that more biogas was produced in the beginning, compared to untreated stillage in which a more streamlined process was observed.

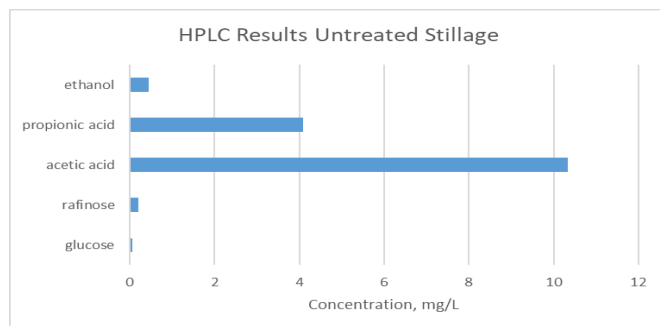


Fig.6 HPLC result Untreated alcoholic stillage

Fig. 6 and Fig. 7 show the results from HPLC analysis of the samples taken from each experiment. As it can be seen from the graphics, more substances were detected, than from the experiment with the treated stillage. The three main substances were propionic acid and acetic acid.

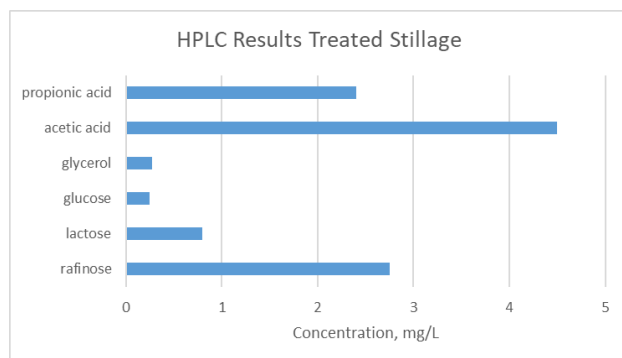


Fig. 7 HPLC result Treated alcoholic stillage

In the experiment with treated alcoholic stillage, there were four main substances detected – acetic acid, raffinose, glucose, lactose and propionic acid. As the number of the detected substance is higher in the treated alcoholic stillage than the untreated one, we believe that, the treatment of stillage probably caused a shift of the metabolic pathway of the bacteria, present in the bioreactor.

3. Conclusion

According to the results obtained from our experiments, we have noticed that treatment did improve the quantity of the collected biogas. While the difference was not in a large order, it proved that treatment techniques were necessary for accumulating higher biogas yields. The results from the HPLC analysis show that the treatment of the alcoholic stillage lead to more diverse compounds, present in the bioreactor. The waste utilization by turning waste into energy is possible way to reduce organic waste, as well as produce energy. It is beneficial for the local environment and economy, by creating job opportunities. Biogas could be used as a substitute (or as a supplementary) of the conventional gas grid system. It could be also used as an alternative to conventional fuels in private and commercial vehicles.

4. Acknowledgement

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Improving the Design and Working Process of a Nut Harvester Shaker

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Abstract: This article examines the issue of improving the design of a nut harvester shaker to improve operator comfort, enhance machine productivity, and improve working conditions. The identified shortcomings of the nut harvester allow for solutions to improve the design of certain components of the working parts and the overall harvester operation, taking into account the vibration transfer coefficient from the machine to the tree trunk. While studying the issue of industrial vibrations, the criteria for classifying vibrations affecting humans were identified. It has been found that the maximum impact of vibrations on the human body occurs in the range of 0.7-90 Hz. It is proposed to minimize harmful vibrations by using elastic systems that will allow energy to be dissipated from the vibration source. This improvement will help reduce the negative impact of vibrations on the operator's body.

Keywords: IMPROVING THE DESIGN, HARVESTER, NUTS, SHAKING HEAD, VIBRATIONS.

Introduction

Modern agriculture is unthinkable without the mechanization of production processes. This requires a transition from labor-intensive manual operations to more productive mechanized technologies.

The level of mechanization has a favorable impact on the cost, output value, income and return rate of all types of agricultural crops. For every 1% increase in the level of mechanization, the yields of all crops increase by 1.2151% [1, 2].

Along with ensuring scientifically sound irrigation standards, mechanization of production increases crop yields and makes the sector more attractive [3, 4]. This also largely refers to the fruit growing sector [5].

Harvesting is the most labor-intensive process, making fruit production an economically unattractive agricultural activity [6, 7]. Of all the production stages, mechanized harvesting is the most important and critical process, reducing harvesting costs by approximately 35-45% and accounting for up to 40-60% of total crop production costs, thereby improving overall production efficiency [2, 7]. The success of this operation largely determines the income.

Analysis of recent research and publications

One of the most critical and labor-intensive stages of the nut production is harvesting [3, 4]. Walnut production in the Republic of Moldova also increasingly requires a transition from labor-intensive manual fruit picking to modern mechanized harvesting technologies, which facilitate a manifold increase in labor productivity while maintaining the quality of the harvested product and improving working conditions for workers [2, 8]. Therefore, it is crucial to improve agricultural working bodies and equipment used for harvesting, as well as working conditions, in order to achieve high income [1, 2].

A study of the design of nut harvesting machines and equipment reveals key shortcomings in the operation of components and operating elements directly affecting the shaking and harvesting process [2, 5]. In this context, the key element of harvesting machines, such as Gacek combines and shakers for plum and cherry harvesting, as well as the Jagoda JPS Agromachines combine, designed for harvesting cherries, as well as other stone fruits such as plums, walnuts, almonds, and others, is the shaking head, the efficiency of which directly determines the fruit yield and the economic viability of the fruit and nut harvesting machines and equipment.

At the same time, the intensification of production processes is often associated with other related problems. Intensification of mechanized harvesting faces a serious challenge: the negative impact of vibrations on humans. The high-frequency vibrations required to separate walnuts from their stems are inevitably transmitted through the machine's structure to the controls.

Prolonged exposure of the operator's hands to localized vibration leads to rapid fatigue, decreased precision, and the risk of developing occupational diseases such as vibration syndrome [9, 10, 11].

Moreover, the rigid transmission of impulses without proper damping contributes to accelerated wear of hydraulic connections and fatigue failure of supporting metal structures, which subsequently need to be restored [11, 12, 13]. To reduce wear of critical parts of nut harvesting machines, methods of increasing the wear resistance of manufactured parts can be used, using atmospheric plasma spraying (APS) [14, 15].

Therefore, the search for technical solutions aimed at isolating the effects of vibrations, while maintaining the amplitude-frequency characteristics necessary for the harvesting process, is an important and pressing scientific and technical task.

The aim of this work is to justify and develop an improved design of the shaking head by integrating an additional specialized damping unit. This upgrade is designed to effectively decouple the vibrational connection between the machine's working element and the operator, thereby improving the ergonomics and operational reliability of the harvesting equipment.

To address this issue, we use the design of the Gacek combine harvester, which controls the shaking process via a handle rigidly attached to the shaking head housing.

The object of this study is the Gacek fruit shaker, equipped with a hydraulic, gripper-type shaking head. The harvester is a trailed agricultural machine designed for the automated harvesting of stone fruit crops (cherries, plums, nuts, and other fruits) in orchards up to 5 hectares in size [16].

This machine consists of a frame supported by four pneumatic wheels. Mounted on the frame is an operator's workstation with controls, as well as an opening hydraulically operated harvesting hood and an inclined belt-type conveyor with a fan at the top for cleaning large leaves from the fruit [17].

The machine operates by mechanically shaking the trees, followed by fruit collection and cleaning. A tractor approaches a tree in an orchard row, and a hydraulic mechanism opens a catching umbrella beneath the tree's crown. The operator approaches the tree trunk, pressing it against the tree, and activates the vibration mechanism. The fruit falls onto the umbrella and rolls toward the central conveyor chute. The fruit is then air-cleaned and collected in containers or boxes [16, 17].

One of the main components of a fruit harvester is an agitator named shaking head. Vibrations are generated by an eccentric mechanism called a directional vibration exciter, driven by a hydraulic motor connected to the tractor's external hydraulic system. This requires an oil flow of 25 l/min at a pressure of 160-200 bar (Fig. 1).

The operating principle of a directional vibration exciter is based on a pair of unbalanced weights rotating synchronously in opposite directions with an angular velocity ω (Fig. 1). As a result, the total centripetal force F_c of the imbalances is equal to:

$$F_c = F_1 + F_2 \quad (1)$$

where: F_1 and F_2 are the centripetal forces of the imbalances.

$$F_c = m\omega^2 r. \quad (2)$$

where: m - the mass of the imbalance;

ω - the peripheral speed;

r - the imbalance vector.

The imbalance vector maintains a constant direction and indicates the degree of unbalance of the structure [18]. The corresponding kinetic reaction of the axis of rotation $F_a = -F_c$ during the active phase of rotation pushes the “machine” forward, and during the passive phase, in the opposite direction [6, 20].

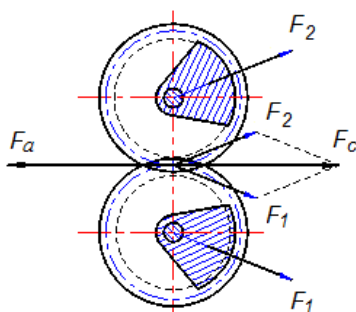


Figure 1. Schematic diagram of a directional vibration exciter: F_1, F_2 - centripetal force of an individual unbalance; F_c - total centripetal force; F_a - kinetic reaction of the axis of rotation.

The vibration frequency is adjusted by the angular velocity ω of the hydraulic motor, allowing for vibration near resonance to be tailored to the type of fruit and tree being harvested. The mass of the rotating weights in the eccentric mechanism can be adjusted by manually adding or removing weights. This allows the vibration to be tailored to the type of fruit and the thickness of the tree trunk.

The machine is controlled via a three-section hydraulic valve, which regulates vibration initiation, required force, and amplitude. The head is equipped with a hydraulic claw that grips tree trunks with a diameter of 0.05-0.22 m at a height of 0.90-1.00 m (Fig. 2). It has an adjustable clamping force to prevent damage to the bark. For additional protection of the trunk, the gripping surface is covered with a cushion (pad) 5 made of rubber or other soft material.

The gripping surface is covered with a soft material for additional tree protection such as rubber or polymer.

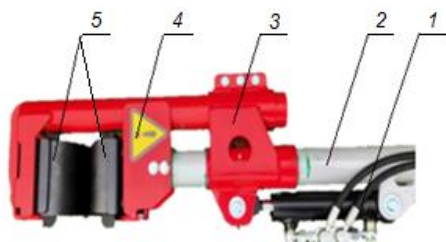


Figure 2. Shaker grip:

- 1 - hydraulic cylinder; 2 - rod; 3 - movable grip part;
4 - fixed grip part; 5 - rubber pad.

The operating principle of the shaking head is as follows: the operator attaches a hydraulic claw to the trunk with a predetermined force. A hydraulic motor is then activated, which drives an eccentric mechanism (unbalanced weights). The vibrations are transmitted through rod 2 to the tree trunk, causing uniform shaking of the branches of the tree (Fig. 2) [16, 17].

Results and discussions

The walnut harvesting process involves detaching the fruit from the stalk due to vibrations transmitted from the source to the trunk, branches, and ultimately, the fruit. These vibrations are beneficial for the harvesting process.

At the same time, vibrations transmitted to the frame and through it to the operator are harmful, as they are unwanted and hazardous to human health. Combating these vibrations improves working conditions for workers and extends the life of agricultural machinery.

The study of the issue of industrial vibrations allowed us to identify the following criteria for classifying vibrations that affect humans [9, 10]:

1. By duration of action: permanent and non-permanent.

2. Based on the method of transmission to humans, a distinction is made between: general vibrations and local vibrations that are transmitted through the worker's hands.

3. By direction of action, depending on the direction of the coordinate axes: parallel to the axis of the vibration source and perpendicular to the body's supporting surfaces at the points of contact with the seat or floor.

4. By vibration frequency type and magnitude:

- 1) low-frequency (1-4 Hz for general vibrations, 8-16 Hz for local vibrations);

- 2) medium-frequency (8-16 Hz for general vibrations, 31.5-63.0 Hz for local vibrations);

- 3) high-frequency (31.5-63.0 Hz for general vibrations, 125-1000 Hz for local vibrations);

5. By the method of impact on the tree: trunk vibration and branch vibration.

6. By drive design:

- mechanically driven (via cardan shaft);
- hydraulically driven (from a hydraulic motor).

A review of technical literature on the operation of the Gacek fruit harvester revealed that the vibration frequency of the harvester shaker is adjustable by the operator within a range of 15-40 Hz. However, the main harvesting of fruits from trees occurs at an operating frequency of 15-30 Hz. The specified frequency range is selected experimentally depending on the ripeness of the fruit and the rigidity of the tree's skeletal branches. These vibration values coincide with the operator's natural frequency (response occurs), which is very dangerous for the worker's health.

To combat harmful vibrations, especially those generated by the studied harvester, the following organizational measures are proposed:

- Limiting the time of continuous operation of the shaker, introducing 10-minute breaks for every hour of operator work;
- Rotating workers during the shift to avoid prolonged exposure to vibrations;
- Adjusting the shaker's oscillation frequency strictly to the physical parameters of the tree, which requires shaking walnut trees of the same diameter.

Necessary technical measures include:

- Use protective covers made of vibration-damping materials (rubber pads) for the shaking head handle;
- Install damping devices (Fig. 3), one of the most effective ways to combat harmful vibration arising.

Thus, when operating a nut harvesting machine, elastic systems such as damping devices are used, which allow the energy received from vibration sources to be dissipated.

To determine how effectively damping devices reduce vibration, it is necessary to determine the vibration (force) transfer coefficient k_F . It is calculated as the ratio of the force F_{t0} transmitted to the tree to the force F_0 generated by the vibration source [18]:

$$k_F = \frac{F_{t0}}{F_0} \quad (3)$$

where: k_F - force transfer coefficient;

F_{t0} - force transmitted to the tree;

F_0 - force from rotating imbalances.

$$k_F = \frac{k}{k - m_1 \omega^2} \quad (4)$$

where: k - stiffness of the elastic element;

m - mass of the unbalance weights;

ω - angular velocity of rotation of the unbalance weights.

This formula shows that at $k_F \approx 1$, resonance occurs and force transfer is maximal, while at larger k_F , the force transfer decreases.

In such problems, it's important that force and power “flow” through the system. This is why the force transfer coefficient k_F is so important in shaking systems.

The following conditions are particularly interesting:

- 1) When $k_F < \sqrt{2}$ - the force is transferred almost completely;
- 2) When $k_F > \sqrt{2}$ - vibration isolation begins;
- 3) When $k_F = 1$ or near unity, i.e. with low damping, a high resonant peak appears.

Therefore, when shaking trees, there is always a compromise between a large amplitude at the object and limiting the force transmitted to the support.

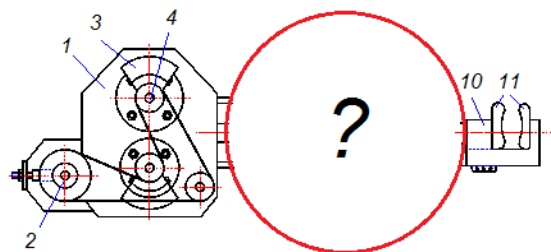


Figure 3. Diagram of a shaking head with a damping device: 1 - shaking head body; 2 - hydraulic motor; 3 - unbalance weights; 4 - shaft; 5-9 - ?; 10 - grippers; 11 - rubber pads.

The installation of a damping device in the design of the Gacek combine harvester shaker is a critical improvement aimed at compliance with occupational safety standards and the prevention of occupational diseases such as operator vibration syndrome.

The proposed design of the shaker damping device is shown in Figure 3. A spring damping mechanism is included in the basic design of the shaking head rod (Fig. 3). This design solution dampens vibrations, reduces pulsation, and softens the return shock transmitted to the operator's hands. The damper's screw mechanism allows for adjusting the spring stiffness, ensuring the most efficient transfer of vibration forces from the unbalance weights 3 to the tree trunk.

Conclusions

1. A study and analysis of the existing Gacek fruit harvester design revealed that the main design flaw is the rigid attachment of the handle to the shaking head housing, which transmits high-frequency vibrations to the operator's hands and organs.

2. A review of technical literature on the operation of the Gacek fruit harvester revealed that the vibration frequency of the harvester shaker is adjustable by the operator within a range of 15-40 Hz. Vibrations in harvesting machines can be beneficial, ensuring a high-quality fruit harvesting process, or harmful to work performance and overall human health.

3. One of the most effective ways to combat harmful vibration is the use of elastic systems (damper devices), which dissipate the energy received from vibration sources. As a result of studying specialized technical literature and theoretical works by scientists researching vibratory shakers for nut harvesting equipment, a prototype design for a shaking head rod with a damper was developed. To determine how effectively damping devices reduce vibration, it is necessary to determine the vibration (force) transfer coefficient k_F . Formula (4) shows that at $k_F \approx 1$, resonance occurs and force transfer is maximal, while at larger k_F , the transfer decreases.

4. Improving the ergonomics of the operator's workplace and working conditions using the proposed design of a shaker with a built-in damper device will increase the productivity of the machine under study when harvesting nut crops.

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Increasing the Durability of Agricultural Working Bodies by Creating Nanostructured Coatings Using Plasma Jet Spraying

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Abstract: The article reveals a new method that relates to the treatment of active surfaces of agricultural working bodies, in particular harrow discs, by applying nanostructured coatings using atmospheric plasma jet spraying (APS). The process consists of preparing the surface by corundum blasting at a pressure of 5.5 bar, followed by preheating to 150°C and depositing a nanostructured powder of the WC-Co 88/12 type.

The technical novelty lies in the synergetic optimization of the deposition parameters: current intensity of 550 A, hydrogen flow rate of 9 L/min, spraying distance of 100 mm and a high scanning speed of 500 mm/s, under forced post-deposition cooling.

The technical result obtained by applying this process consists of creating a protective layer with porosity below 1.2%, adhesion of over 65 MPa and a hardness of 1150-1250 HV0.3, ensuring an increase in the durability of the working element of up to 2.8 times under conditions of severe abrasive wear.

Keywords: DURABILITY, WEAR PERFORMANCE, AGRICULTURAL WORKING TOOLS, PLASMA-JET SPRAYING.

Introduction

Agricultural machinery production is constantly evolving. At the same time, methods and techniques for producing the best parts and working components for performing various mechanized technological operations under challenging conditions are also being refined.

Increasing the durability of agricultural working tools of farming machines, such as plows, harrows, cultivators, seeders, etc. is one of the main problem areas in production of agricultural machinery. As a result of soil cultivation these machines are subject to severe abrasive wear.

Analysis of plasma-jet spraying on the active part of working tools of agricultural machines allows to evaluate the resistance to abrasion and corrosion. So, the use of such working bodies increases productivity, reduces costs and ensures the main good results in modern agriculture [1, 2].

Formulation of the problem

To ensure efficient soil cultivation and improve the quality of technological processes, the working parts of agricultural tillage machines must be highly wear-resistant. However, during soil cultivation, the active elements of all tillage machines (including disc harrows) are often subject to significant wear due to abrasive soil particles.

It should be noted that these working elements must have significant impact resistance [3, 4].

A known process for hardening the working parts of agricultural machinery is the use of traditional material heat treatments (quenching and tempering) applied to 65G steel or boron-alloyed steels, achieving a hardness of approximately 48-52 HRC [5].

The proposed technical solution for hardening the agricultural working parts has several drawbacks:

- 1) limited resistance to severe abrasive wear in heterogeneous soils;
- 2) rapid changes in the geometry of the harrow disc cutting edge;
- 3) the need for frequent replacement of parts, which increases operating costs.

During 2024-2026 it was conducted tests of disc harrows in accordance with the current standards for testing agricultural machinery and their working parts [6, 7, 8]. It means also using of efficient methods to improve needed parameters.

Analysis of recent research and publications

All agricultural working bodies wear out faster as the amount of sand particles in the soil increases, which requires improving the mechanical properties of the surfaces of the processed working elements [3, 4].

That assumes a relationship between the wear of the active area of the working parts of the machine, the size of the sand particles and the optimization of their mechanical properties to increase the wear resistance of the working bodies of agricultural machinery which is crucial for increasing the service life of the active areas [5, 6].

Therefore, the active area of the working bodies, especially of tillage machines must have significant impact resistance [1, 4, 6]. It means using effective methods to improve the parameters of the active surface of the working bodies of agricultural machinery, and subsequently conducting tests of these machines in accordance with current standards for testing.

Plasma-jet thermal spray deposition is one of the effective methods for improving the main parameters of the working elements material of machines for farming, considered an advanced method capable to achieve high-quality surface depositions [5, 7].

Currently, the application of this method is generally limited to coatings up to 100 μm [8, 9].

Another process of thermal spraying deposition in atmospheric plasma jet (APS) of tungsten carbide (WC-Co) or ceramic mixtures (Cr₂O₃-SiO₂-TiO₂) powders is known, using standard operating parameters according to the technical data sheets of powder manufacturers, [1, 7, 10].

To improve the microstructural and tribological properties of coatings on the active areas of studied harrow discs and the quality of the agricultural working bodies, three types of coatings were applied to the active areas of the discs [7, 8]:

- W₂C/WC12Co (Metco71NS);
- Cr₂O₃-4SiO₂-3TiO (Metco136F);
- Co25.5Cr10.5Ni7.5W0.5C (Metco45CNS).



Figure 1. Atmospheric plasma jet thermal spraying coating process

Experimental coatings on harrow discs were applied using a Sulzer Metco 9MCE deposition system operating on Ar (5.3 bar, 45 NL/min) and H₂ (3.5 bar, 7.0 NL/min).

After mechanical grinding and intensive sandblasting, samples with thermally applied APS were tested on the active areas of the harrow discs of the working parts of agricultural disc harrows.

The experimental setup for the study included a rotating support, an automated arm connected to a Sulzer 9MB sprayer, and a sample holder (Fig. 1).

In order to determine the main parameters of the material of the studied coatings obtained by thermal spraying with an atmospheric plasma jet, such as adhesion to the substrate, coefficient of friction (COF), Young's modulus (modulus of elasticity), rigidity (stiffness) and hardness a tribological analysis was carried out.

Tribological tests were held by a group of researchers from the Technical University of Moldova (Republic of Moldova) and the Technical University "Gheorghe Asachi", Iasi (Romania) in a specialized laboratory of the Technical University "Gheorghe Asachi", Iasi, Romania (Fig. 2).



Figure 2. Conducting tribological tests in the laboratory of Technical University „Gheorghe Asachi”, Iasi, Romania

In these conventional solutions, the thermal regime is optimized for general depositions, without taking into account the specifics of abrasive stresses in heterogeneous agricultural soils.

The technical solution presented has the disadvantage that standard sputtering processes (characterized by low scanning speeds of 200-300 mm/s and large sputtering distances of over 120 mm) often lead to thermal degradation of carbides through the decarburization phenomenon [5, 7].

During the flight of particles in the plasma jet with temperatures exceeding 10,000 K, the hard WC (tungsten carbide) phase decomposes into more brittle and less hard phases, such as W₂C or metallic tungsten. This chemical and structural transformation process results in a layer with high porosity (above 2-3%) and a coarse microstructure.

Excessive porosity allows moisture and acids from the soil to penetrate, leading to corrosion of the interface between the layer and the substrate, which causes premature exfoliation of the coating. Also, structural degradation limits the hardness of the layer below the threshold of 1000 HV, an insufficient value to ensure long-term protection against silica (quartz) fractions present in the soil, which have a comparable or higher hardness.

The purpose of the innovation is to increase the durability and resistance to abrasive wear of agricultural working bodies by creating a coating with a nanometric, dense and ultra-hard structure, without affecting the mechanical properties of the metal substrate.

Results and discussion

The stated problem is solved by using plasma-jet spraying to produce a nanostructured coating, which involves strict heat transfer control using a current of 550 A, a hydrogen flow rate of 9 L/min and a high scanning speed of 500 mm/s at a distance of 100 mm.

This ensures a particle temperature sufficient to melt the binder phase without degradation of the nanometric carbide cores, resulting in a layer with a porosity of less than 1.2% and a hardness exceeding 1150 HV0.3.

The essence of the innovation consists in solving the problem of increasing durability of active areas of agricultural working bodies by applying a well-studied technological regime that allows preserving the nanometric structure of the WC-Co powder (type Metco 71NS or similar) in the deposited layer.

The technical result is that the process of producing nanostructured coatings by plasma jet spraying to increase the durability of agricultural working elements ensures obtaining a hardness of 1150-1250 HV0.3, 20-30% higher than standard methods, reducing the porosity of the layer below 1.2-1.5%, preventing the infiltration of corrosive agents from the soil and increasing the service life of metal working elements by up to 3 times in abrasive soil conditions.

The peculiarities of the process of making nanostructured coatings are ensured by a researched technological regime and can be applied by selecting as the base material a working element with a metallic surface (disks, cutters, knives, blades) made of boron alloyed steel (27MnCrB5) or spring steel (65G), having a thickness of 4-6 mm.

The actual deposition is performed using an atmospheric plasma spraying installation, fed with a nanostructured powder of the WC-Co 88/12 type (cobalt cemented tungsten carbides), with an average carbide crystallite size below 500 nm.

The working parameters used to obtain the nanometric structure are:

- electric current intensity: 550 A;
- arc voltage: 65-70 V;
- primary plasma gas flow rate (Argon): 45 L/min;
- secondary plasma gas flow rate (Hydrogen): 9 L/min;
- spraying distance: 100 mm;
- torch scanning speed: 500 mm/s.

By applying this process, a protective layer with a thickness of 250-300 µm is obtained, characterized by a porosity of 1.1% and an average microhardness of 1210 HV0.3. Laboratory tests (according to ASTM G65 standard) have demonstrated a reduction in mass loss through abrasive wear of 2.8 times compared to untreated discs and an increase in the adhesion of the layer to the support of up to 68 MPa.

Further research

Further research into ways to increase the durability of agricultural machinery by creating nanostructured coatings using plasma jet spraying relates to substantiating the application modes and parameters for APS coatings and conducting further experiments directly related to the working parts of transplanting machines and seeders [11, 12, 13].

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Conclusions

1. Morphological analysis of the studied coatings W₂C/WC12Co (Metco71NS), Cr₂O₃-4SiO₂-3TiO (Metco136F) and Co25.5Cr10.5Ni7.5W0.5C (Metco45C-NS), applied to the active surface of harrow disks using the atmospheric plasma spraying method, revealed shortcomings that allowed us to draw conclusions regarding the spraying process and methods for improving operating parameters.

2. A study of coated samples followed by tribological analysis of surface scratches on three groups of samples revealed shortcomings and next steps for improving the atmospheric plasma spray (APS) thermal deposition process.

3. The features of the process of manufacturing nanostructured coatings are provided by the studied technological regime and can be implemented by choosing as the main material of the working element with a metal surface (discs, cutting elements, knives) on such agricultural machines as plows, scarifiers, disc harrows, seeders, transplanting machines, etc. made of boron-alloyed steel (27MnCrB5) or spring steel (65G) with a thickness of 4-6 mm.

4. Excessive porosity of the coatings obtained using the studied APS modes allows moisture and acids from the soil to penetrate inside, causing corrosion of the interface between the layer and the substrate, which leads to premature delamination of this coating. Also, structural degradation limits the layer hardness below the threshold of 1000 HV, which is insufficient to provide long-term protection against silica fractions present in the soil, that have comparable or higher hardness.

5. The innovative proposal involves the actual deposition being carried out using an atmospheric plasma spraying unit, into which nanostructured powder of the WC-Co 88/12 type (tungsten carbides bonded with cobalt) with an average carbide crystallite size of less than 500 nm is fed.

6. The operating parameters and modes of the system used to produce the nanometric structure are as follows:

- Electric current: 550 A;
- Arc voltage: 65-70 V;
- Primary plasma gas flow rate (argon): 45 l/min;
- Secondary plasma gas flow rate (hydrogen): 9 l/min;
- Spray distance: 100 mm and torch scanning speed: 500 mm/s.

7. By applying the proposed process of atmospheric plasma spray thermal deposition, a protective layer with a thickness of 250-300 µm is obtained, characterized by a porosity of 1.1% and an average microhardness of 1210 HV0.3.

8. Theoretical studies and laboratory tests (in accordance with the ASTM G65 standard) have shown a reduction in mass loss due to abrasive wear by 2.8 times compared to untreated discs and an increase in layer adhesion to the substrate to 68 MPa.

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Symmetry-Reduced Optimal Control of Quadrotor Dynamics via Noether's Theorem

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Abstract: Modern quadrotor unmanned aerial vehicles (UAVs) rely extensively on numerical trajectory optimization and path-planning algorithms for navigation in complex environments. While these approaches emphasize feasibility, collision avoidance, and control constraints, they often overlook underlying physical symmetries in the governing dynamics, leading to redundant computations and underutilization of system structure. This work introduces a symmetry-aware trajectory optimization framework that leverages principles from classical mechanics, specifically Noether's theorem, to exploit the rotational invariance of quadrotor dynamics about the yaw axis. By treating yaw as a cyclic coordinate in the Lagrangian formulation, a conserved quantity corresponding to angular momentum about the inertial vertical axis is derived and enforced as a constraint using Noether's theorem. This eliminates redundant yaw dynamics and replaces them with an algebraic conservation law, yielding a reduced-order model that preserves the essential nonlinear behavior of the system. To evaluate the proposed framework, physics-based models are implemented using CasADi, where both full-order and symmetry-reduced models are formulated as nonlinear optimal control problems, which are then solved using the Acados multiple shooting OCP solver. CasADi is then used for solution verification against physical constraints. A multi-objective cost function is considered, incorporating energy expenditure, control effort, and total travel time. Comparative analyses are performed to assess solution quality and computational efficiency across both formulations versus existing solutions. Comparative results indicate that the proposed framework achieves improved computational efficiency relative to conventional formulations, operating within modest memory requirements of approximately 1-2 GB of RAM. In addition to these results, the symmetry-reduced model is expected to improve algorithmic speed by reducing system dimensionality and eliminating redundant dynamics. A practical consideration of the proposed framework is that representing yaw as a cyclic coordinate reduces direct control over heading, making the approach most suitable for scenarios where yaw tracking is not a primary requirement. Extensions of the framework could incorporate hybrid strategies to accommodate applications requiring explicit heading control.

KEYWORDS: NOETHER'S THEOREM, SYMMETRY REDUCTION, LAGRANGIAN DYNAMICS, OPTIMIZATION, CONSERVATION LAWS

An algorithm for the automatic categorization of SVG wallpapers into plane crystallographic groups

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Abstract: Wallpapers are 2-dimensional images that repeat in two directions, classified into 17 groups by the symmetries they have: namely rotational, glide, and reflectional symmetries. Most algorithms to classify wallpapers into groups require complex image processing, making them computationally expensive and reducing their reliability. This project aims to use the Scalable Vector Graphics (SVG) standard to make a faster and more reliable algorithm for identifying wallpaper groups. The algorithm first organizes the wallpaper groups into binary decision trees based on their common symmetries, then descends one of the trees by eliminating possible groups until a single group remains. Because of the SVG standard's simplicity relative to raster image formats, being that it represents images using shapes and curves instead of pixels, the new algorithm is expected to run faster than alternative solutions, especially with less complex wallpapers.

KEYWORDS: CRYSTALLOGRAPHY, GROUP THEORY, PLANE CRYSTALLOGRAPHIC GROUPS, AD-HOC ALGORITHM, SCALABLE VECTOR GRAPHICS