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C O N T E N T S

INNOVATION POLICY AND INNOVATION MANAGEMENT

Beyond Traditional Healthcare: The Expanding Role of eHealth and Telemedicine in the Digital Era Martin Čillík, Ivan Kuric, Miriam Kuricová	44
Application of Artificial Intelligence in Mechanical Engineering Mechanics and Fracture Mechanics with an Overview of ANSYS SimAI Platform Pejo Konjatić, Ana Konjatić, Željko Blavicki, Mato Jakus	53

INNOVATIVE SOLUTIONS

Vibration-Based Monitoring of DMLS Ti-6Al-4V Micro-Milling Michal Demko, Marek Vrabel', Jozef Brindza, Ján Kušnir, Mario Semkov, Mihail Zagorski	58
Synchronous Electric Motor with Permanent Rare Earth Magnets and with Increased Power Georgy Drensky, Nikolay Pavlov, Mirosława Yotova, Milen Peev, Georgy Parvanov, A. Stefanov	62
A Comparative Analysis of the Main Methods of 3D Steganography Veselka Stoyanova, Veselina Gagamova	65
Design, Implementation, and Performance Analysis of a Single-Pole Dual-Axis Solar Tracking System for Photovoltaic Energy Improvement Shpetim Lajqi, Zgjim Guraziu	68
Dimensional limitations in the manufacture of tubular filter elements from flat porous powder blanks Aliaksandr Ilyushchanka, Iryna Charniak, Aliaksei Kusin, Anastasia Astapenka, Margaruta Kuntsevich, Ruslan Kusin ...	74
Biogas production from alcoholic stillage Ivan Angelov, Venko Beschkov, Stefan Stefanov	77
Antimicrobial activity of aqueous-alcoholic extracts of waste materials from red sweet pepper, red hot pepper and eggplant against spoilage microorganisms. Part 2 Petar Gatev, Naiden Delchev	80
Advanced metal additive manufacturing using xBeam 3D metal printing technology: processing, microstructure, mechanical performance and emerging applications Nevmerzhytskyi Vasyl, Kovalchuk Dmytro, Stasiuk Oleksandr, Tretiakov Leontii, Taran Serhii	83
Improving the Design and Working Process of a Nut Harvester Shaker Costantin Zîrnescu, Vasile Pavliuc	89

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]

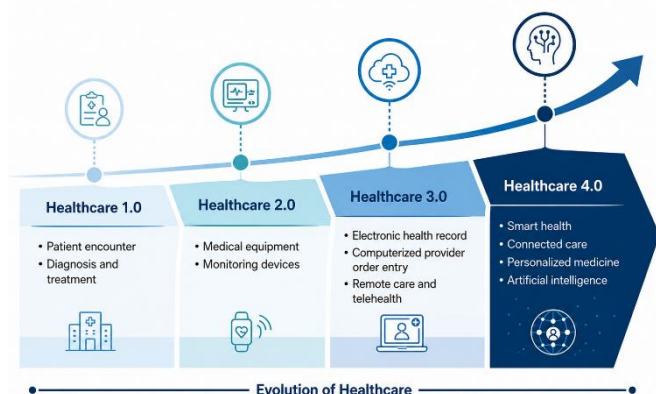


Fig. 1 Revolution of Health Care from Health Care 1.0 to Health Care 4. [7]

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]

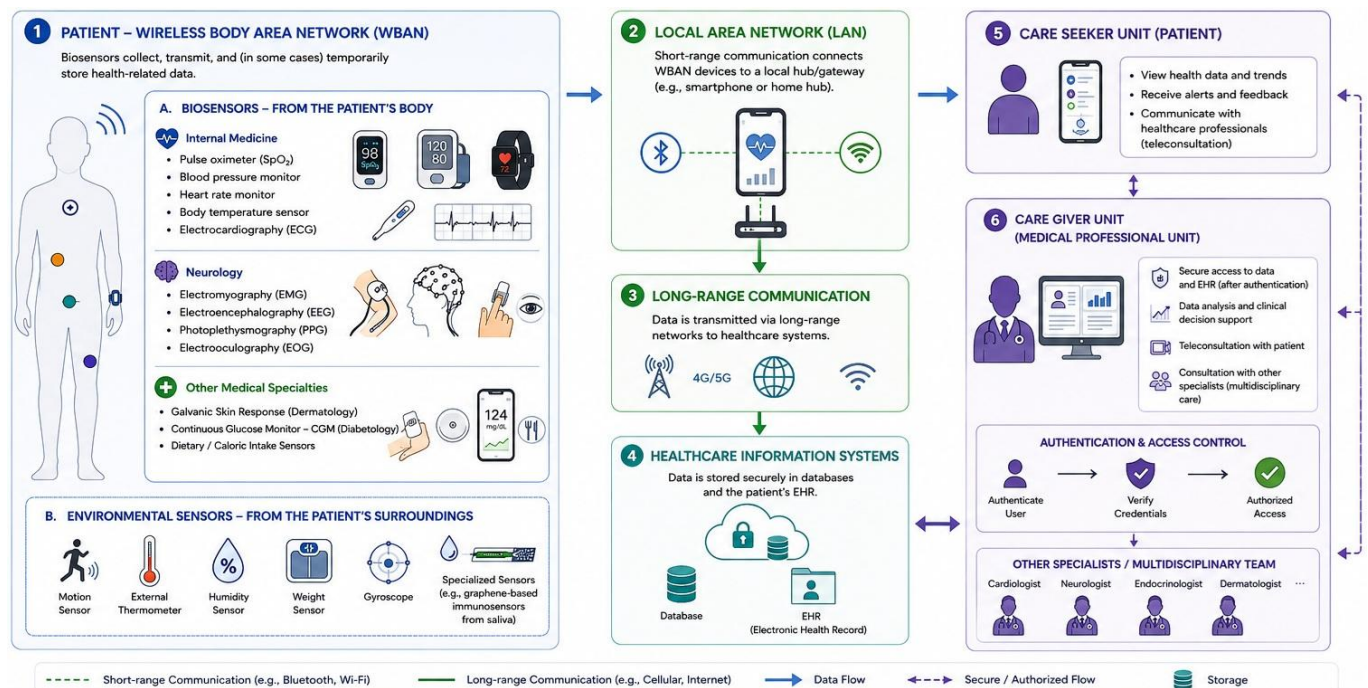


Fig. 2 Operational scheme of patient-based telemedicine systems integrated with the patient's EHR and hospital information systems as a unified ecosystem [27, 32]

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]

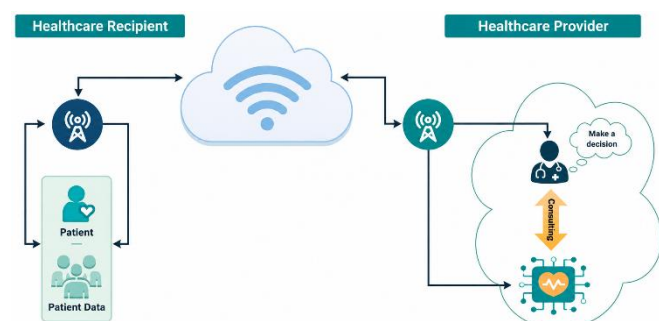


Fig. 3 CDSS using AI and its role in supporting clinical decision-making [36]

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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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].

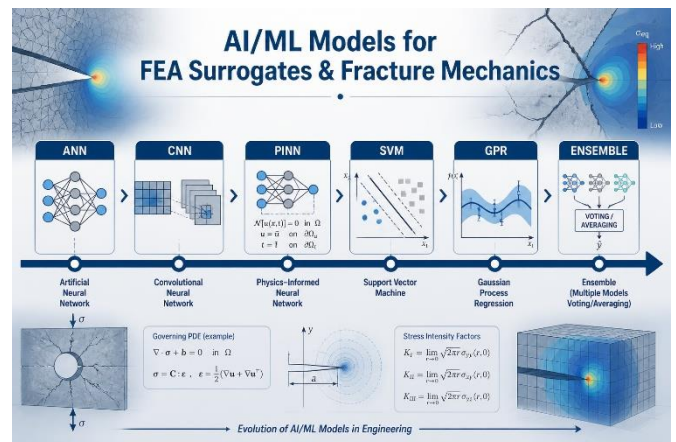


Fig. 1 Development of AI/ML models for approximation in engineering and fracture mechanics

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.

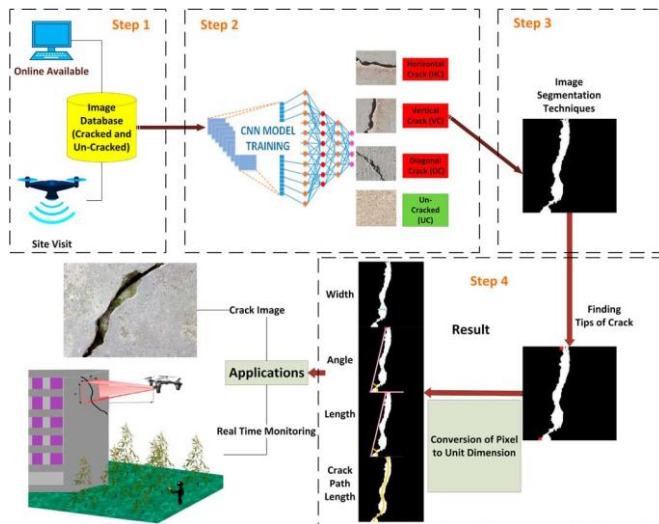


Fig. 2 Workflow diagram of a CNN for crack detection [18]

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.

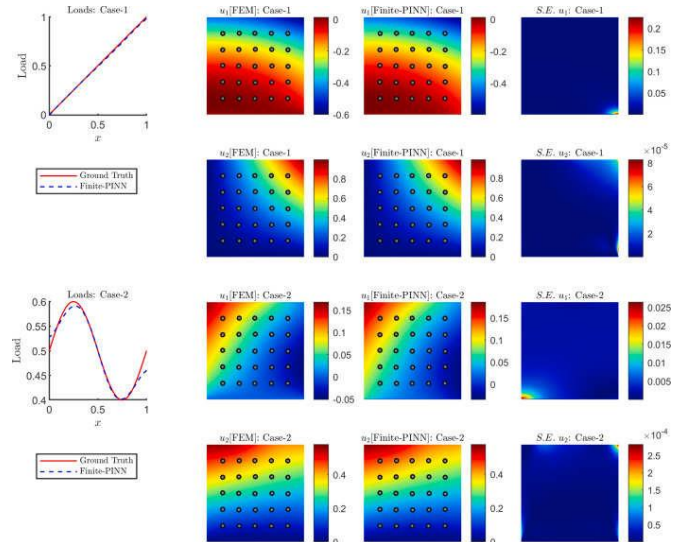


Fig. 3 Finite-PINN mesh-free simulation of solid deformation: heat-map comparison and accuracy analysis [20]

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.

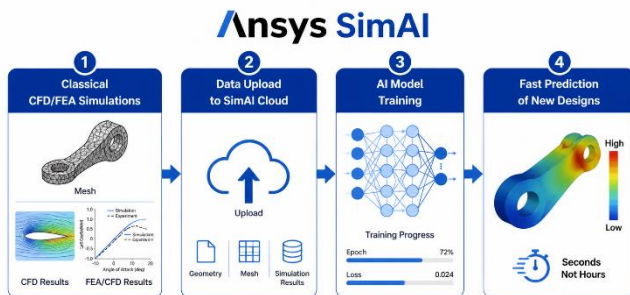


Fig. 3 SimAI workflow diagram

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.

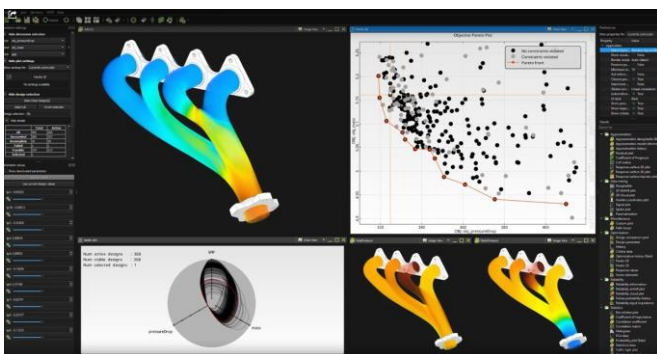


Fig. 4 Example of design-space exploration

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.

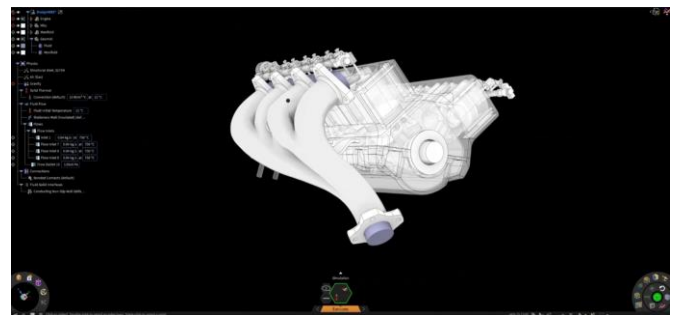


Fig. 5 SimAI user interface display

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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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.

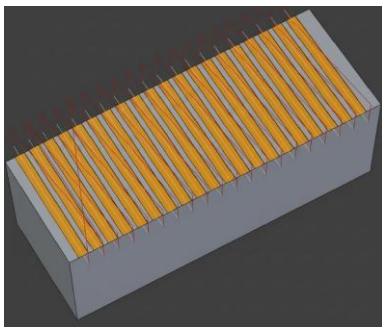


Fig. 1 Programmed toolpath

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.

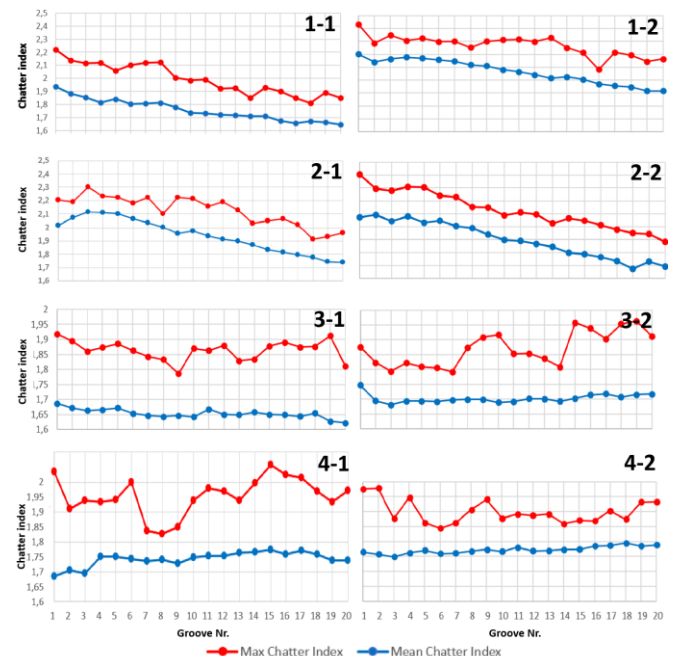


Fig. 2 Chatter index trends for all tested samples

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.

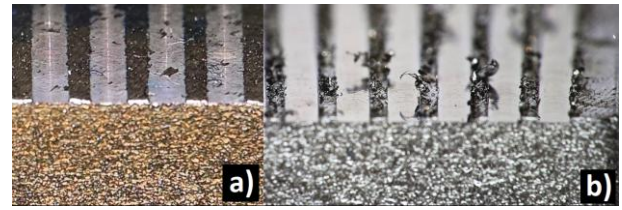


Fig. 3 Comparison of burr on annealed and non-annealed sample

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.

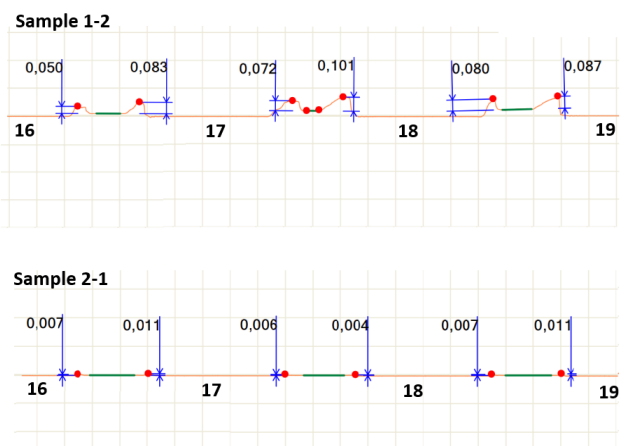


Fig. 5 Representative profilometric comparison of burr height

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

This work was supported by the Slovak Research and Development Agency projects APVV SK-BG-23-0020 / № КІР-06 Словакия/6 "Intelligent Quality Systems for Flawless Production of Critical Machined Parts" and APVV SK-HU-24-0036 "Industry 4.0 based control of machining process in cutting of difficult-to-cut materials."

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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.

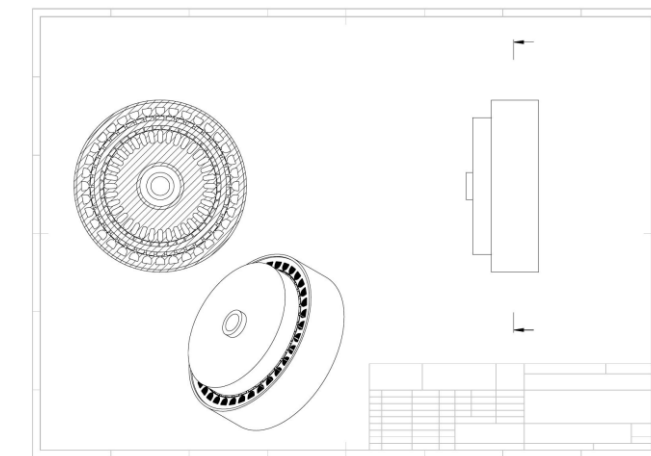


Fig. 1 A diagram of the electric motor with permanent rare earth magnets and increased power.

4. Experimental upgarde, 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.

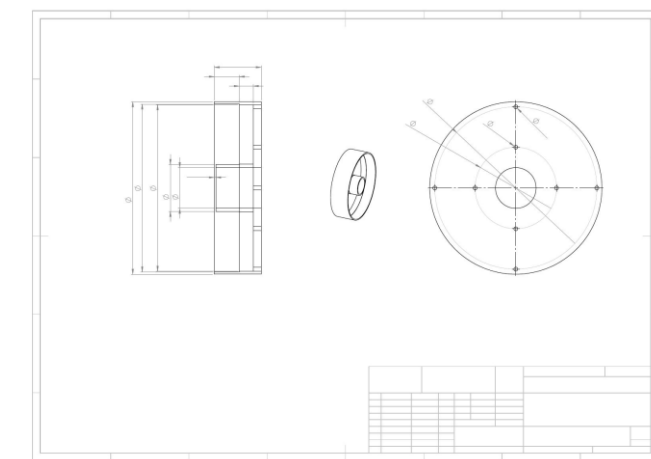


Fig. 2 A diagram of the corpus electric motor with permanent rare earth magnets and increased power.

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 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 STEGANOGRAPY, 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.

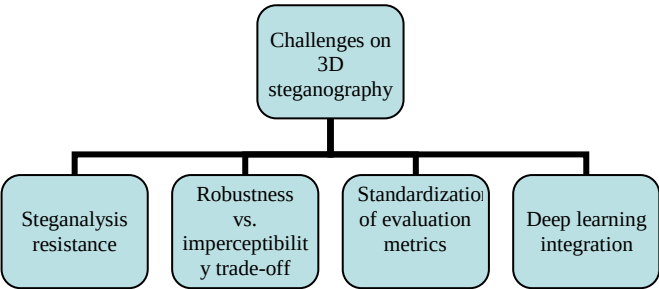


Fig. 1 Challenges on 3D steganography

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.

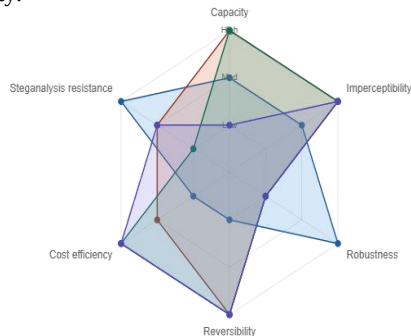


Fig.2. Performance evaluation by criterion

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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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].

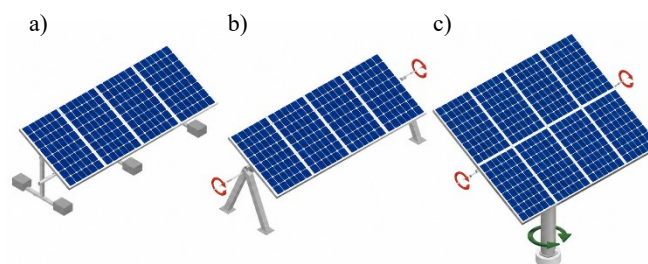


Fig. 1 Types of solar module installations: a) static (fixed) configurations; b) single-axis configurations and c) dual-axis configuration.

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.

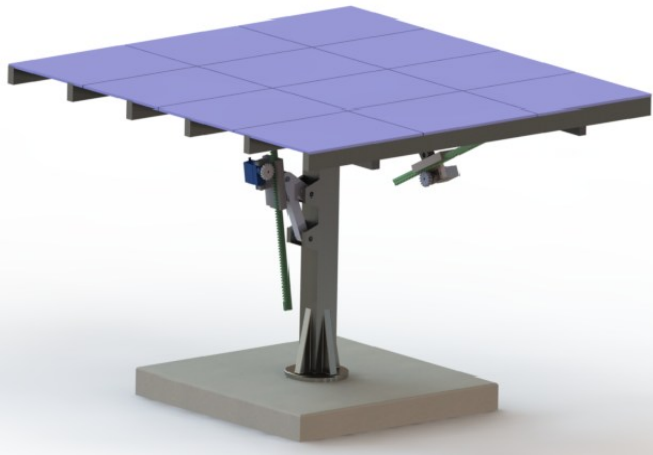


Fig. 3 3D CAD model of the single-pole dual-axis tracking system

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.

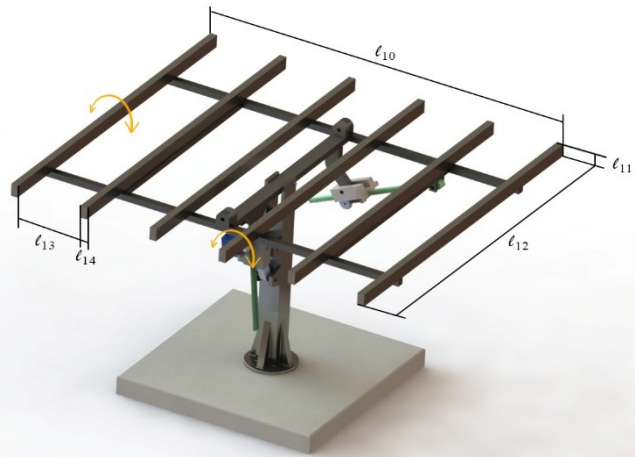


Fig. 4 Mechanical assembly decomposition of the tracking system

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.

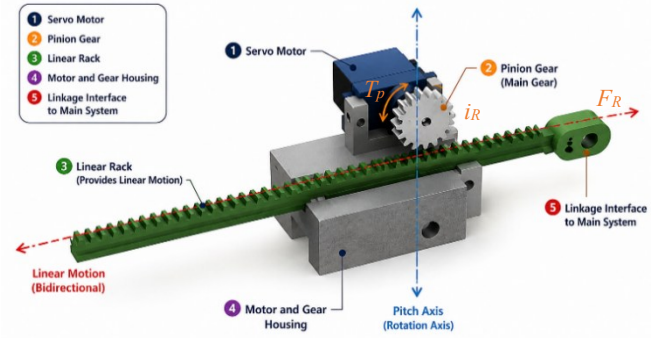


Fig. 5 Rack-and-pinion actuation mechanism driven by a Servo Motor

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)

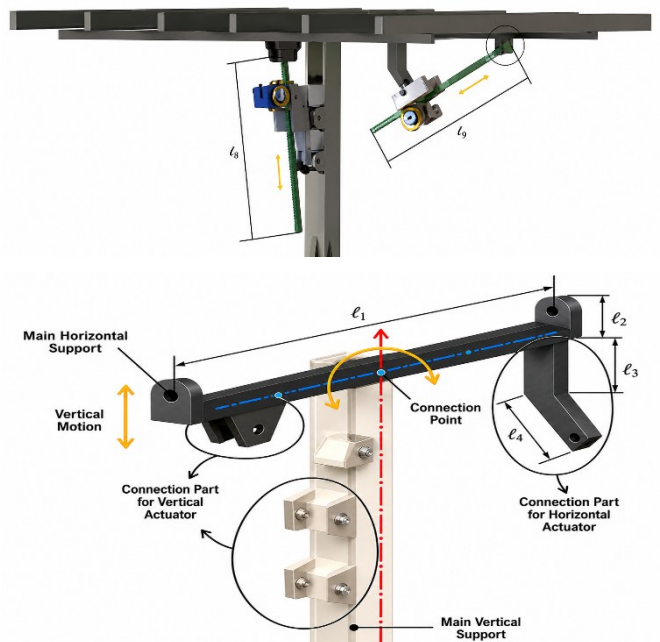
a [m/s²] – acceleration to which the system is subjected

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.



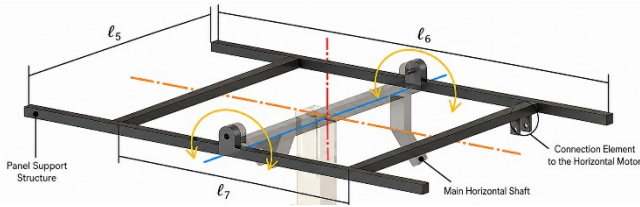


Fig. 6 Mechanism for single-pole dual-axis tracking system

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.

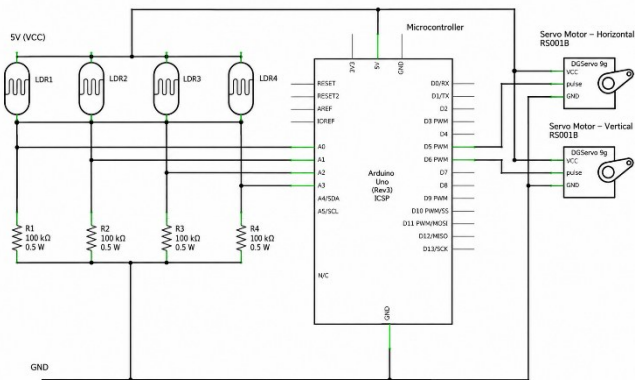


Fig. 7 Circuit diagram of the Arduino-based dual-axis solar tracking system using LDR sensors and servo motors

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.

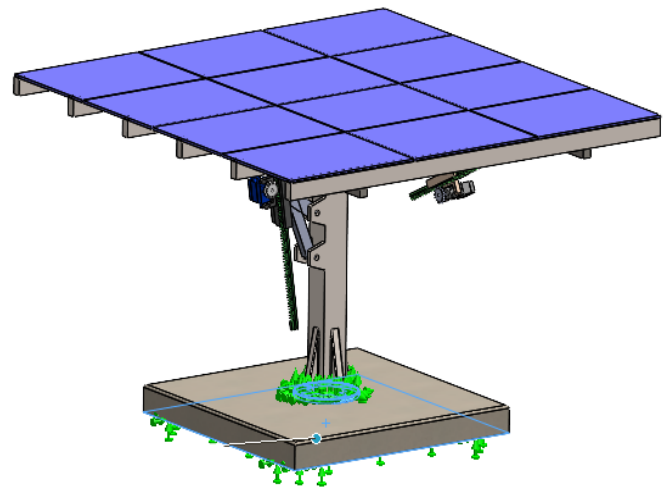


Fig. 8 Fixed boundary conditions of the structure

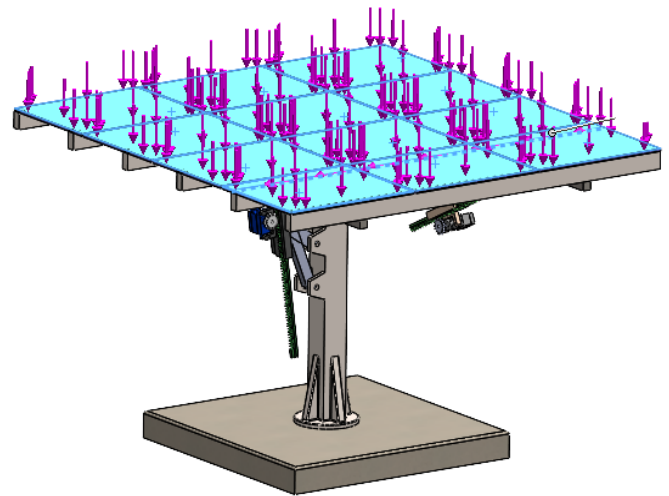


Fig. 9 Applied load distribution

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.

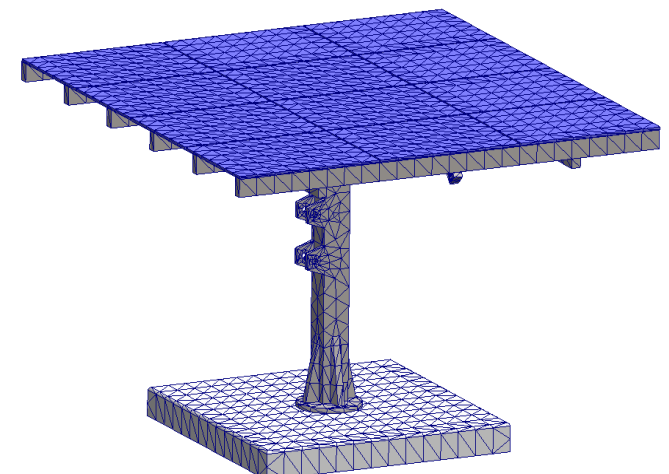


Fig. 10 Finite element mesh model

3.3. Simulation Results

Stress distribution results are presented in Figure 11, showing that maximum stress values remain within safe material limits.

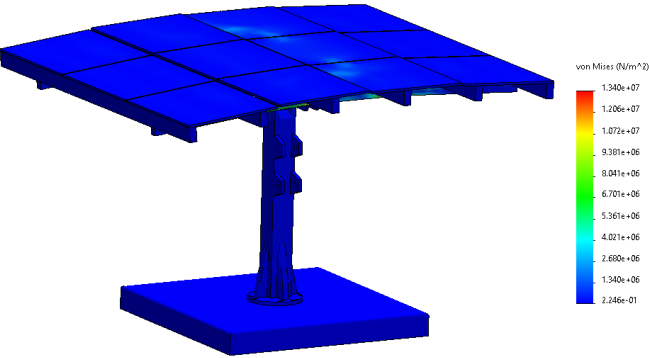


Fig. 11 Von Mises stress distribution

Structural displacement is illustrated in Figure 12, indicating minimal deformation under applied loads.

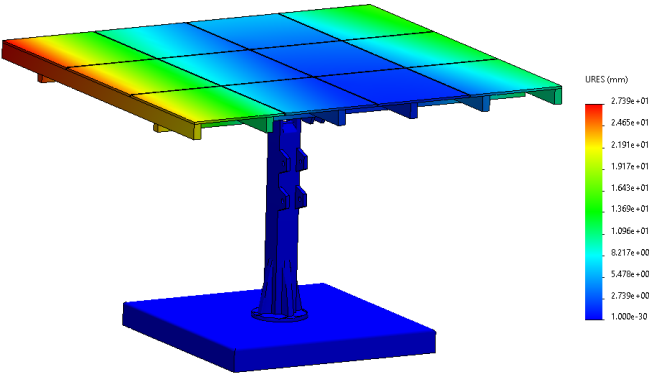


Fig. 12 Displacement contour results

Strain distribution is shown in Figure 13, confirming structural stability under operational conditions.

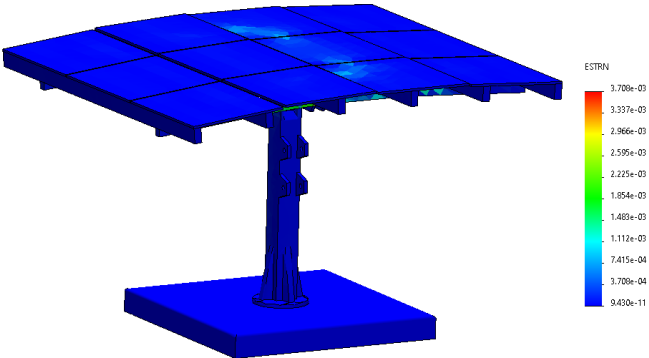


Fig. 13 Equivalent strain analysis

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 m²
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.

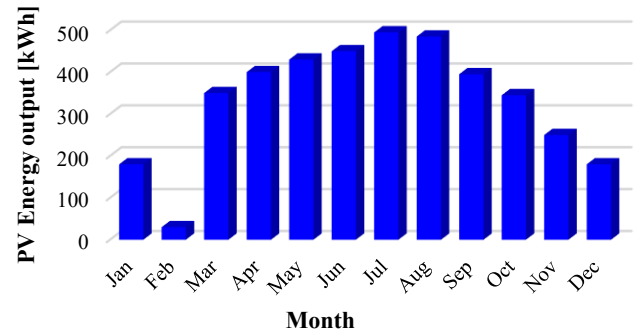


Fig. 18 Monthly energy production (fixed system) from 3240 Wp

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.

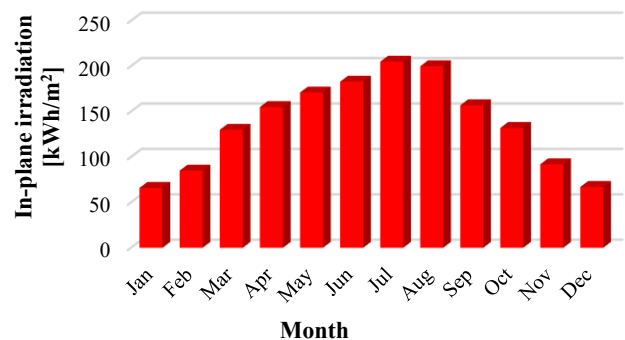


Fig. 19 Monthly in-plane solar irradiation incident on the photovoltaic array (fixed system)

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.

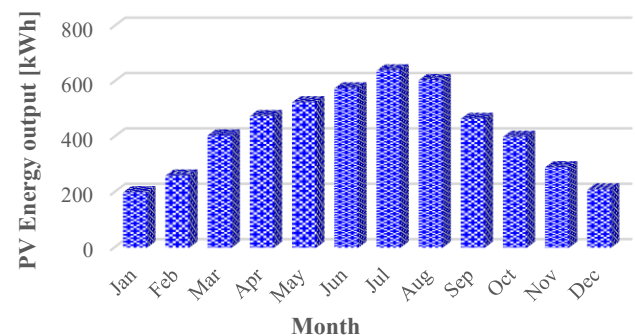


Fig. 20 Monthly energy production (dual-axis tracking system) from 3240 Wp

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.

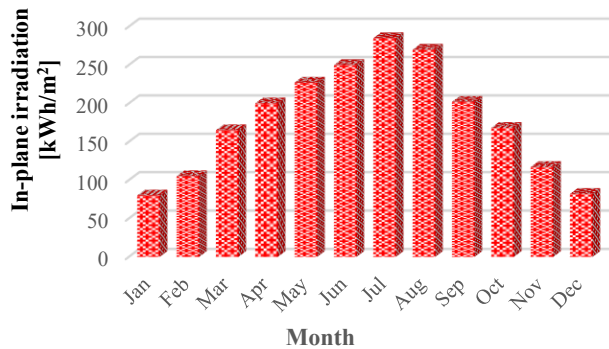


Fig. 21 Monthly in-plane solar irradiation incident on the photovoltaic array (dual-axis tracking system)

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.

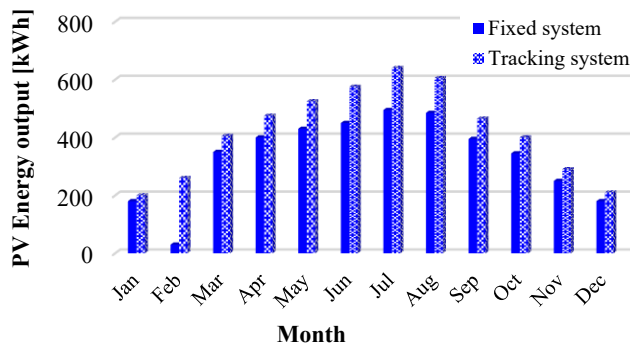


Fig. 22 Energy production comparison between fixed and tracking system

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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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.

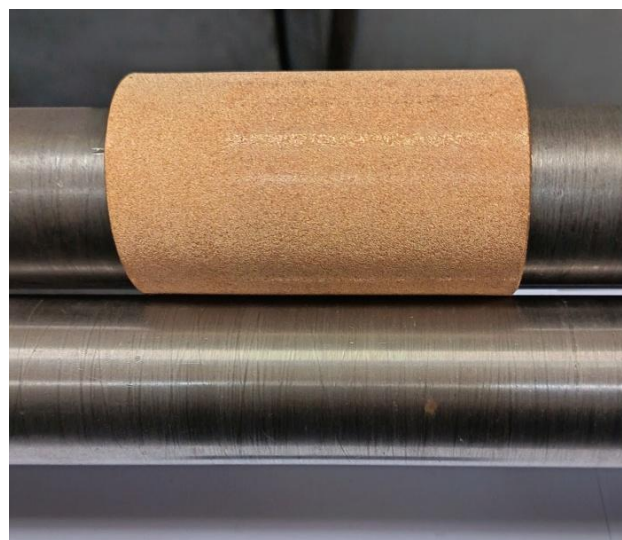


Fig. 1 The process of rolling a flat (sheet) porous blank based on tin-phosphorous bronze powder on rollers.



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).

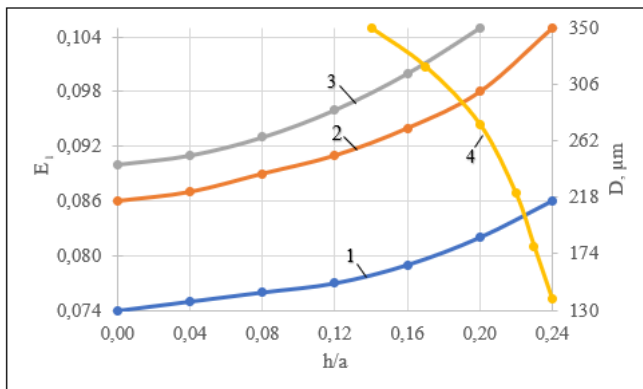


Fig. 3 Efficiency parameter dependences on the ratio of sample thickness to bending radius for three powder fractions: (minus 160 + 125) μm (1), (minus 315 + 250) μm (2) and (minus 400 + 315) μm (3) and ratio critical values of sample thickness to bending radius, at which the cracking process begins, 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.

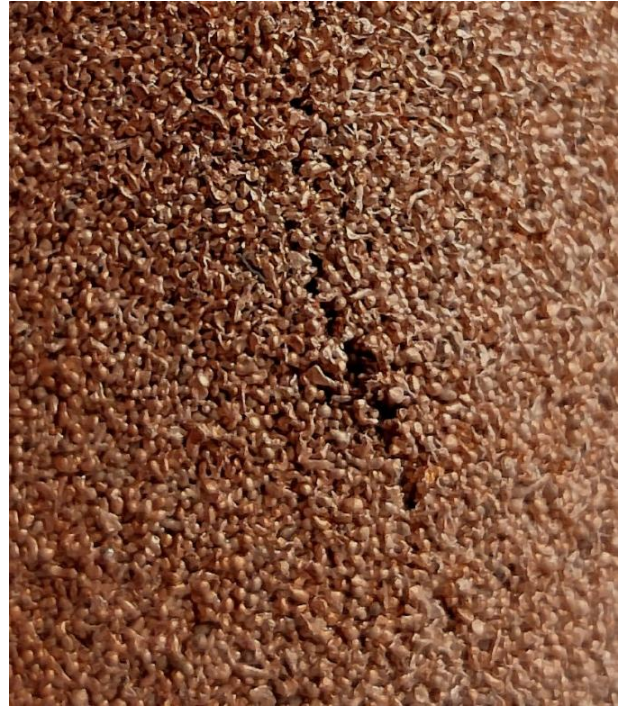


Fig. 4 Initial stage of crack formation on the outer surface of a curved sample.

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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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).

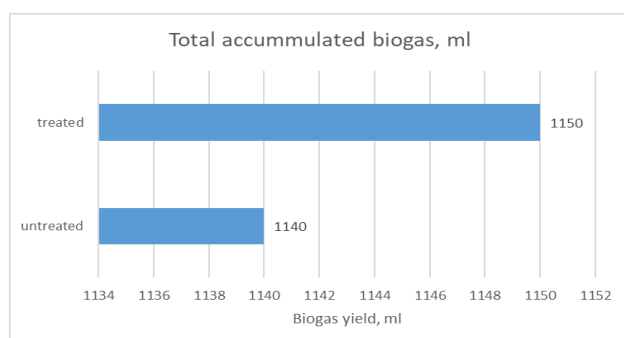


Fig.2 Total biogas yield comparison

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.

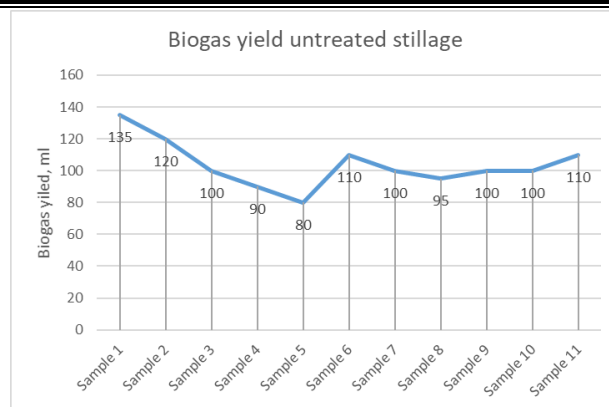


Fig.3 Biogas yield Experiment 1 untreated stillage

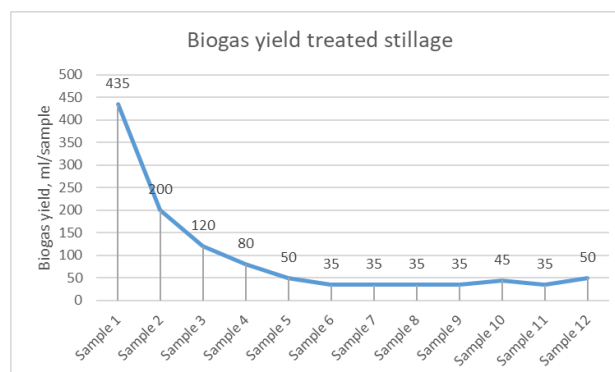


Fig.4 Biogas yield Experiment 2 treated stillage

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.

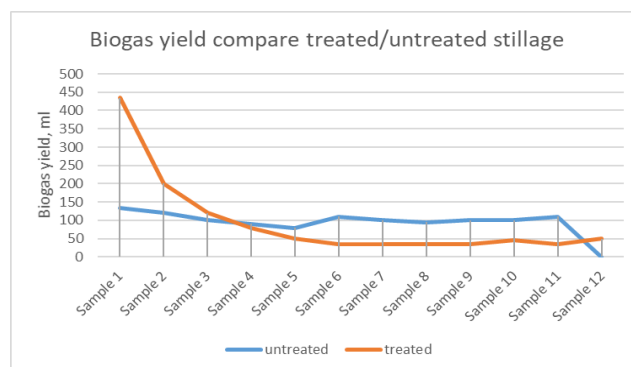


Fig.5 Biogas yield comparison between untreated and treated stillage

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.

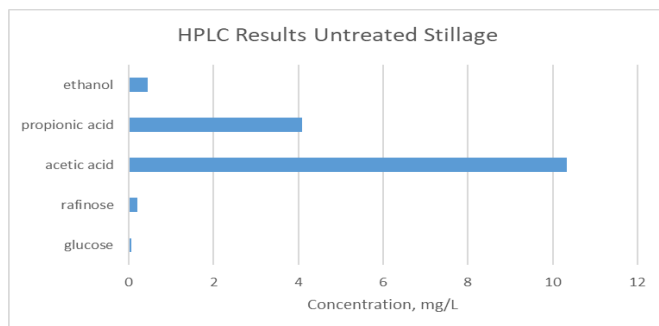


Fig.6 HPLC result Untreated alcoholic stillage

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.

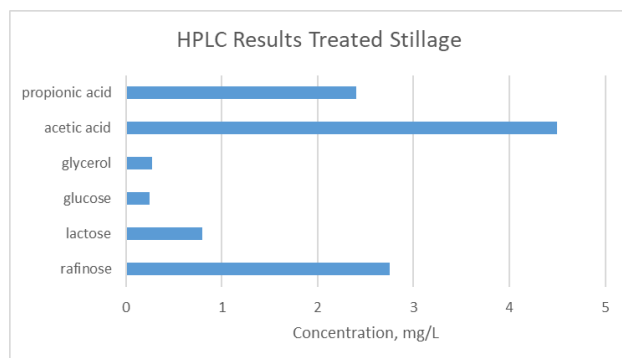


Fig. 7 HPLC result Treated alcoholic stillage

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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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	-	-
20% ethanol; eggplant stems	-	-	-	-	-	-	-	-
40% ethanol; eggplant stems	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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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.

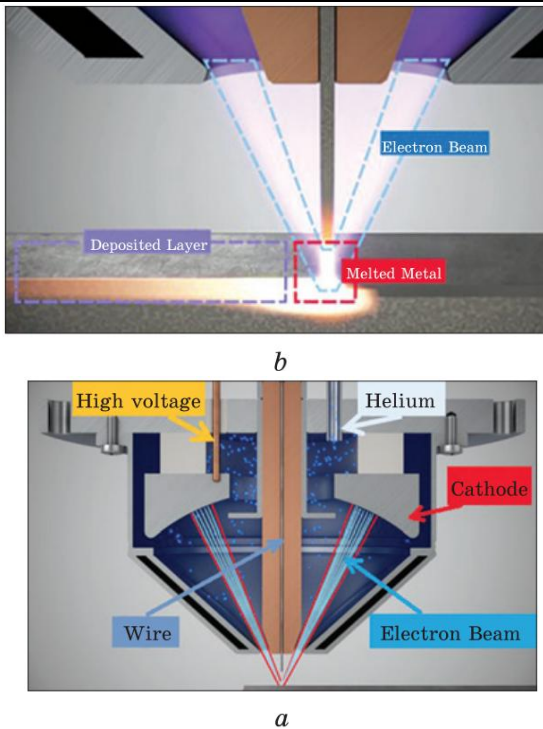


Fig. 1. Principle of xBeam additive manufacturing: (a) schematic arrangement of the coaxial wire-feed deposition process and (b) design of the xGun gas-discharge electron gun generating a hollow conical electron beam [14].

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.

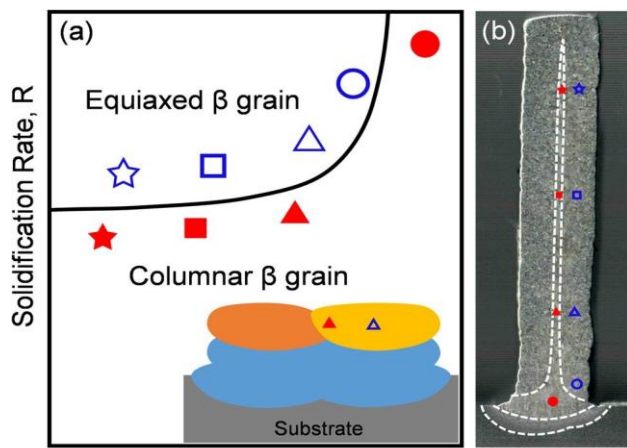


Fig. 2. Ti-6Al-4V solidification map showing the relationship between thermal gradient (G), solidification rate (R), and grain morphology, including the columnar-to-equiaxed transition (CET) boundary [9].

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].

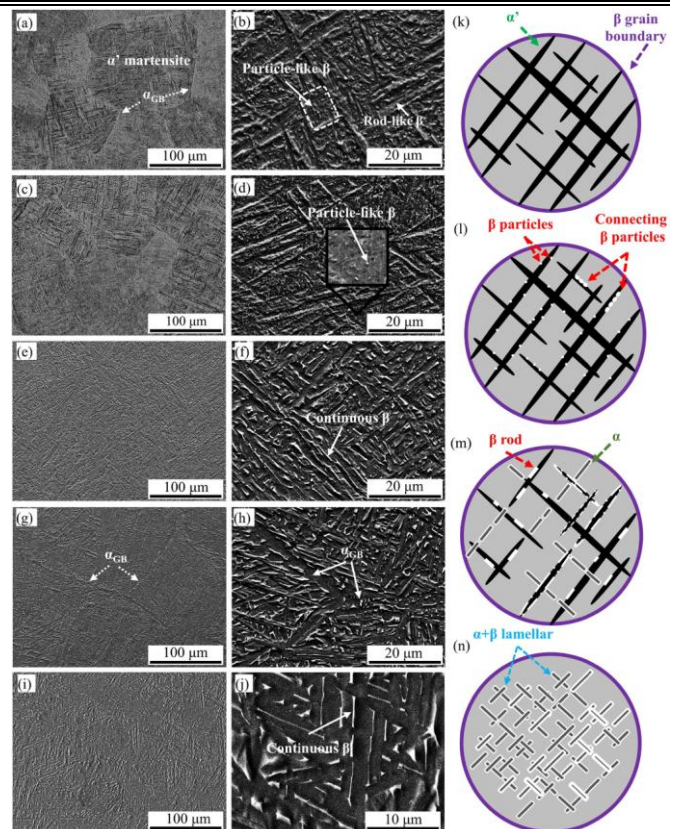


Fig. 3. SEM images of samples annealed at (a, b) 690°C/2 h/FC (HT1), (c, d) 750°C/2 h/FC (HT 2), (e, f) 810°C/2 h/FC (HT3), (g, h) 870°C/2 h/FC (HT4), and (i, j) 900°C/2 h/FC (HT5). The α phase is dark, β phase is bright. (k–n) Schematic diagrams of β phase precipitation during decomposition of α' martensite 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 α + β 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.

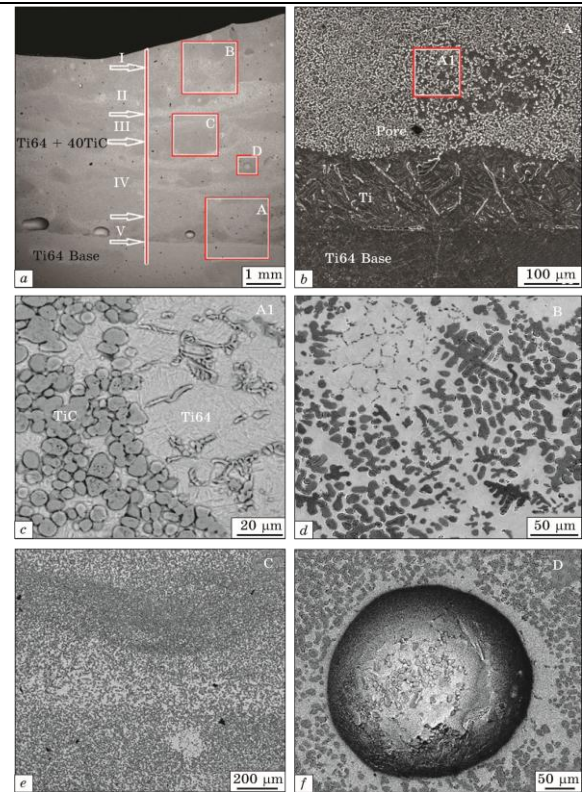


Fig. 4. SEM micrographs showing the morphology and distribution of endogenous TiC particles formed during fabrication of Ti-6Al-4V + 40%TiC metal matrix composites using cored-wire xBeam deposition: (a) General view of Ti-6Al-4V-40%TiC MMC at Ti-6Al-4V base plate with indicated line where hardness was 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.

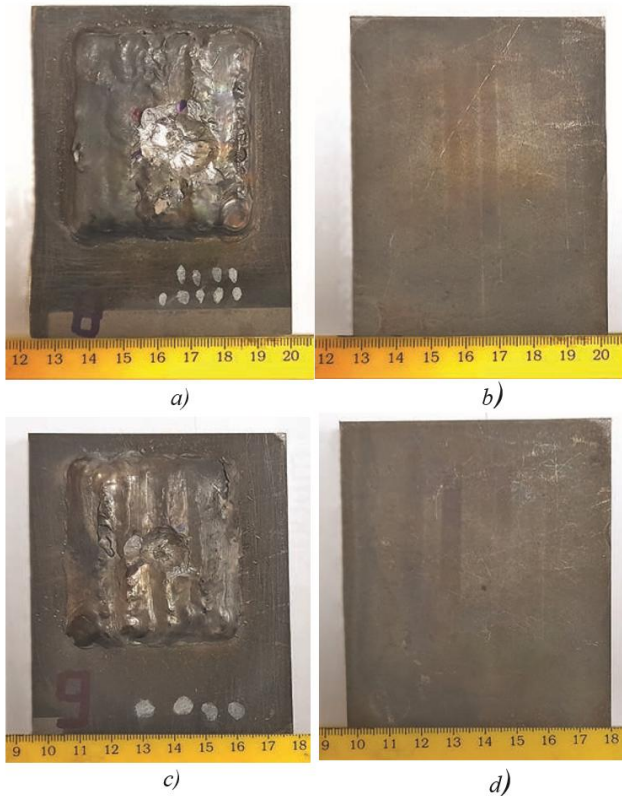


Fig. 5. Appearance of layered titanium-based armour specimens after ballistic testing: front (a,c) and rear (b,d) surfaces of impacted samples [17].

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].

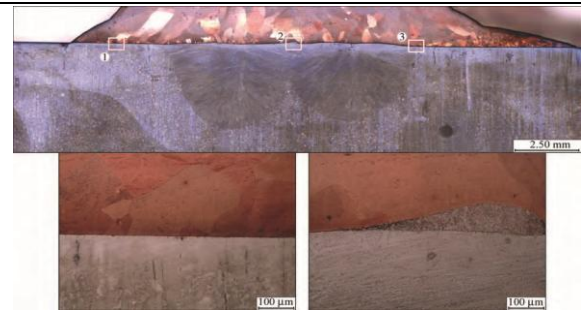


Fig. 6. (upper) Macrograph of etched copper/stainless steel interface demonstrating heat affected zone in stainless steel as well as variable grain size distribution in the substrate/copper interface. (bottom-left) Micrograph of copper/substrate interface at region 1 highlighted above, demonstrating 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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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].

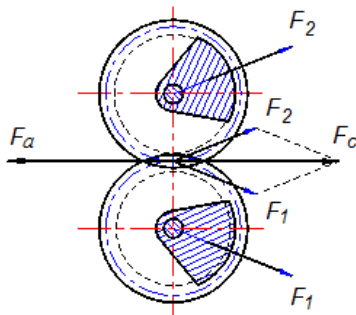


Figure 1. Schematic diagram of a directional vibration exciter: F_1, F_2 - centripetal force of an individual unbalance; F_c - total centripetal force; F_a - kinetic reaction of the axis of rotation.

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.

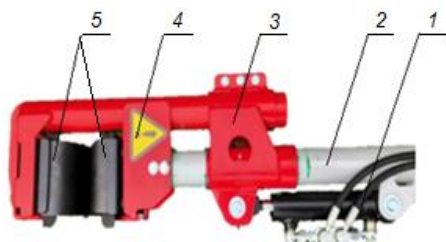


Figure 2. Shaker grip:

- 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.

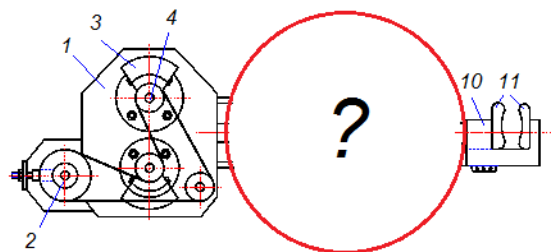


Figure 3. Diagram of a shaking head with a damping device:
1 - shaking head body; 2 - hydraulic motor; 3 - unbalance weights;
4 - shaft; 5-9 - ?; 10 - grippers; 11 - rubber pads.

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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