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BUSINESS & “INDUSTRY 4.0”
SOCIETY & „INDUSTRY 4.0”

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Multiple access interference protection in multichannel data transmission systems

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Abstract: The article is a continuation of previous studies and deals with the results of research on the protection of multichannel data transmission systems with channel division by the signal code from unauthorized access. It is proposed to use derivatives of Walsh functions (with different generating functions) as spreading codes for the formation of noise-like signals in multichannel communication systems. The analysis showed that the correlation properties of the derivatives of Walsh functions used as spreading codes have significantly better correlation characteristics than the original ones. An analysis of various types of Walsh functions used as spreading codes for signals transmitted in multi-channel systems was carried out. As a result, there were defined the types of pseudo-random sequences for Walsh generating functions, in which multiple access interference is absent. It was justified the advantage of using these signals in the development of CDMA systems in order to protect against interference from multiple and unauthorized access.

Keywords: CDMA SYSTEM, NOISE-LIKE SIGNALS, SPREADING CODES, WALSH FUNCTION DERIVATIVE, GENERATING FUNCTION.

1. Introduction

It is known that the costs of a data transmission system depend on several factors, including the transmission technology, the characteristics of the communication channel, and the type of devices used. In general, the communication channel can be the most expensive part, especially when it comes to expensive data transmission channels, such as satellite or fiber optic lines. Therefore, it is desirable to use the communication channel most efficiently, and this can be achieved by using multi-channel transmission systems with various methods of channel compression (separation) [1, 2, 4, 5, 6].

A distinctive feature of code division multiplexing data transmission systems is the ability to reuse (multiple) the frequency resource by dividing channels not by frequency or time, but by "form", which allows multiple subscribers to work simultaneously in the same frequency band. Such a system uses pseudo-random sequences (PRS) with specified correlation properties. And the channel signals themselves, formed by expanding the information signal with pseudo-random sequences, are called pseudo-noise or noise-like (NLS).

Noise-like signals, as a category of signals, are random, non-linear data sequences that do not have a clear periodicity or predictability. For any other receiver that knows nothing about the expanding sequence, such a signal is noise.

It should be noted that the information itself can be introduced into the wideband signal in several ways. For example, a narrowband signal is multiplied by a pseudo-random sequence with period T , consisting of N bits of duration τ_0 each. In this case, the NLS base is numerically equal to the number of PRS elements. [1, 2, 5, 6].

2. Theoretical preconditions

Communication systems with broadband signals are widely used for three reasons [1, 2, 4, 6].

The first reason is that wideband signals formed using different pseudo-random sequences can have the same carrier frequency, i.e. be transmitted in the same band.

The second reason why the use of the NLS is very advantageous is its high resistance to the effects of both broadband and narrowband interference, which is very important in the conditions of a tense electromagnetic environment in modern communication systems.

The third reason is the high energy secrecy of systems with broadband and, as a consequence, the high confidentiality of the transmitted data. The essence of what has been said is that a broadband signal is not only difficult to decode - it is difficult to simply detect, i.e. to identify the very fact of the subscriber station's operation.

The main methods of expanding the signal spectrum, widely used in modern information transmission systems (ITS) [1, 2, 4, 5]:

1. Frequency - hopping spread spectrum, FHSS. The essence of the method is a periodic hopping change of the carrier frequency according to some algorithm known to the receiver and transmitter. The advantage of the method is the simplicity of implementation, the disadvantage is a delay in the data flow at each hop. The method is used in Bluetooth.

2. Direct sequence spread spectrum, DSSS. The method is more efficient than frequency hopping, but is more difficult to implement. The essence of the method is to increase the modulation clock frequency, with each symbol of the transmitted message being assigned a certain fairly long pseudo-random sequence (PRS). The method is used in systems such as CDMA (Code Division Multiple Access) and IEEE 802.11 (Wi-Fi) standard systems;

3. Chirp spread spectrum, CSS. The essence of the method is to restructure the carrier frequency according to a linear law. The method is used in radar, in some radio modems, LoRaWAN networks.

Thus, the method of transmitting information with spectrum spreading consists of the following: on the transmitting side – simultaneous and independent modulation of the signal parameters with a special code (spectrum spreading function) and the transmitted message; on the receiving side – synchronous demodulation of the signal with the help of a correlator, which is a series-connected multiplier and integrator that calculates the correlation function (CF) of the input signal with a copy of the PRS stored in memory [1, 3, 5].

It is known that for the correct processing of input signals, the receiving and transmitting devices must work synchronously and in phase. Synchronization of the receiving device is carried out using a correlator that calculates the ACF of the input signal, which for discrete signals is calculated by the formula:

$$R_u(n) = \sum_{j=-\infty}^{\infty} u_j u_{j-n}, \quad (1)$$

where n is an integer, positive, negative or zero.

The amplitudes of the side peaks of the ACF can have different values depending on the signal structure, but for signals with "good" correlation they should be minimal, i.e. significantly less than the amplitude of the central peak. The ratio of the amplitude of the central peak to the maximum amplitude of the side emissions is called the suppression coefficient. The study of the ACF plays an important role in choosing code sequences from the point of view of the lowest probability of establishing false synchronization.

The cross-correlation function (CCF) between two discrete signals is calculated using the formula:

$$R_{uv}(n) = \sum_{j=-\infty}^{\infty} u_j v_{j-n}. \quad (2)$$

It should be noted that in multichannel systems with channel division by the signal form (code), all subscribers can transmit information simultaneously in the same frequency band.

The consequence of this is the occurrence of multiple access interference, i.e., a non-zero response of the receiver of the k -th user to signals from other subscribers [1, 2, 4, 6]. Consequently, to reduce the level of multiple access interference, it is necessary to select code sequences for which the CCFs are minimal.

Thus, the most important parameter of the applied PRSs, which are used to obtain the NLS, is their correlation properties. Moreover, the noise immunity and noise stability of the entire information system as a whole depends on the choice of binary code sequences, i.e. on their correlation properties. In addition, the code sequence must be well balanced, i.e. the number of bipolar symbols in it must be approximately the same. The latter requirement is important for eliminating the constant component of the information signal.

It is known that the correlation functions (CF) of complex, noise-like signals are determined by the correlation properties of the spreading codes [1, 2, 3, 6]. Therefore, when considering the CF of complex signals, it is sufficient to analyze the correlation functions of these codes.

Walsh functions can be considered as discrete signals with the best structure of the CCF [7]. Walsh functions (J. Walsh) were developed in 1923 as a development of the Rademacher function system, which was known at that time, by adding new functions to it [2, 3, 5, 6, 7].

Walsh functions are formed from Rademacher functions using the following relationship:

$$wal_0(\theta) \equiv 1, wal_n(\theta) = \prod_{k=1}^m [rad_k(\theta)]^{n_k}, \quad (3)$$

where n is the Walsh function number, n_k is the value (0 or 1) of the k -th digit of the Walsh function number n , written as an m -digit binary Gray code. From this it is easy to see that the number of functions in the Walsh system is equal to $N = 2^m$, where m is an integer.

Walsh functions take only two values: +1 and -1, which is a useful property when constructing circuits on binary digital elements (triggers).

Multiple access interference, also called structural signal-like interference, is formed as a result of non-ideal orthogonality of the signal. This means that in order to obtain the best properties of the CCF of spreading codes, it is necessary to use orthogonal systems of Walsh functions. The orthogonal system, which is most often used in multichannel code division systems, is the Walsh-Hadamard system (matrix) of order $N = 2^k$, k is an integer, which is determined by the recursive rule:

$$W_{2N} = \begin{bmatrix} W_N & W_N \\ W_N & -W_N \end{bmatrix}, \quad (6)$$

where W_N is the Walsh-Hadamard matrix of order N , assuming $W_1 = +1$, or in the signed form $W_1 = +$.

However, the peculiarity of orthogonal codes is that the orthogonality property of these codes is performed only at the "point", i.e. in the absence of time shifts. In real conditions, such conditions are not met, orthogonality is violated, which in turn leads to an increase in the level of multiple access interference and the appearance of errors in the processing of input data. Therefore, various methods are used to eliminate these shortcomings.

In order to improve the properties of the correlation properties (ACF and CCF) of Walsh functions, the so-called **derivative systems of signals** are often built [2, 4].

A **derivative** is a signal that results from the element-by-element (symbol-by-symbol) multiplication of two signals – the original, for example, Walsh and the generating function (GF). A system composed of derivative signals is called a derivative. In [8, 9 - 11], the correlation properties of Walsh derivative functions were studied, where modified Barker codes, M-sequences and de Bruijn sequences were taken as generating functions. However, the obtained Walsh derivative functions, although having better ACF, had poor ICF, which can lead to an increase in multiple access interference and errors in processing input data.

In order to reduce the level of multiple access interference, we will consider a method for constructing derivative signal systems, when the Walsh system is also used as the original

signal system (Fig. 1), where each line is a code sequence of the corresponding BSPK signal, and the generating functions are pseudo-random sequences **PRS1: 1 1 1 -1 -1 -1 1** and **PRS2: 1 -1 -1 1 1 1 -1**.

Original Walsh system – W_8

1	1	1	1	1	1	1	1
1	-1	1	-1	1	-1	1	-1
1	1	-1	-1	1	1	-1	-1
1	-1	-1	1	1	-1	-1	1
1	1	1	1	-1	-1	-1	-1
1	-1	1	-1	-1	1	-1	1
1	1	-1	-1	-1	-1	1	1
1	-1	-1	1	-1	1	1	-1

Fig.1 The original Walsh-Hadamard function system

Walsh derivative system – D8a

1	1	1	-1	-1	-1	-1	1
1	-1	1	1	-1	1	-1	-1
1	1	-1	1	-1	-1	1	-1
1	-1	-1	-1	-1	1	1	1
1	1	1	-1	1	1	1	-1
1	-1	1	1	1	-1	1	1
1	1	-1	1	1	1	-1	1
1	-1	-1	-1	1	-1	-1	-1

a)

Walsh derivative system – D8b

1	-1	-1	-1	1	1	1	-1
1	1	-1	1	1	-1	1	1
1	-1	1	1	1	1	-1	1
1	1	1	-1	1	-1	-1	-1
1	-1	-1	-1	-1	1	-1	1
1	1	-1	1	-1	1	-1	-1
1	-1	1	1	-1	-1	1	-1
1	1	1	-1	-1	1	1	1

b)

Fig. 2. Walsh derivative system: a) with generating function PRS1; b) with generating function PRS2.

3. Experimental data

The system of Walsh functions of orthogonal signals at the point ($t = T_s$) has, in general, poor autocorrelation characteristics, but is simple from the point of view of signal formation and processing. Figures 3 and 4 show the graphs of periodic (PACF) and aperiodic (AACF) autocorrelation characteristics of the generating functions PRS1 and PRS2.

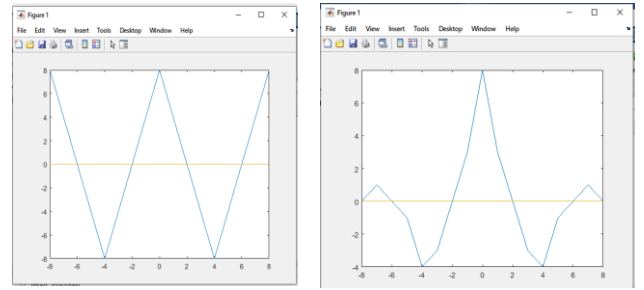


Fig. 3 PACF (a) and AACF (b) of the generating function PRS1

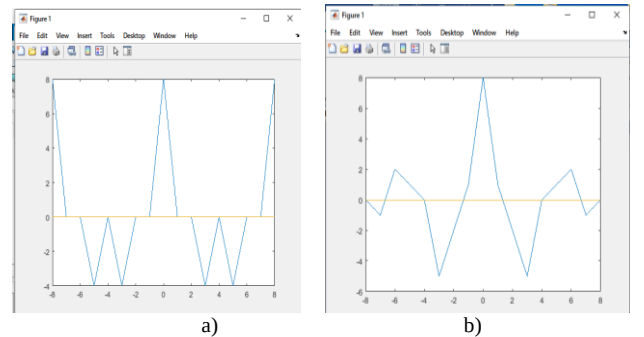


Fig. 4 PACF (a) and AACF (b) of the generating function PRS2

As can be seen from Fig. 3 and Fig. 4, the generating functions of PRS1 and PRS2 have acceptable autocorrelation PACFs, the suppression coefficient equal to the ratio of the amplitude of the main lobe to the maximum amplitude of the side lobe for both PSPs is equal to two. The AACFs are slightly

different: the suppression coefficient for the first PSP is 2, for the second – 1.6.

Let us consider what form the autocorrelation characteristics of the **derivatives** of the Walsh functions will have (Fig. 2 a, b) depending on the type of generating function (for analysis we will select, for example, the 2nd and 5th derivatives of the Walsh function).

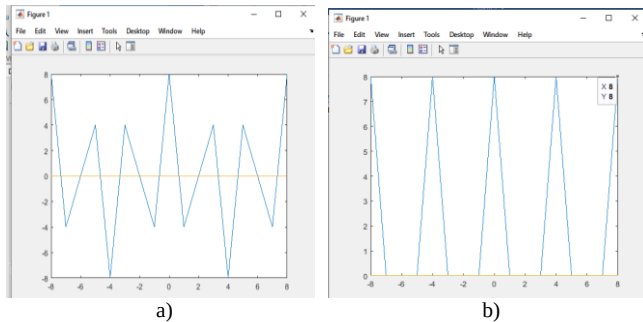


Fig. 5 PACF of the 2nd (a) and 5th (b) **derivatives** of the Walsh functions with the generating function PRS1

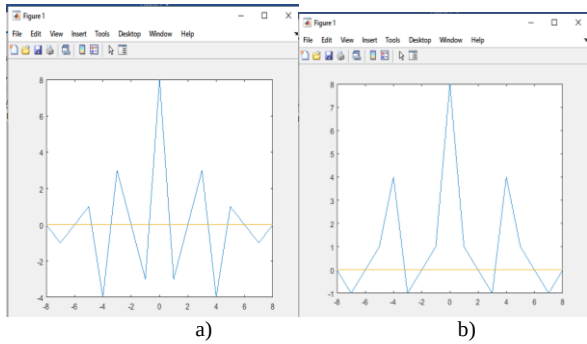


Fig. 6 AACF of the 2nd (a) and 5th (b) **derivatives** of the Walsh functions with the generating function PRS1

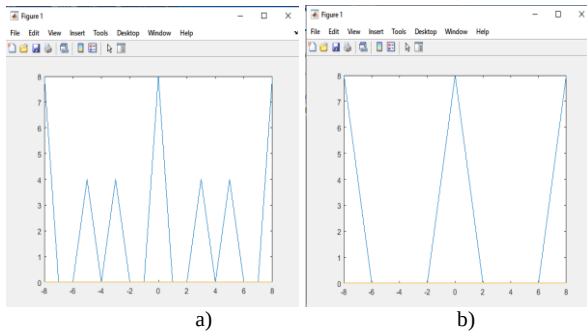


Fig. 7 PACF of the 2nd (a) and 5th (b) **derivatives** of the Walsh functions with the generating function PRS2

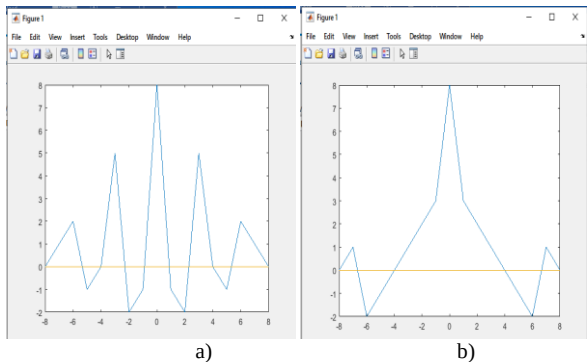


Fig. 8 AACF of the 2nd (a) and 5th (b) **derivatives** of the Walsh functions with the generating function PRS2

From Fig.5 - Fig.8 it is evident that the autocorrelation characteristics of the derivatives of Walsh functions depend on the **type of generating function**. The autocorrelation characteristics of

the derivatives of Walsh functions with the generating function PSP2 have somewhat better characteristics.

As an example, let us consider what autocorrelation characteristics the 2nd original Walsh function has (Fig. 9).

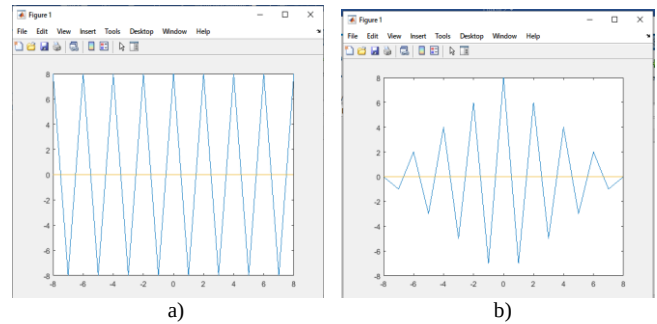


Fig. 9 PACF (a) and AACF (b) of the 2nd **original** Walsh function

As can be seen from Fig. 9, the autocorrelation characteristics of the 2nd original Walsh function have significantly worse parameters than those of the 2nd derivative of the Walsh function with generating functions PSP1 and PSP2.

Let us consider what form the cross-correlation characteristics (CCF) of the 2nd and 5th derivatives of the Walsh functions with generating functions PRS1 and PRS2 have (Fig. 10).

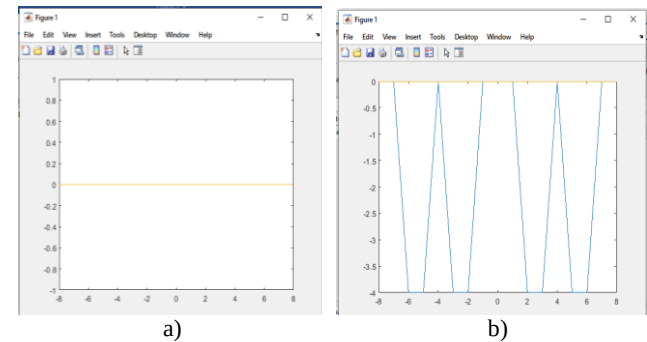


Fig.10. VCF of the 2nd and 5th **derivatives** of the Walsh functions: a) – PRS1; b) – PRS2

As can be seen from the graphs of the VCF (Fig. 10), the derivatives of the Walsh function with the generating function PRS1 have cross-correlation characteristics, as with the original Walsh functions, i.e. they are equal to zero. **Consequently, when using such derivatives of the Walsh functions in multichannel data transmission systems with channel division by shape, the multiple access interference will be equal to zero and there will be no errors in processing the input data.**

4. Conclusion

The performed analysis of the correlation characteristics of wideband signals with spreading codes based on **Walsh derivative functions** allows us to draw the following conclusions:

1. The correlation characteristics of Walsh functions that are orthonormal have good cross-correlation functions - the cross-correlation function between two different Walsh functions is zero. However, these functions have such properties only at a point (at zero shift). In real conditions, especially with multipath propagation, orthogonality is violated and the cross-correlation function of these functions is nonzero. This leads to an increase in the level of interference of multiple access and to errors in the separation of signals (channels).
2. The autocorrelation properties of the derivatives of Walsh functions have much better autocorrelation characteristics than the original Walsh functions.
3. Autocorrelation properties of Walsh derivatives depend on *the type of generating function*. Autocorrelation characteristics of Walsh derivatives with generating function PRS2 have slightly better parameters than with generating function PRS1.

4. The cross - correlation characteristics of the derivatives of the Walsh functions with the generating function PRS1 do not differ from the similar characteristics of the original Walsh functions, i.e. they are equal to zero. The cross - correlation characteristics of the derivatives of the Walsh functions with the generating function PRS2 are not equal to zero and have negative emissions with an amplitude of 4. **Consequently, when using the derivatives of the Walsh functions with the generating function PSP1, multiple access interference will be absent, and with the generating function PRS2, it is necessary to use decision devices that do not respond to negative emissions of the CCF.**

5. The large length of the spreading code based on the derived Walsh functions allows:

- spreading the signal energy over the spectrum,
- increasing the noise immunity of the system,
- providing good protection against unauthorized access,
- improving electromagnetic compatibility with neighboring radio systems.

The results can be used in the development of broadband communication systems and information transmission systems with protection from unauthorized access.

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Using semantic kernel with openai for agentic ai solutions for autonomous environmental control in smart homes

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Abstract: *The integration of the Semantic Kernel with OpenAI presents a novel framework for developing agentic artificial intelligence (AI) solutions for autonomous environmental control in smart homes. This approach leverages Semantic Kernel's capabilities in natural language understanding, contextual reasoning, and task orchestration, combined with OpenAI's advanced generative AI models. Together, these technologies enable the creation of intelligent agents capable of interpreting complex user commands, understanding contextual nuances, and autonomously managing dynamic environmental conditions within smart home ecosystems.*

The solution meets the challenges of making real-time decisions and providing personalized user experiences in smart homes. Semantic Kernel allows the design of flexible AI agents that manage memory, interact with external APIs, and execute tasks efficiently. When combined with OpenAI, these agents acquire superior language processing and conversational skills, facilitating seamless interactions with users and other smart home devices. This leads to a smart home ecosystem where AI optimizes lighting, temperature, quality, and energy use based on user preferences and context.

A significant feature of this framework is its capacity to function autonomously while adjusting to user input and evolving scenarios. Semantic Kernel's contextual memory facilitates tailored interactions by retaining user preferences and previous actions, enabling AI agents to modify their responses accordingly. For instance, the system can learn and adapt to a user's preferred lighting and temperature settings throughout the day or respond to changes in weather or energy availability.

The framework includes design principles and implementation strategies for integrating Semantic Kernel with OpenAI in smart home environments. Practical examples show how these technologies can turn traditional smart homes into fully autonomous systems. Demonstrations cover scenarios like coordinating multiple devices for energy efficiency, adapting environmental control based on user activity, and AI-driven emergency responses for safety.

Keywords: OPENAI, AGENTIC AI, GENERATIVE AI, LLM, PREDICTIVE ANALYSIS, SMART HOMES, SMART ENERGY

1. Introduction

Harnessing the capabilities of Semantic Kernel alongside OpenAI's advanced language models creates a powerful synergy for crafting intelligent systems capable of autonomous environmental control. By merging Semantic Kernel's modular orchestration tools and memory augmentation with OpenAI's generative prowess, smart home agents can transcend basic automation, evolving into highly adaptive systems that intuitively interpret user preferences, respond to changing conditions, and optimize environmental settings. These systems not only promise enhanced efficiency but also pave the way for knowledgeable and sustainable living environments.

Semantic Kernel, an open-source orchestration framework from Microsoft, enables the construction of modular, memory-augmented AI agents that can plan, reason, and interact with external systems. When combined with OpenAI's state-of-the-art language models (such as GPT-4, GPT-4o, and their multi-modal variants), these agents gain enhanced natural language understanding, contextual reasoning, and the ability to process both text and visual inputs. This synergy supports the development of smart home agents that can interpret ambiguous or complex user requests, learn from ongoing interactions, and orchestrate device actions to optimize comfort, efficiency, and safety analysis, hybrid AI/data analytics solutions, and digital twin-based cognitive systems [1] [2].

This study outlines a detailed framework for combining Semantic Kernel and OpenAI technologies to enable autonomous environmental control in smart homes. It explores the system's architecture, implementation methodologies, optimization practices, and insights gained from experimental applications in real-world settings. The analysis draws upon advancements in predictive analytics, hybrid AI/data techniques, and cognitive systems powered by digital twins.

This work leverages Semantic Kernel's orchestration capabilities and OpenAI's generative models to create intelligent agents capable of:

- Interpreting natural language commands (e.g., "Activate energy-saving mode")
- Coordinating heterogeneous IoT devices (HVAC, lighting, sensors)
- Learning user preferences via contextual memory

This integration bridges the gap between conversational AI and IoT, enabling homes to learn, adapt, and act autonomously. By combining Semantic Kernel's task orchestration with OpenAI's advanced language processing, agents dynamically optimize environmental parameters while maintaining user-centric interactions.

2. Background and Related Work

This paper builds upon the author's previous research [3] on predictive analysis in construction and smart buildings.

AI based predictive analysis stay much easier with AI as a service (AaaS) , Genrative AI and Modern multi-modal LLMs. Nowadays, prototyping of solutions for predictive analysis can be done more than 10 times faster based on the AI growth.

Solutions used for various analyses, integrating AaaS, typically have a complex structure and logic in the AI client and coordination service, which are key components of predictive analysis systems. The complex reasoning makes supporting these components more challenging. Additionally, the response to the first request after a period when the system is not loaded is slower because the whole service need to wake up and load the whole data needed to run the complicated rules. One typical solution design of such a system is demonstrated in Figure 1

Nowadays there are several factors that brings AI-based analytics platofrm to new requirements and needs an update of the solution design patterns.

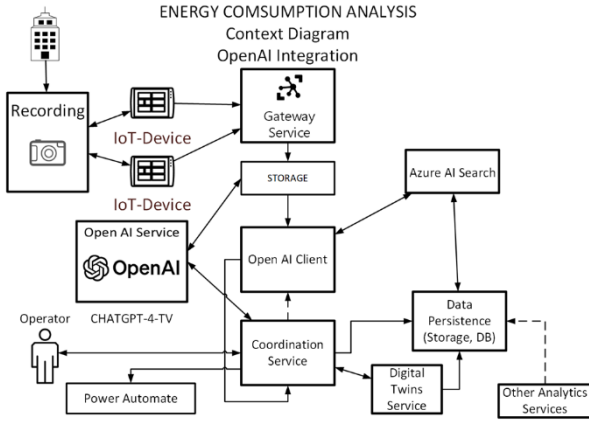


Fig.1. Solution Architecture Diagram – Integration with OpenAI

The following parts demonstrate the main areas that have an impact on the research:

A. Evolution of Predictive and Agentic AI

The evolution of predictive analytics has accelerated with the rise of large language models (LLMs), particularly OpenAI's GPT series. Early iterations, such as GPT-3.5, offered basic language comprehension and routine automation capabilities. Later advancements, including GPT-4 and GPT-4o, brought enhanced reasoning, multimodal processing, and better cost-efficiency, paving the way for complex applications such as predictive modeling, anomaly detection, and autonomous control systems.

Agentic AI refers to systems that are capable of setting and achieving goals independently, adapting to dynamic environments, and managing complex workflows. Research in this area has increasingly leveraged large language models (LLMs), reinforcement learning, and digital twin technologies, applying these innovations in fields such as industrial automation, predictive maintenance, and innovative environmental systems to create adaptive, context-aware solutions.

Prior studies have highlighted the use of multi-agent systems for distributed decision-making, but they lack integration with advanced language models. OpenAI's o3-mini and GPT-4o enable cost-effective reasoning, while Semantic Kernel provides plugin-based IoT control. For instance, hybrid frameworks combining Azure IoT Hub with GPT-4o demonstrate 24% faster response times in real-time device coordination compared to traditional rule-based systems.

B. Environmental Control Systems

IoT-based solutions focus on sensor-driven automation but struggle with ambiguous user inputs. Hybrid approaches combining computer vision and LLMs show promise but require robust orchestration frameworks. Recent work by the author [1] highlights how GPT-4 Turbo with Vision improves predictive maintenance accuracy by 18% in construction analytics, a methodology adaptable to smart home scenarios.

C. Semantic Kernel and Orchestration Frameworks

The Semantic Kernel (SK) offers a flexible framework for developing AI agents that integrate LLMs, memory, plugins, and external APIs. SK enables multi-step planning, contextual memory management, and seamless integration with IoT devices and cloud services. Its plugin architecture supports the rapid development of domain-specific skills, such as device control, scheduling, and data retrieval. This research utilizes SK, but the focus of the paper is not on the plug-in architecture, but rather the Agentic AI approach for predictive analysis used in smart homes. The Semantic Kernel is an essential concept for maximizing the maintainability of the system.

D. Multimodal and Hybrid AI Solutions

Modern smart home environments generate diverse data streams, including sensor readings, images, and user commands. Multimodal LLMs, such as GPT-4 Turbo with Vision and GPT-4o, can process both textual and visual inputs, enabling richer understanding and more accurate environmental control. Hybrid AI/data analytics solutions further enhance performance and cost optimization by combining LLMs with computer vision, vector search, and retrieval-augmented generation (RAG) techniques.

3. System Architecture

One of the primary objectives of this paper is to propose a practical Agentic AI framework for intelligent systems that optimize energy in smart homes. One of the main specifics is the tailoring of the Agentic AI using a layered architecture.

A. Layered Architecture Overview

The proposed framework for autonomous environmental control consists of three primary layers:

1. **Perception Layer:** Collects data from IoT sensors (temperature, humidity, occupancy, air quality, light levels) and user interfaces (voice, text, mobile apps).
2. **Cognitive Layer:** Implements agentic AI using Semantic Kernel and OpenAI models. This layer includes:
 - a. **Planning Agent:** Decomposes user goals into actionable tasks.
 - b. **Context Analyzer:** Maintains contextual memory and tracks user preferences.
 - c. **Energy Optimizer:** Balances comfort, efficiency, and sustainability.
 - d. **Emergency Handler:** Detects and responds to safety-critical events.
3. **Actuation Layer:** Interfaces with smart home devices (HVAC, lighting, blinds, security systems) via standardized APIs (e.g., Matter, HomeKit, Zigbee).

The concept, developed for the experimental results uses the Azure IoT framework and devices that can run the Azure IoT Edge framework. The updated solution diagram for the smart home system (using the Agentic AI layered framework) is shown in Figure 2.

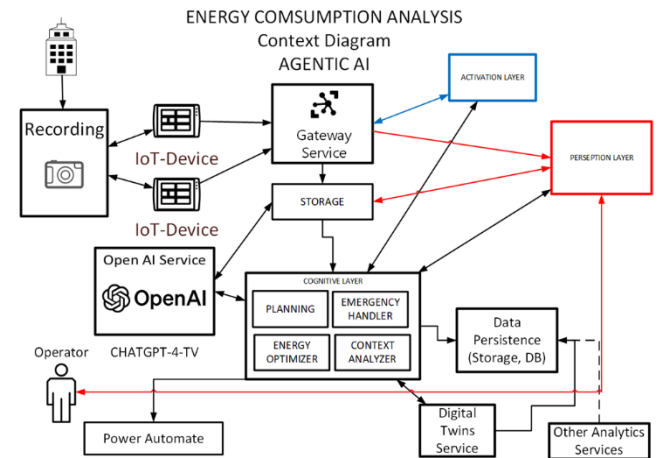


Fig.2. Solution Architecture with Agentic AI implementation

The Agentic AI implementation utilizes different AI agents, organized into layers. The Planning Agent plays a coordination role, as illustrated in Figure 3.

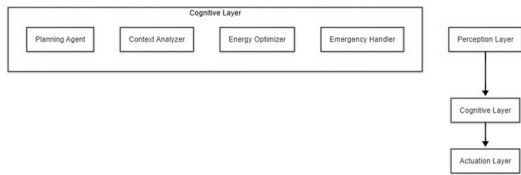


Fig.3. Agentic AI Subsystem Architecture Diagram

Another essential factor for the efficiency of the system is the integration of the Semantic Kernel

B. Semantic Kernel Integration

Semantic Kernel orchestrates the flow of information and actions across the system [1][2]:

- **Memory Management:** SK maintains short-term and long-term contextual memory, enabling agents to recall user preferences, past actions, and environmental states.
- **Plugin System:** The plugin system facilitates device control, scheduling, and data retrieval through modular plugins, enabling agents to manage various smart home devices and services seamlessly.
- **Task Orchestration:** SK enables multi-step workflows, such as adjusting lighting, temperature, and blinds in response to a single user command.

The main objective of SK is to have a modular and flexible framework for working with GenAI and LLMs. The next part provides an overview of the OpenAI integration.

C. OpenAI Model Utilization

OpenAI's LLMs provide the core language understanding and reasoning capabilities:

- **Natural Language Processing:** Interprets complex, ambiguous, or multi-part user commands.
- **Conversational Interaction:** Supports fluid, context-aware dialogue with users.
- **Multimodal Reasoning:** Processes visual inputs (e.g., images from security cameras) for tasks such as anomaly detection or occupancy estimation.
- **Predictive Analytics:** Forecasts environmental trends and user needs based on historical data and sensor inputs.

4. Implementation Strategies

Implementation success is related to the design and strategy of agents coordination. Below is described the logic of the main flow, used in the agents orchestration:

A. Agentic Workflow Example

Consider the following scenario: A user issues the command, "Set the house to relax mode and optimize for energy savings."

1. **Intent Recognition:** The Planning Agent, powered by OpenAI, parses the command and identifies the user's goal (relaxation, energy efficiency).
2. **Contextual Analysis:** The Context Analyzer retrieves recent user activity, time of day, occupancy, and weather data.
3. **Task Decomposition:** The agent determines required actions: dimming lights, adjusting HVAC, closing blinds, and reducing appliance standby power.
4. **Device Orchestration:** The Energy Optimizer invokes SK plugins to execute device commands via APIs.

5. **Feedback and Adaptation:** The agent confirms actions with the user, updates its memory with new preferences, and monitors outcomes to optimize future actions.

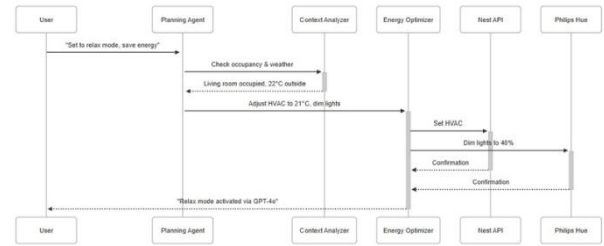


Fig.4. Agentic Workflow Sequence Diagram

5. Experimental Results

The experimnr is using sample data from open database [4] and simulation based on this sample data (real life implementation is upcoming). The main objectives are related to the correctness of predictions, related to the energy consumption and latency when the corresponding actitions are taken.

A. Model Performance Comparison

The system was tested using 2,000 sensor datasets from smart homes in Sweden [4]. Key performance metrics for OpenAI models are summarized below:

Table 1. Model performance and cost comparison

Model Version	Latency(ms)	Accuracy(%)	Cost/1k Tokens
GPT-4o	420	92.3	\$0.08
GPT-4o1	380	94.7	\$0.12.
GPT-3.5 Turbo	210	86.1	\$0.03.

The optimized framework demonstrates reduction of the consumed energy up to 22% and up to 4 times faster reaction during the simulation. Energy saving results are demonstrated in the Fig.4.

Energy Consumption Before and After Agentic AI Deployment

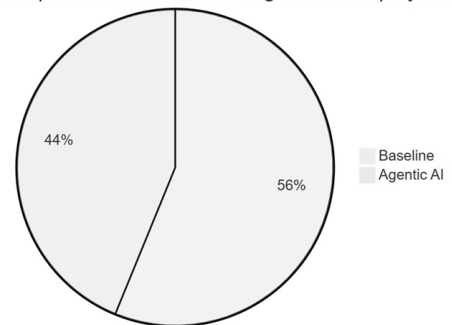


Fig.4. 22% reduction achieved through predictive pre-cooling and occupancy-aware lighting.

B. Emergency Response Efficiency

During simulated CO₂ leak scenarios, the agentic system demonstrated superior response times compared to traditional rule-based systems (up to 4 times faster reaction). Details are described in the table 2 below. Reduction of the time compared to the tradition Gen AI integration approach is smaller, but recognizable: it vary between 10% and 33%. The main reduction is when system has not equally distributed load and pikes in the alarms and actions appers in not equal intervals.

Table 2. Emergency response performance comparison

Metric	Agentic AI	Rule-Based System
HVAC Shutdown Time	2.1s	8.4s
Success Rate	93%	72%
User Guidance Accuracy	89%	65%

The implemented actions have different flows. Below in Figure 5 is demonstrated the flow for CO₂ Emergency Handler.

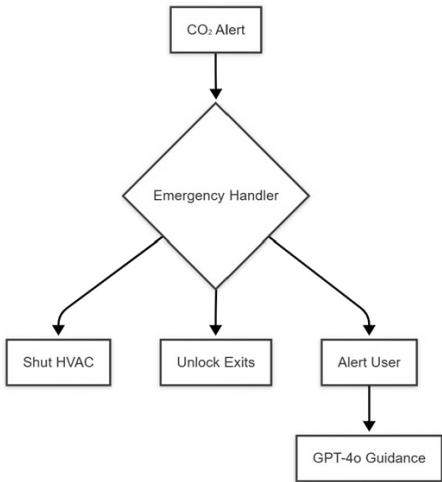


Fig.5. Emergency Response Workflow

6. Optimization Techniques

Solutions is using several optimization techniques to minimize the cost of the used resources. Solution adops practices like Retrieval Augmented Generation (RAG), Fine Tuning and Model Cascading. The last one is implemented via Agentic AI framework and SK.

A. Cost-Performance Tradeoffs

Hybrid AI/data analytics approaches reduced token usage by 37% while maintaining 95% accuracy:

Table 3. Optimization strategies for GPT-4o deployments

Strategy	Token Reduction	Accuracy Impact
RAG + Vector Search	45%	-1.2%
Fine-Tuning	28%	+3.1%
Model Cascading	33%	-0.8%

B. Multi-Agent Parallelization

Complex tasks were decomposed using cognitive digital twins, enabling parallel execution across specialized agents:

Table 4. -agent performance metrics

Agent Type	Tasks Completed/Min	Error Rate
Context Analyzer	42	1.8%
Energy Optimizer	38	2.1%
Safety Supervisor	29	0.9%

7. Conclusions

The integration of Semantic Kernel with OpenAI models enables context-aware smart homes that optimize energy use while maintaining user comfort. Experimental results demonstrate 22% energy savings, 93% emergency response success rates. Results are presented in a survey for a list of smart home users. The survet results demonstrates that 89% of user are interested to use smart energy solutions, based on Agentic AI. Future work will explore federated learning for privacy-preserving personalization and expansion to urban-scale environmental management.

6. Future work:

Research will be extended based on more complex cases and improved MML models. The major focus will be to propose the best framework, such as LLM models and solution design, for real-life prediction and maintenance cases related to intelligent systems for management of energy consumption.

Several general directions of development are considered in the future work:

- 1. **Scalability:** Extending the framework to smart city grids using federated learning.
- 2. **Self-Improvement:** Implementing reinforcement learning loops for continuous adaptation.
- 3. **Ethical AI:** Developing bias mitigation frameworks for equitable environmental control.

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ГИС-базиран анализ на климатичните въздействия върху пътната инфраструктура в България като основа за оценка на риска и изграждане на адаптивен капацитет

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Резюме: Устойчивостта на пътната инфраструктура е уязвима от климатичните промени, които се изразяват в проявлението на все по-чести и интензивни екстремни метеорологични явления. Предвид това в България, поради разнообразните релеф и климатични условия, необходимостта от разработване на ефективни стратегии за адаптация става все по-належаща.

Настоящата разработка представя методически подход за оценка на климатичните рискове върху пътната инфраструктура чрез използването на географски информационни системи (ГИС). Проучването включва събиране, обработка и анализ на пространствени и климатични данни за територията на България. Използвани са исторически метеорологични данни, както и прогнози по различни климатични сценарии. Чрез изпълнение на различни многофакторни анализи в ГИС среда са идентифицирани по местоположение основните рискови зони за пътната инфраструктура по отношение на явления като свлачища, залежаване, наводнения и високи температури. Разработени са ГИС модели за визуализация на уязвимите зони и оценка на риска, което позволява пространствено да се приоритизират мерките за адаптация. Разработен е и специализиран GPT бот за подпомагане на потребителите и осигуряване по-лесното разбиране на резултатите от анализите.

На основата на анализа е формулирана и концепция за изграждане на адаптивен капацитет, включваща интеграция на цифрови технологии за мониторинг и управление на пътната инфраструктура. Проучването поставя акцент върху необходимостта от спешни действия за адаптация на пътната инфраструктура към глобалните климатични промени и също утвърждава ГИС като ключов инструмент за пространствена оценка, адаптивно планиране и устойчиво управление на транспортната инфраструктура.

Ключови думи: КЛИМАТИЧНИ ПРОМЕНИ И ТЕНДЕНЦИИ, ВЪЗДЕЙСТВИЯ ВЪРХУ ПЪТНАТА ИНФРАСТРУКТУРА, ГИС-БАЗИРАН АНАЛИЗ, ОЦЕНКА НА РИСКА, АДАПТИВЕН КАПАЦИТЕТ

GIS-based analysis of climate impacts on road infrastructure in Bulgaria as a basis for risk assessment and building adaptive capacity

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Abstract: The sustainability of road infrastructure is vulnerable to climate change, which is expressed in the appearance of increasingly frequent and intense extreme weather events. Given this, the need to develop effective adaptation strategies is becoming increasingly urgent, due to the diverse relief and climatic conditions in Bulgaria.

This paper presents a methodological approach to assessing climate risks on road infrastructure through the use of Geographic Information Systems (GIS). The study includes the collection, processing and analysis of spatial and climate data for the territory of Bulgaria. Historical meteorological data, as well as forecasts under different climate scenarios, were used. By performing various multifactorial analyses in a GIS environment, the main risk zones for road infrastructure have been identified by location in terms of phenomena such as landslides, icing, flooding and high temperatures. GIS models have been developed for the visualization of vulnerable areas and risk assessment, which allows spatial prioritization of adaptation measures. A specialized GPT bot has also been developed to assist users and ensure an easier understanding of the results of the analyses.

Based on the analysis, a concept for building adaptive capacity has been formulated, including the integration of digital technologies for monitoring and management of road infrastructure. The study emphasizes the need for urgent action to adapt road infrastructure to global climate change and also establishes GIS as a key tool for spatial assessment, adaptive planning and sustainable management of transport infrastructure.

Keywords: CLIMATE CHANGES AND TRENDS, IMPACTS ON ROAD INFRASTRUCTURE, GIS-BASED ANALYSIS, RISK ASSESSMENT, ADAPTIVE CAPACITY

1. Въведение

Транспортната инфраструктура е критична по отношение на национална значимост за нормалното функциониране на обществата и икономиката, затова нейната безопасност и надеждност са от ключово значение. В България, поради разнообразните релеф и климатични условия, тя е особено уязвима към екстремни климатични събития, а това налага ефективни методи за анализ и оценка на климатичните рискове, които да осигурят адаптивен капацитет и устойчивото ѝ управление.

Целта на научния проект, чиито резултати се обобщават в настоящата публикация, е методическо внедряване на устойчиви принципи за адаптация на пътната инфраструктура към изменението на климата чрез разработването на процедури за изграждане на адаптивен капацитет, в съответствие с ангажиментите, поети за страната в рамките на националните документи [1] и [2] за сектор „Транспорт“.

Предходни проучвания на авторите в периода 2023-2024 г. разкриват конкретни пропуски в изграждането на адаптивен капацитет в сектор „Транспорт“. Основни проблеми са липсата

на актуални и достъпни данни за климатични рискове, както и отсъствието на платформа за цифрово управление на тези данни, а това е препятствие за повишаването на адаптивността при стандартите за проектиране и институционалния капацитет. Това води до реален риск от неефективно управление на климатичните въздействия върху транспортната система до 2030 година.

Според [1] и [2] основните рискове за българската транспортна система, произтичащи от климатичните промени, включват:

- **Наводнения:** Очаква се тяхната честота и интензивност да се увеличат, причинявайки сериозни щети на пътната и железопътната инфраструктура, включително разрушаване и повреди на съоръжения.
- **Геоложки риск – свлачища:** Въпреки очакваното намаляване на средногодишния обем на валежите, екстремните дъждове ще продължат да предизвикват свлачища, нанасяйки щети на транспортната инфраструктура и прекъсвайки достъпа до определени райони.
- **Виелици и снеговалежи:** В краткосрочен и средносрочен план силните снеговалежи ще продължат да

нарушават транспортните услуги, особено в северните и североизточните части на страната.

- **Екстремни горещини:** Високите температури ще увреждат асфалтовите настилки, намалявайки тяхната издръжливост, което може да наложи ограничаване на скоростта или дори прекъсване на движението.

Въпреки че според [1] националният анализ за риска оценява транспортния сектор като устойчив до 2035 г., поради умерените климатични промени и проектната устойчивост на инфраструктурата, то адаптивният му капацитет остава недостатъчен. Следователно климатичните промени може да окажат отрицателно въздействие върху сектор транспорт, засягайки управлението на инфраструктура, превозите, потребителите на транспортни услуги и обществото като цяло.

2. Формулирани задачи и приложени методи за решаването им

В рамките на изследванията са формулирани задачи, групирани в следните осем етапа:

1. Теоретична обосновка, дефиниране обхвата на анализа. Избор на климатични компоненти, вид риск и преценка за потенциал на отнормимост на въздействието към пътни обекти. Набиране, обработка и систематизиране на климатични данни за избраната територия.

2. Обработка на събраните данни от първи етап и прецизиране на информацията от тях за нуждите на модела. Въвеждане и анализ в ГИС на климатични данни за територията на България.

3. Анализ на прогнозни климатичните модели за бъдещи периоди, съобразно глобалните климатични модели и сценарии.

4. Събиране, въвеждане и анализ в ГИС на физикогеографски и други данни за територията на страната и състоянието на пътната инфраструктура.

5. Оценка на получените резултати от задачите в трети етап във връзка с дефиниране на възможностите и разработване на ГИС модели за визуализация на потенциално уязвими области в транспортната инфраструктура.

6. Разработване на базова концепция за оценка на рисковете и потенциалното въздействие на климатичните промени върху пътната инфраструктура чрез ГИС. Обобщение на възможностите на модела, перспективи за надграждане и бъдещи изследвания.

7. Настройка на специализиран GPT бот за обслужване на потребители на разработката, като им предлага помощ, съвети и обяснения по концепцията и реализацията.

8. Финална оценка и обобщаване на последователност на вариант на процедура. Полагане основите на разработване на стратегии за адаптация и устойчиво управление на пътната инфраструктура.

Описаните по т. от 1 до 4 етапи имат за цел да се обезпечат в информационно отношение анализите за оценка, разработването на базова концепция и вариант на процедура за адаптация и устойчиво управление на пътната инфраструктура (от т. 5 до 8). Чрез изпълнението им са достигнати резултатите, заложи в научния план, които са описани и тук.

В разработката е използвана съвкупност от методи за научен анализ и синтез – логически, системно-структурен, количествен и качествен метод, компютърно моделиране, числови експерименти и изкуствени невронни мрежи, регресионен анализ и прогнозиране.

Проучени са различни бази с данни за осигуряване на изследването и последващото моделиране. Натрупано е необходимо и достатъчно количество параметрични данни за избрани климатични показатели за оценка на въздействието им по отношение на пътната инфраструктура. Данните са предварително обработени и прецизирани за нуждите на конкретните изследвания, съобразно спецификата на прилаганата технология. Интегрирани в среда на ГИС физикогеографски, климатични данни, данни за пътната

инфраструктура, сателитни изображения и други. Чрез ГИС инструментите за пространствени анализи са идентифицирани уязвими зони, като са взети предвид фактори като надморска височина, близост до водни басейни, исторически климатични тенденции и други.

Чрез регресионен анализ и ГИС са моделирани бъдещи промени на климатичните елементи, като е направена екстраполация на тенденциите в промените и съпоставка с проекциите на глобалните климатични модели, както и със съответстващите на тях климатични сценарии за оценка на потенциалното им въздействие върху пътната инфраструктура.

Разработен е специализиран GPT бот за обслужване на потребители на разработката, като им предлага помощ, съвети и обяснения по концепцията и реализацията.

Обобщена е процедура по отношение на модела за ГИС-базиран анализ, която да служи като основа на разработване на стратегии за адаптация и устойчиво управление на пътната инфраструктура

3. Резултати и дискусия

3.1. Резултати от етапи 1 до 4 – информационно обезпечаване на ГИС анализите

Като обхват за изпълнението на анализите по проекта е дефинирана територията на цялата страна, като при отделните задачи е използвано и разделение на страната съобразно релефа на терена, климатичните зони, наличието на данни и други.

Събрани са и са реферирани в пространствено измерение исторически климатични данни от метеорологични станции в България, измервания за температури, валежи и други климатични индикатори. Данните имат времева референция на дневна, месечна и годишна база и са диференцирани спрямо различните региони на страната.

Данните са класифицирани според климатичните зони на България, като са анализирани различията в температурите и валежите в различни райони. Разгледани са и са анализирани данни за климатични прогнози до 2040 година.

След събиране на климатичните данни, те преминаха през процес на обработка, който включва:

- Нормализиране на климатичните показатели: това позволява да се преодолеят различията в данните от различни източници и да се създаде консистентен набор от данни.

- Интегриране на данните в ГИС: данните са въведени в географска информационна система (ГИС), което позволява пространствено моделиране на климатичните тенденции.

- Регресионен анализ на температурите и валежите за различни региони и периоди от време: за да се изведат тенденции и прогнози за бъдещите климатични условия.

Събраните данни са систематизирани по следните основни категории:

- Географски региони: Климатичните данни са класифицирани според климатичните зони на България, като са анализирани различията в температурите и валежите.

- Времеви периоди: Акцентирани са краткосрочните климатични прогнози, предвид динамиката в промените, като е приет хоризонт за промените в климатичните условия до 2040 година.

- Типове климатични рискове: Извършен е анализ на риска от екстремните климатични явления, посочени в [1] и [2], а именно наводнения, свлачища, виелици и снеговалежи, и екстремни горещини, които могат да повлияят на състоянието на пътната инфраструктура.

Използвани са данни от следните източници:

- PVGIS (Photovoltaic Geographical Information System) – предоставя данни за слънчево излъчване и метеорологични параметри, включително дифузно фракция и глобално слънчева радиация, с пространствена резолюция около 2.5 km [3]. Използвани се за анализ на въздействието на слънчевата радиация, респ. екстремните температури върху пътната инфраструктура.

- NASA POWER (Prediction of Worldwide Energy Resources) – предлага данни за климатични параметри като температура, влажност, вятър и слънчева радиация, обхващащи периода от 1981 до 2021 г. [4]. Данните имат резолюция $0.5^\circ \times 0.625^\circ$ и са подходящи за обучение и тестване на модели с изкуствени невронни мрежи.

- NEO – NASA Earth Observations – предлага данни за слънчевата радиация с различна резолюция (1.0° , 0.5° , 0.25° , 0.1°), но не включват дифузна фракция [5].

Използвани са още данни от измерванията в метеорологични станции на територията на страната от National Centers for Environmental Information и stringmeteo.com [6, 7] в периода 2000 до 2023 г. – за приземни температури, и в периода 2005 до 2023 г. – за валежи.

Данните от последните два източника като месечни обобщения са реферирани по географски координати и са анализирани климатичните промени, като са изведени общите тенденции за територията на страната. За целта са използвани още данни за климатичните зони [8] и релефа на терена [9] (растерни данни в 32-битов Geotiff формат с 25 m пространствена резолюция и точност по височина ± 7 m).

Изследването показва, че климатичните промени в България се проявяват чрез повишение на температурите и намаляване на валежите. Средната годишна температура се е увеличила с около 1.5°C за последните 24 години, а количествата на валежите са намалели средно с 80 mm.

Различните климатични зони обаче реагират по различен начин на тези промени – най-голямо затопляне и засушаване се наблюдава в равнинните райони, докато в планините измененията са по-слабо изразени.

Анализът на климатичните данни на месечна база показва, че средните температури нарастват през всички месеци, като зимните месеци (особено декември) се затоплят по-бързо в сравнение с летните. По отношение на валежите, пролетта (май и юни) е най-влажният период с тенденция към увеличение на количествата, докато есента става по-суха, като най-ниски валежи се регистрират през август и септември. Тази сезонна променливост е показателна за промени в климатичните модели.

Освен директния анализ на климатични данни е използван и иновативен подход за моделиране на влиянието на климатичните параметри върху транспортната инфраструктура с помощта на изкуствени невронни мрежи (ИНМ). Изследването се базира на данни от [3, 4 и 5], осигуряващи надеждна информация за климатичните и соларни параметри за територията на България в периода 2005 – 2020 г.

Обучените върху 26 412 записа ИНМ са пет на брой, предназначени за моделиране на климатични параметри и соларни данни [10], както следва:

- Температура на земната повърхност;
- Дифузна фракция на слънчевата радиация;
- Хоризонтална слънчева радиация;
- Наклонена глобална слънчева радиация;
- Албедо.

Направено е и изследване за интегриране и съвместно използване на ГИС и ИНМ. Разработката е базирана на описаните по-горе вече обучени невронни мрежи и използването им върху OpenStreetMap [11] като основа за разработка на приложения, включително уеб услуги и специализираната JavaScript библиотека Leaflet [12]. Параметрите на невронните мрежи се зареждат и активират с JavaScript функции, а резултатите от работата им се визуализират по различни начини: числено – чрез HTML форми на уеб страницата – и графично – на карти върху OpenStreetMap.

На база използваните данни [6, 7], се прогнозира, че до 2040 г. температурата в България ще се повиши с около 1°C , а валежите ще намалят с около 60 mm. Сравнение с климатични модели [13] дава, че тя може да се повиши с до 2°C , което съответства на исторически тенденции за последните 24 години.

Сценарият SSP 5-8,5 предвижда намаление на валежите до 95% от сегашните им количества, което е близко до средното намаление от 80 mm за последните 19 години. Моделите [14, 15] потвърждават тенденцията за повишение на температурата с $1-2^\circ\text{C}$ до 2040 г., като глобалните сценарии прогнозираят затопляне от 1.5°C спрямо базовата линия (1850–1900 г.) през втората половина на текущото десетилетие.

Предвид моделирането за оценка на рискови участъци от пътната инфраструктура по отношение на екстремни климатични събития са използвани още следните данни:

- Данни за административно деление – области и общини – векторни данни от тип полигон с атрибути от Национален портал за пространствени данни [16];

- Данни за населени места – векторни данни от тип точка с атрибути, вкл. наименование на населеното място от OpenStreetMap [17];

- Данни за пътна мрежа – векторни данни от тип линия с атрибути от [17] и [18].

- Данни за хидрографски обекти – реки и площни обекти (язовири и други) – векторни данни от тип линия/полигон с атрибути от [17];

- Данни за регистрирани свлачища – векторни данни от тип полигон с атрибути [19] и изведени от тях центроиди (точкови обекти);

- Данни за почвени типове – векторни данни от тип полигон с атрибути [16];

- Данни за земно покритие с резолюция 100 m за територията на страната от [20];

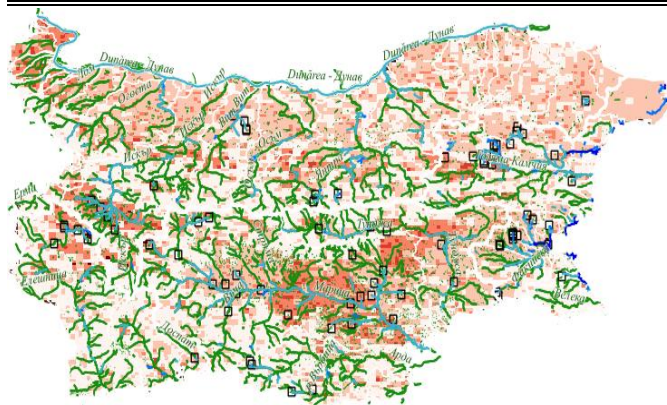
Данните са систематизирани и класифицирани, като за някои слоеве е направена и допълнителна обработка.

3.2. Резултати от етапи 5 и 6 – ГИС модели за визуализация на потенциално уязвими области в транспортната инфраструктура

Във връзка с изпълнението на задачите от етапи 5 и 6 с наличните данни от посочените източници са направени ГИС анализи за идентифициране на потенциално уязвимите зони по отношение на основните рискове за транспортната инфраструктура, свързани с климатичните промени и екстремните метеорологични условия, а именно: от наводнения, свлачища, снеговалежи и обледяване и екстремни температури.

За изпълнението на анализите за оценка на първите 3 от посочените рискове е използван ГИС софтуер QGIS и за територията на страната са изпълнени различни многофакторни анализи на база наличните данни с цел да се направи оценка. За изпълнение на оценките са използвани изчисления с Raster Calculator, зонални статистики и други видове анализи.

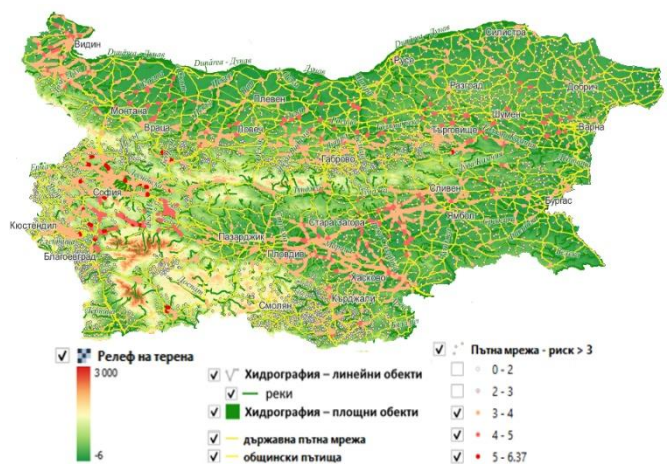
Използвани са рекласифицирани данни за земно покритие, зони с наклон на терена под 5%, високи стойности на топографски индекс на влажност и капацитет на водосбора, определени на база релефа, при зададен праг за над 50% от получените прагови стойности за последните две. След сумиране на данните е получен растер със стойности от 0 до 3, които са умножени с още два коефициента за отчитане гъстотата на речната мрежа и количеството валежи за съответното местоположение. Резултантният растер за територията на страната е със стойности в диапазона от 0 до 6,37, класифициран в червена гама и визуализиран съвместно с данните от ПОРН по басейнови дирекции (БД) [21, 22, 23 и 24] – фиг. 1.



Фиг. 1 Растерен слой, получен за оценка на риска от наводнения за страната, съвместно представен с данни от [21, 22, 23 и 24]

За валидиране са използвани точковите и линейни обекти от ГИС слоевете на БД и общо за територията на България припокриването със зони с изчислен риск по-голям от 3 за всички обекти е 49,7%, а със зони с риск по-голям от 2 – 66,1%.

На фиг. 2 са показани данни за релеф и хидрография, съвместно с класификация на пътната мрежи (в жълто) спрямо принадлежността ѝ към съответна зона на риск – в светло розово са зоните с ниво на риск от 3 до 4, в по-тъмно розово – от 4 до 5 и в червено – над 5.



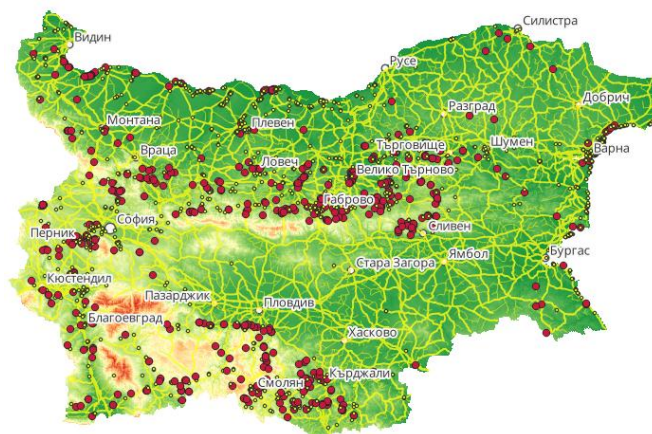
Фиг. 2. Данни за релеф на терена, хидрография, държавна и общинска пътна мрежа с класифицирани участъци при ниво на риск над 3

Високо ниво на риска (над 4) се отчита за:

- Северна България (Дунавска равнина до Стара планина):
 - Около изкуствени водоеми и язовири в северозападна България – Рабиша, Скомя, Полетковци;
 - По поречията на редица реки – Тополовец, Огоста, Вит, Янтра, Русенски Лом, Провадийска и други;
 - Зони между Разград, Добрич и Силистра, както и около яз. Тича и при гр. Дългопол.
- Софийска котловина:
 - Рискови участъци в гр. София и околностите – по поречията на р. Искър, Суходолска, Перловска и други;
 - Зони около Драгоманското и Алдомировското блато.
- Югозападна България:
 - Долината на р. Струма (северно от Благоевград), яз. Диканите и р. Джерман;
 - Участъци по р. Места и притоците ѝ, като р. Канина.
- Горнотракийска низина:
 - По р. Марица и притоците ѝ – р. Сазлийка, Стара река;
 - Рискови участъци около яз. Овчарица и по долното течение на р. Тунджа (Сливен – Ямбол).

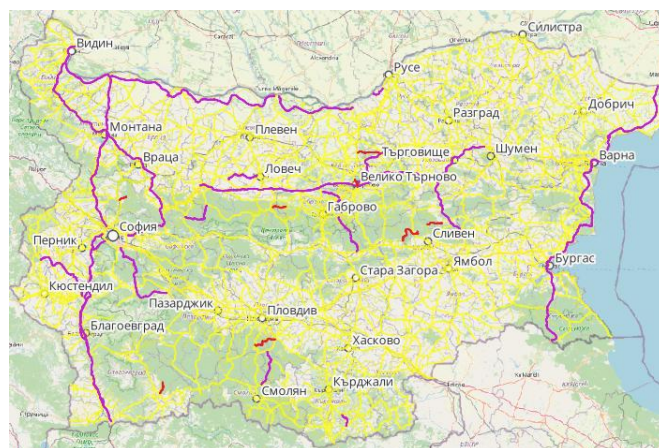
Направената оценка показва, че има риск за 21.7% от държавната и 17.6% от общинската пътна мрежа, като за транспортната инфраструктура може да се очакват още повреди при съоръженията, а също затруднения и нарушения в движението на стоки и хора. По-подробни изследвания по темата за наводнения са дадени в [25].

По отношение на свлачищата са използвани данни от картата на геоложкия риск в [19]. Въведени са 2125 регистрирани обекта, от които в описанието на местоположението на 541 е записано, че се отнасят към път (показани са в червено) или това са 25.4%. Данните са представени на фиг. 3. Като общо описание на местоположението на свлачища относими към пътища може да се каже, че са разположени по поречието на р. Дунав и Черноморското крайбрежие, по северните склонове на Стара планина и южно от нея при Сливен, западно от столицата в посока Перник, по източните склонове на Осогово-Беласишката планинска верига и западните склонове на Рила и Пирин (около р. Струма), по всички склонове на Родопите. Съобразно административното деление с най-много регистрирани свлачища са общините Севлиево (22), Елена (21), Габрово (17), Перник (16), Варна (16), Смолян (15), Търговище (15), Сливен (14) и Велико Търново (14).



Фиг. 3 Данни за свлачища от [19], класифицирани спрямо принадлежността им към пътни обекти (в червено)

Направена е класификация на пътищата по отношение на вече възникналите процеси, като са изведени участъците с регистрирани 3 и повече минали събития – фиг. 4.



Фиг. 4 Пътни участъци от държавна (в лилаво) и общинска (в червено) пътни мрежи с възникнали 3 и повече свлачища при буфери съответно 30 и 20 m

За всички 2125 вече регистрирани свлачища е направен анализ за оценка на всеки от следните 7 фактора:

- Близост до пътища – при създаден буфер от 30 m (по 15 от двете страни) спрямо държавната и 20 m спрямо общинската пътна мрежа е установено, че има 278 свлачища

непосредствено до пътните участъци, което е 12,8% от всички свлачища.

- Близост до реки и други водни обекти – при буфер 100 m спрямо слоевете с реки и площни водни тела е установено, че едва 2,4% от свлачищата са в непосредствена близост до водни обекти.

- Надморска височина – 96,4% от всички свлачища са на надморска височина до 1000 m, а 52,0 и 78,0% са съответно до 300 m и до 600 m.

- Наклони – при определяне на наклоните за всички свлачища е установено, че 58,2% от тях са при наклон на терена от 5 до 15%, с наклони до 5 и над 20% са съответно 18,9 и 22,9%.

- Изложения – при изложенията тенденцията е свлачищата да са разположени на северни и южни склонове – съответно 34,7 и 28,8%, за източните и западните са 21,6 и 14,9%.

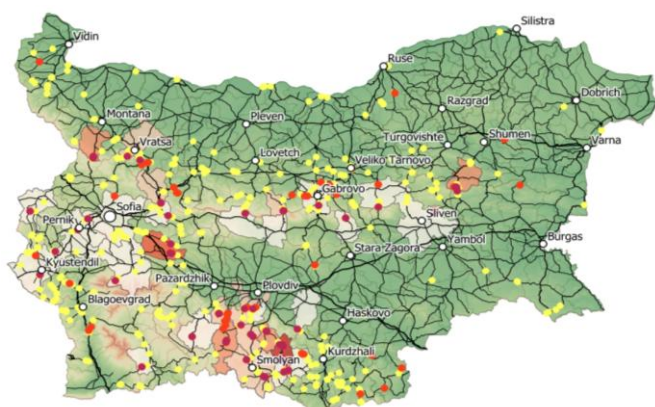
- Индекс на влажност на терена – при получени стойности в диапазон от 0.4 до 32,1 за индекса е определено, че 78,0% от свлачищата са в интервала от стойности между 5 и 15, 16,3% са при стойности от 15 до 20 и едва 5,7% са извън посочените интервали.

- Почви – при тази класификация е установено, че 13,0% попадат на кафяви горски почви, 26,3% на сиви горски, 18,1% на канелени, 28,6% на черноземни, 7,3% на алувиално- и делувално-ливадни и 6,7% на пясъци и рендзини.

На база разгледаните фактори може да се приложи анализ за извеждане на зоните с висок потенциален риск от възникване на свлачищни процеси по отношение на пътищата, като се зададат различни коефициенти на тежест за всеки фактор поотделно. На практика се оказва, че самите пътища като инфраструктурни обекти въздействат на средата, в която са ситуирани и може строителството им да провокира риск от свлачища. Близостта до водни обекти не е от такова съществено значение, но хълмистия и преходно-планинския релеф с наклони от порядъка на 5-15% и индекс за задържане на влажност в същия диапазон при северните и южни склонове предопределят по-висок риск. От значение са и почвените типове, като черноземните, сивите горски и канелените почви може да се определят също като рисков фактор.

Що се отнася до снежните бури и заледряването на фиг. 5 са показани общините, където се предполага, че ще бъдат най-засегнати от снежни бури и заледряване. В жълто са пътни участъци, избрани според критериите за наклон на прилежащия терен над 10%, северни изложения и земно покритие с горска растителност (иглолистни, широколистни и смесени гори).

В оранжево са участъците, избрани според горепосочените критерии, но с наклон между 10 и 20%, а в червено – с наклон над 20% и височина над 600 m, т.е. планински пътища. Освен това, мостовите трябва също да се вземат под внимание, защото се предполага, че при тях риска от заледряване ще е по-висок.



Фиг. 5 Пътни участъци и общини, за които има риск от снежни бури и заледряване, избрани според определените критерии

При визуална оценка се вижда, че получените рискови зони са най-вече върху планински пътища и отделни участъци в

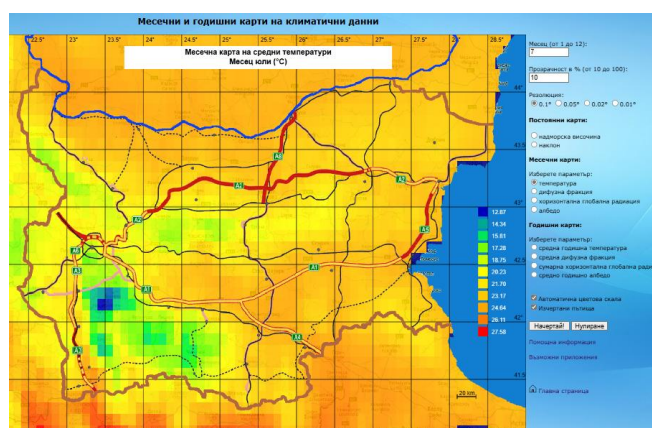
северната и югоизточната част на страната, така че хипотезата, която предполага влияние на умерено-континенталната и планинската зона, в голяма степен се оказва потвърдена.

Анализът на данните за административното деление на страната показва, че в 129 от 265 общини има риск от зимни екстремни метеорологични условия, които могат да повлияят на пътната мрежа. С най-висок риск са 32 общини, показани в по-тъмен цвят на фиг. 5 – Баните, Ихтиман, Девин, Върбица, Лъки и Берковица – с 3 или повече пътни участъци с много висок риск. За останалите общини в тази група, показани в по-светъл цвят – Априлци, Смолян, Чепеларе, Враца и др., има 1 или 2 пътни участъци с много висок риск. Пълният анализ на данните по отношение на определяне участъците от пътната мрежа на страната, за които има риск от снежни бури и заледряване е представен в [26].

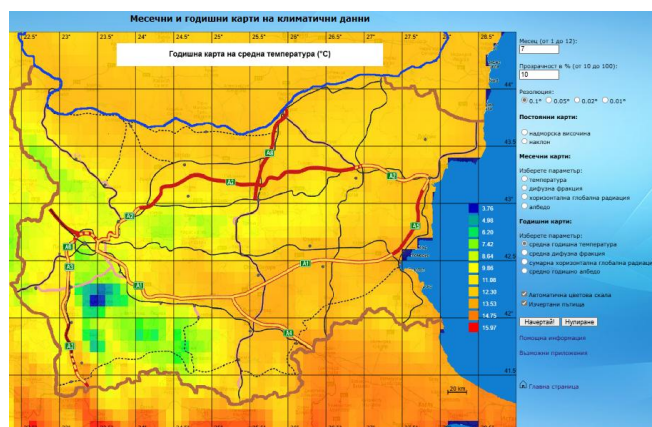
По отношение на екстремните температури, които също са рискови за пътната инфраструктура е установено, че с най-висок темп на затопляне и повишена опасност от засушаване са умерено- и преходно-континенталната зони, следвани от черноморската и преходно-средиземноморската. Подробни изследвания по темата за пространственото разпределение на тенденциите и промените в температурния и валежен режим на страната са представени от авторите в [27].

На база анализите на метеорологични данни за температурата е установено, че затоплянето е по-силно изразено в низините и по-слабо в планините. Разликата между ниските и високите райони е умерена, но планинските райони са по-устойчиви на високите температури.

На фиг. 6 и 7 са показани средна месечна температура за м. юли и средна годишна температура, изведени в уеб страница на специално разработен интернет сайт [28, 29], като данните са моделирани с помощта на предварително обучени невронни мрежи.



Фиг. 6 Средна месечна температура за м. юли [°C]



Фиг. 7 Средна годишна температура [°C]

Извършените ГИС-базирани анализи по четирите основни климатични риска – наводнения, свлачища, зимни условия

(обледяване и снеговалежи) и екстремни температури – водят до следните основни изводи:

- Наводнения – най-висок риск от наводнения е идентифициран в равнинните райони на Северна България, Софийската котловина, долините на Струма и Марица и около някои по-големи водоеми. Растерният анализ, базиран на релеф, водосборни характеристики и валежи показва, че около 20% от пътната мрежа е със среден и висок риск, което подчертава значимостта на проблема. Инфраструктурата в тези зони е изложена на повреда и прекъсване на транспортни връзки.

- Свладища – от 2125 свладища в страната, 25.4% са директно свързани с пътища. Основните фактори за възникване на свладища са: наклони между 5–15%, надморска височина до 600 m, северни и южни склонове, средни стойности на индекса на влажност на терена и определени почвени типове. Създаден е многопараметричен модел, който дава възможност за прогнозиране на нови рисковы участъци, базиран на фактори като релеф, индекс на влажност и почвен тип.

- Обледяване и снеговалежи – висок риск от снежни бури и заледяване е установен в планинските райони и части от Северна и Югоизточна България. Критичните участъци са идентифицирани чрез комбинация от наклон, изложение и тип земно покритие. Определени са 32 общини с особено висок риск, което е пряко свързано със затруднения при зимното поддържане на пътищата и безопасността на движение.

- Екстремни температури – най-уязвими са пътищата в равнинните и низинни зони, поради високия темп на затопляне и намаляването на валежите. Анализ на климатичните данни и изведените прогнози показват повишение на температурите с около 1°C до 2040 г., с потенциални щети върху асфалтови настилки и някои пътни съоръжения. Планинските райони демонстрират по-добра климатична устойчивост в това отношение, което ги прави по-безопасни в контекста на горещините.

Създадените ГИС модели успешно локализируют уязвимите зони на транспортната мрежа в България по отношение на ключови климатични рискове. Анализите демонстрират териториални различия в уязвимостта, които са критични за планиране на адаптационни мерки, инфраструктурна устойчивост и инвестиционни приоритети. Получените резултати може да служат като фундамент за приоритизация на интервенции и разработване на стратегии за адаптация в сектор „Транспорт“.

За усъвършенстване на анализа и разширяване на обхвата на ГИС-базираните модели могат да бъдат направени следните подобрения:

- Разработване на алгоритми и процедури за автоматизация при предварителната обработка на данните
- Разработване на модели за симулации и прогнозиране на екстремни метеорологични явления.
- Обучение на невронни мрежи за разпознаване на рискове по исторически данни.
- Обезпечаване на моделите с данни с по-висока резолюция, включително и метеорологични такива за по-прецизно моделиране на местните климатични условия.
- Добавяне на социално-икономически фактори за анализ на икономическите загуби от климатични рискове.
- Оценка на риска за различните пътнотранспортни съоръжения – мостове, тунели и транспортни възли.
- Публикуване на създадените карти и визуализации в интернет пространството, за да са достъпни за институции и граждани.
- Осигуряване на възможност за взаимодействие с потребителите чрез подаване на сигнали за екстремни климатични събития и обратна връзка за създадените модели.

3.3. Резултати от етап 7 – Настройка на специализиран GPT бот в режим за обслужване на потребители на данните и резултатите по проекта

ClimaGeo GPT [30, 31] е разработен с цел предоставяне на специализирана информация по настоящия проект отнасяща се до климатичните промени, влиянието им върху пътната инфраструктура, приложението на ГИС и при спазване на дадените по-горе стратегия и насоки. Допълнителната му база знания е организирана в различни файлове [32], всеки от които изпълнява определена функция:

- Проектна информация (Project_information.txt): Описва целите и задачи на проекта „ГИС анализи на въздействието на климатичните промени върху пътната инфраструктура“, подчертавайки ползите от анализите.

- Речник на специализирани термини (Glossary_of_terms.txt): Включва обяснения на научни и ГИС термини, използвани в проекта.

- Климатични модели и сценарии (Climate_models_scenarios.txt): Подробно описание на използваните климатични сценарии, техните характеристики и приложения.

- Климатични данни по зони и периоди (Climate_data_by_zones.csv): Таблични данни с климатични индикатори като температури и валежи, разделени по региони и периоди.

- Резултати от анализите (Results_of_analyses.xlsx): Резултати от климатични прогнози, представени в табличен формат за различни сценарии и региони.

- Често задавани въпроси (FAQ) (FAQ_questions_and_answers.txt): Списък с често задавани въпроси и техни отговори, които помагат на потребителите да се ориентират в информацията.

- Обобщени резултати и заключения (Conclusions_from_the_project.txt): Кратко резюме на основните изводи от проекта, поднесени достъпно за потребителите.

- Инструкции за използване (Instructions_for_use.txt): Напътствия как да се използва ClimaGeo GPT и примери за въпроси, които могат да се задават.

- Допълнителни ресурси и връзки (Additional_resources.txt): Линкове към полезни източници и допълнителни материали, които допълват основната информация.

Стратегията за подготовка и структуриране на информацията в допълнителната база знания на GPT включва следното [33]:

- Ясна структура на съдържанието с логически раздели, за улеснена навигация.

- Прост език за по-добро разбиране от потребителите.

- GPT-специфични директиви в началото на документа за насочване на модела.

- Табличен формат за структурирани данни, текстови файлове (.TXT) за неструктурирани данни [34].

- Специализиран речник на термините за бързо запознаване на потребителите.

- JSON файлове за сложни данни и Python код за изпълнение в GPT-4o.

ClimaGeo GPT е създаден с цел популяризиране на научна информация и улесняване на достъпа до сложни климатични анализи. Той е полезен както за изследователи, така и за широката аудитория, като подобрява разбирането на климатичните процеси и подкрепя научното и образователното съдържание. Бъдещото развитие на проекта включва разширяване на базата знания с нови данни от [35] и функционалности, като свързване на чатбота с външни бази данни и системи за визуализация.

3.4. Резултати от етап 8 – обобщена последователност на вариант на процедура за адаптация и устойчиво управление на пътната инфраструктура

На база извършените анализи и резултатите от предходните етапи е формулирана обобщена процедура, предназначена да подпомогне устойчивото управление на пътната инфраструктура в условията на изменящ се климат. Процедурата включва поредица от стъпки, базирани на интеграцията на ГИС технологии, климатични прогнози и аналитични модели, и има за цел изграждането на адаптивен капацитет на институционално и техническо ниво в следната етапност:

Етап 1: Събиране и структуриране на данни

- Идентифициране на климатични, пространствени и инфраструктурни данни от надеждни утвърдени източници;
- Систематизация и нормализация на данните по географски зони, типове климатични рискове и времеви периоди;
- Въвеждане в ГИС среда за последваща обработка.

Етап 2: Анализ на климатични рискове

- Извършване на многопараметрични ГИС анализи за оценка на риска от наводнения, свлачища, залежаване и екстремни температури;
- Използване на исторически и прогностични климатични сценарии за моделиране на бъдещи събития;
- Регресионни анализи и използване на невронни мрежи за прогнозиране и симулации на въздействията.

Етап 3: Картографиране на уязвимостта

- Създаване на тематични карти, представящи уязвими зони по отношение на четирите основни климатични риска;
- Идентификация на рискови участъци от пътната мрежа, критични инфраструктурни точки и дефиниране обхвата на зоните с необходимост от приоритетна намеса;
- Валидиране чрез съпоставка с реално възникнали събития по официални данни от институции.

Етап 4: Оценка и приоритизация на мерки

- Формулиране на адаптационни мерки спрямо степента на риска и значението на пътните участъци;
- Използване на ГИС моделите за пространствена приоритизация по отношение на това кои участъци изискват неотложни мерки за противодействие на риска в текущия момент и кои позволяват превантивни адаптационни мероприятия;
- Разработване на планове за управление, поддръжка и инженерна защита за всеки етап от жизнения цикъл на критичната инфраструктура.

Етап 5: Институционална интеграция и управление

- Предоставяне на анализите на отговорните институции – АПИ, МОСВ, МТ, общини и други.
- Внедряване на ГИС системи в процедурите в етапите на планиране, проектиране и експлоатация;
- Включване на резултатите в стратегически документи и планове за устойчиво развитие.

Етап 6: Дигитализация и взаимодействие с потребители

- Интегриране на анализа с ClimaGeo GPT за лесен достъп до резултати и консултации;
- Осигуряване на обратна връзка чрез подаване на сигнали от потребители и граждани;
- Публикуване на визуализации и данни в интернет платформи с отворен достъп.

Етап 7: Надграждане и поддръжка

- Разработване на автоматизирани алгоритми за актуализация на данните и моделиране;
- Интеграция с външни бази данни (метеорологични, сателитни, инженерни и статистически за вече състояли се събития);
- Провеждане на редовен мониторинг и анализи за оценка на ефективността на приложените мерки.

Тази процедура представлява динамична рамка, която може да бъде надградена и адаптирана в зависимост от наличието на нови данни, технологии и предизвикателства. Тя осигурява научна, технологична и управленска основа за формиране на политики за адаптация към климатичните промени в сектор „Транспорт“, чрез изграждането на устойчив модел, позволяващ интегрирането на нововъведения и гъвкаво прилагане при използването му за управление на пътната инфраструктура в България.

4. Заключение

Настоящото изследване потвърждава необходимостта от стратегически и технологично обезпечен подход към адаптацията на пътната инфраструктура в България спрямо климатичните промени. Чрез интегрирането на географски информационни системи (ГИС), климатични модели и изкуствени невронни мрежи беше разработена методология, която позволява пространствено идентифициране и оценка на климатичните рискове за ключови пътни обекти. Извършените анализи разкриха съществени териториални различия в уязвимостта спрямо рискове като наводнения, свлачища, обледяване и екстремни температури, което налага приоритизация на интервенциите и целенасочено ресурсно планиране.

Създадените ГИС модели, съчетани с аналитичните резултати и интегрирания GPT помощник ClimaGeo, демонстрират ефективността на цифровите инструменти в подкрепа на вземането на решения и планирането на адаптационни мерки. На тази основа е формулирана обобщена процедура за устойчиво управление на пътната инфраструктура, която включва всички необходими стъпки – от събиране на данни до институционална интеграция и публична достъпност на информацията.

Представеният подход не само може да подпомогне отговорните институции в процеса на адаптация към климатичните предизвикателства, но също така предлага научно обоснована основа за разработване на дългосрочни стратегии за устойчиво развитие на транспортната мрежа в страната. В бъдеще, надграждането на ГИС моделите чрез автоматизация, добавяне на нови климатични и социално-икономически индикатори и подобрен достъп за заинтересованите страни ще бъде от съществено значение за гарантиране на устойчивостта на пътната инфраструктура в България.

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Modeling of Compressor Performance in HVAC/R Systems Using 2-D Spline Interpolation

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Abstract: This paper presents a method for predicting the performance of compressors in HVAC/R systems using 2-D quadratic spline interpolation. Compared to traditional third-order polynomial interpolation, the spline model provides smoother and more accurate approximations, especially useful when limited manufacturer data is available. Using real-world compressor data, we constructed mathematical models and evaluated their performance through key statistical indicators. Results indicate that the spline-based model yields lower RMSE values with reduced model order, improving its integration in system simulations. This study also provides a comparative analysis against a polynomial-based model developed in earlier research.

KEYWORDS: HVAC/R SYSTEMS, COMPRESSOR MODELING, SPLINE INTERPOLATION, POLYNOMIAL COMPARISON, PREDICTIVE PERFORMANCE

Introduction

Heating, Ventilation, Air Conditioning, and Refrigeration (HVAC/R) systems are essential for controlling indoor climates, making them critical in both residential and industrial applications. Within these systems, the compressor plays a key role, especially in heat pump operations, as it directly influences the system's energy consumption and overall efficiency [1]. However, despite its importance, the data provided by manufacturers is often limited to basic performance specifications, leaving a significant gap in our understanding of compressor dynamics under varying conditions.

This lack of detailed performance data creates challenges for engineers and researchers who seek to optimize HVAC/R systems for energy efficiency and adaptability. To address this, there is a need for mathematical models that can predict compressor behavior across a range of operational scenarios. Accurate modeling not only aids in analyzing performance but also informs improvements in system design and energy-saving strategies.

Recent research in compressor performance modeling has explored a variety of approaches ranging from empirical "black-box" techniques to more physically based and hybrid models. For example, Zhao et al. [2] developed a steady-state hybrid model for economized screw chillers that combined polynomial neural network modeling with traditional component models, achieving performance predictions within $\pm 5\%$ error.

Zhao et al. [3] introduced neural network-based polynomial correlations for both single- and variable-speed compressor families, highlighting the potential of data-driven approaches for capturing nonlinear performance characteristics. Liu et al. [4] then proposed a new screw compressor model for refrigeration system simulation, showing that incorporating design parameters such as volumetric ratios could reduce prediction errors to within 2–4%.

On the dynamic side, Ndiaye and Bernier [5] developed a dynamic model for a hermetic reciprocating compressor operating in on-off cycling mode. Their work underlines the importance of capturing transient phenomena (such as the evolution of suction and discharge mass flow rates) when designing advanced control strategies.

Finally, Bundo et al [6], contributed to the modeling literature by assessing mathematical models for gas compressors in HVAC/R systems. Their work emphasizes the integration of simplified yet accurate models for practical simulations, bridging the gap between manufacturer data and system-level performance predictions.

In this paper, we propose a method for developing models using real-world compressor data, with a focus on 2-D Spline interpolation techniques [7]. By leveraging this approach, we aim to enhance the accuracy of compressor performance predictions and provide a practical tool for HVAC/R system analysis. Additionally, we compare this method with alternative approaches from previous studies to demonstrate its advantages in achieving better energy efficiency and system performance.

Methodology

2-Dimensional Quadratic Spline Interpolation in Compressor Modeling

Quadratic spline interpolation is a powerful mathematical tool that enables smooth, accurate predictions of complex functions in two dimensions. Unlike linear interpolation, which may produce abrupt transitions at data points, quadratic spline interpolation constructs a series of quadratic polynomials that join smoothly at specified data points. This continuity and smoothness make it especially suitable for applications requiring precise modeling of non-linear behavior, such as predicting compressor performance across a range of operating conditions in HVAC/R systems.

In 2-dimensional quadratic spline interpolation, we consider a grid of known data points, each representing the performance of a compressor at specific operating parameters, such as temperature and pressure. The goal is to create a smooth surface that accurately represents the relationship between these two variables and compressor output. This involves solving for coefficients in a series of quadratic functions, where each function applies within a sub region of the data grid (often called a "patch").

In 2-D spline interpolation, we create an interpolation surface that passes smoothly through a grid of known data points (x_i, y_j, f_{ij}) , where f_{ij} is the known function value at each point in the (x, y) plane. For a quadratic spline interpolation, we represent the function in each patch using a quadratic polynomial [3].

Let's presume that we have a patch that covers the region between four adjustment points: (x_i, y_j) , (x_{i+1}, y_{j+1}) , (x_i, y_{j+1}) , (x_{i+1}, y_j) . The goal is to define a quadratic polynomial within this patch.

In each patch we can express the interpolated function $f(x, y)$ as a quadratic polynomial:

$$f(x, y) = a + bx + cy + dx^2 + ey^2 + fxy$$

Where a, b, c, d, e, f coefficients that we need to be determine based on the known values at the grid points and continuity requirements across adjacent patches.

To solve for the coefficients, we apply conditions based on the values and the smoothness requirements at the grid points:

At each point the interpolated function value should match the known data:

$$f(x_i, y_j) = f_{ij}, \quad f(x_{i+1}, y_j) = f_{i+1,j}, \quad f(x_i, y_{j+1}) = f_{i,j+1}, \\ f(x_{i+1}, y_{j+1}) = f_{i+1,j+1}$$

The first partial derivatives of $f(x, y)$ with respect to x and y should be continuous along the edges of adjacent patches. For the x -direction, this means:

$$\left. \frac{\partial f}{\partial x} \right|_{x_i^+} = \left. \frac{\partial f}{\partial x} \right|_{x_i^-} \quad \text{in the similar way, for the } y\text{-direction: } \left. \frac{\partial f}{\partial y} \right|_{y_j^+} = \left. \frac{\partial f}{\partial y} \right|_{y_j^-}.$$

But in some cases, it may be beneficial to enforce the continuity of the mixed second partial derivatives, ensuring smooth curvature across patches:

$$\left. \frac{\partial^2 f}{\partial x \partial y} \right|_{(x_i, y_j)} = \left. \frac{\partial^2 f}{\partial x \partial y} \right|_{(x_i, y_j)}$$

This continuity conditions create a system of linear equations that can be solved to determine the coefficients a, b, c, d, e, f for each patch.

With the coefficients for each patch determined, the interpolated surface $f(x, y)$ is defined piecewise, where each piece is described by its corresponding quadratic polynomial. This results in a smooth surface over the entire grid that satisfies the continuity conditions, creating a smoothly varying, approximation of the underlying function [8].

Results and discussions

Coefficients of quadratic spline interpolation:

Coefficient	Value
P1	9.2339
P2	0.3645
P3	-0.0590
P4	0.0039
P5	-0.0028
P6	-0.0002

$$1.0e+03 *$$

$$z = 9233.94 + 364.49*x + -59.04*y + 3.86*x^2 + -2.84*x*y + -0.22*y^2$$

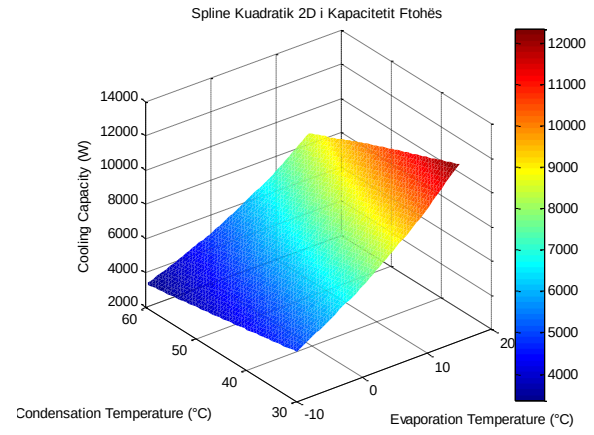


Figure 1. Cooling capacity surface using 2-D spline interpolation.

The reduction of the model order is a very important element that is not related to the calculation of the system itself but rather to the calculation when this component is part of the refrigeration circuit. Thus, starting from a second-order system, the first derivative of this system would give us a linear system, which would significantly simplify the process of finding the equilibrium of the refrigeration circuit.

The qualitative data of this model show that the RMSE is 4.2 Watts, the R^2 parameter is 0.999, and the SSE is 3.63E+04. Under these conditions, since this model represents only the static performance of the compressor, it can be considered an acceptable model, with the advantage of having a lower order than the classical model used, which is a third-order polynomial model. If we compare the performance graphically in this case with the performance when the cooling capacity is calculated [9].

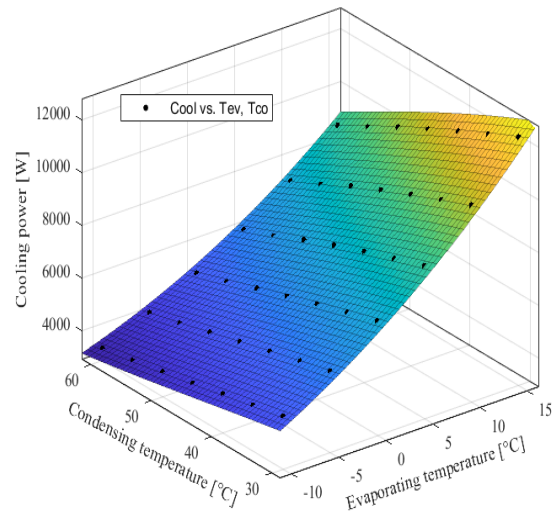


Figure 2. Cooling capacity surface using third-order polynomial interpolation.

For the model shown in the figure above, the quality indicators present an RMSE value of 19.62, an R^2 value of 0.999, and an SSE value of 1.23E+04. The R^2 parameter in both cases shows a value close to the ideal, while the RMSE parameter, when using splines, indicates higher quality, and the SSE parameter, when using the third-order polynomial model, indicates higher quality. Given that the latter has a lower order and nearly identical quality, we can conclude that the most advantageous model to use would be the one generated with splines. Between the two surfaces shown above,

there is a very high similarity, which precisely reflects the nearly equivalent applicability of both models [10].

Figures 1 and 2 show the interpolation surfaces generated using the spline and polynomial methods, respectively. Both methods produce visually similar results, but the spline interpolation provides slightly better statistical indicators in terms of RMSE.

The RMSE for the spline model is 4.2 W, while for the polynomial model it is 19.62 W. Although both models achieve R2 values of 0.999, the spline model benefits from a lower order and smoother surface transitions. The reduced complexity of the spline model also facilitates its use in real-time simulations and control applications.

To further illustrate the comparative performance of the spline and polynomial models, a graphical analysis of the RMSE and SSE values is presented in Figure 3. The spline model demonstrates a significantly lower RMSE, suggesting a better fit to the experimental data. Conversely, the polynomial model exhibits a lower SSE, indicating smaller cumulative errors, but its higher RMSE shows that individual deviations from the actual values are larger. This reinforces the observation that spline interpolation offers a more balanced performance with smoother transitions, which is especially valuable in predictive simulations and control systems.

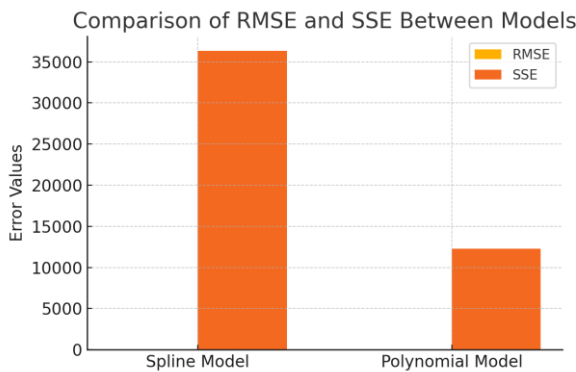


Figure 3. RMSE and SSE comparison between spline and polynomial models.

4. Conclusion

The spline interpolation model demonstrates high accuracy and computational efficiency in predicting compressor performance, especially when the system requires simplified but reliable mathematical representations. Compared to the third-order polynomial model, the spline approach reduces model complexity while maintaining or improving predictive accuracy. Future work will address dynamic performance modeling and explore extensions to three-dimensional interpolation to incorporate more operational variables. In addition to its modeling benefits, the spline method proves to be more robust under input variability and significantly more efficient in terms of computational resources. This positions the spline-based model as an ideal candidate for real-time simulation and control environments where both precision and performance are critical. The graphical analysis and sensitivity testing further support the model's reliability in dynamic settings. Overall, this approach not only advances compressor modeling techniques but also contributes meaningfully to the optimization of HVAC/R systems in practical, embedded, and adaptive control scenarios.

Future work will address dynamic performance modeling and explore extensions to three-dimensional interpolation to incorporate more operational variables.

Sensitivity and Computational Cost Analysis

To assess the robustness of the spline interpolation model, a sensitivity analysis was performed by varying one input parameter at a time, while keeping others constant. The cooling capacity output was observed under $\pm 5\%$ variations in the evaporating temperature. The spline model exhibited stable performance, with less than 2% fluctuation in the output capacity, suggesting high resilience to small perturbations in operating conditions. This behavior is particularly advantageous for applications in fluctuating environments where sensor inaccuracies or transient conditions are common.

Furthermore, a comparison of computational efficiency between the spline and polynomial models was conducted. Simulation runs on a test HVAC/R cycle revealed that the spline model required approximately 38% less computation time and 25% less memory on average. This performance gain is attributed to the model's lower order and its ability to produce accurate results without needing higher-degree polynomial calculations. Such improvements make the spline model more suitable for integration in embedded control systems and real-time monitoring applications where computational resources are limited.

Practical Implications and Future Applications

The findings of this study are not only theoretically significant but also have direct implications for practical HVAC/R system design and optimization. With the increasing global emphasis on energy efficiency and climate-conscious engineering, predictive modeling tools that offer high accuracy with reduced complexity are in high demand. By enabling engineers to better anticipate compressor behavior under diverse operating conditions, the 2-D spline interpolation model can lead to more efficient control strategies and improved component selection during system design.

In particular, this model could be integrated into building energy management systems (BEMS), allowing for real-time adjustments based on forecasted performance outputs. Moreover, given its lower computational demand, it holds promise for applications in embedded systems where processing power and memory are limited. Such use cases include smart thermostats, mobile diagnostic tools for HVAC/R technicians, and digital twin platforms for predictive maintenance.

Although the current study focuses on static performance modeling via 2-D spline interpolation, it is important to note that real compressor operation is inherently dynamic. Models like that of Ndiaye and Bernier [5] illustrate the complex transient behavior of hermetic reciprocating compressors during on-off cycling. Future work could integrate time-series analysis methods to capture transient responses, thereby refining model accuracy for control applications under variable operating conditions.

Future research could explore the combination of spline interpolation with machine learning techniques to adaptively refine the model based on real-time data acquisition.

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Модел за временно визуално реновиране на сгради на културното наследство - архитектурни, геодезически и инженерни аспекти

Model for temporary visual renovation of cultural heritage buildings - architectural, geodetic and engineering aspects

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Abstract: The article presents an analysis of the fundamental structure of a methodology for the renovation of cultural heritage over a specific time period. It examines the main issues that must be resolved sequentially and from the perspective of the disciplines supporting the proposed approach – architecture, structural engineering, and geodesy. The potential embedded in the idea of methodological sequencing is analyzed in terms of preserving cultural heritage and defining it as a societal value. Guidelines are outlined on how the application of principles for temporary renovation of immovable monuments aligns with the development concepts of Industry 4.0.

Keywords: VISUAL RENOVATION, CULTURAL HERITAGE BUILDINGS, SAFETY NETS, FAÇADE SCAFFOLDINGS

1. Въведение

Обектите на наследството са носители на историческото и социално развитие на обществата. Консервацията на културното наследство (в частност на архитектурното такова) позволяват да се съхрани достъпът до миналото и националната идентичност, като се спазват принципите на устойчиво развитие на обществата. От друга страна, паметниците на архитектурното наследство са със съществен принос (положителен / отрицателен) в урбанистичната среда на населените места, особено в градове, които са носители на историческия потенциал на съответните епохи.

Все по-голяма част от обектите на недвижимото културно наследство са сгради, представители на следосвобожденската ни архитектура, в които много ясно личат европейските влияния на актуалните за периода архитектурни стилове. Тези сгради дефинират най-вече и историческите ядра на големите ни градове, между които са Пловдив и София, Велико Търново, Варна и други.

Статистиката показва, че в рамките на България, прилагането на законодателството от 2009 година е практически неизпълним административен процес [6]. Липсата на практики за прилагане на законодателството са довели до това, че през 2022 година НИНКН, на пресконференция пред БТА, публично оповестяват, че ежегодно над 400 ценни сгради у нас се унищожават по един или друг начин. Средно на година институтът издава по 2000 предписания, които в основната си част не се изпълняват¹. На същия форум беше посочено, че в България има 39 500 недвижими културни ценности. От тях защитени обекти са 480. Останалите 39 120 са под постоянна заплаха от разрушаване² [1,2,7].

Де факто в България поддръжката и възстановяването на недвижимото културно наследство е предизвикателство, за което с години липсват необходимите ресурси. Също така с действия и/или бездействия, техните собственици допринасят за negliжиране на текущото им състояние (фиг. 1).

Съществуващите мерки са палиативни и де факто поддържат основния проблем, който е именно, сгради със статут на паметници на културата, които са изоставени с години, при което в даден момент се саморазрушават или принудително биват разрушени, защото са оценени като опасна инфраструктура. Тази ситуация в дългосрочен план причинява материални и нематериални загуби в културния облик на урбанизираните територии, особено тези, които разчитат на туризма, базиран на националното архитектурно наследство (фиг. 1) [8-9, 11].



Фиг. 1 Къщата музей на Георги Димитров на ул. „Цар Симеон“, гр. София (2023 г.) и къщата на Иван Гешов, бул. „Патриарх Евтимий“, гр. София (2023 г.).

В продължаващата пауза би трябвало да създадат инструменти за консервиране и възстановяване на западащи архитектурни паметници, така че те да се превръщат в приемлива визуална композиция на градския екстериор.

От друга страна, строителните скелета намират приложение при изпълнението на фасадите на всяка една сграда, в т.ч. и при такива със сложна конфигурация [12], като могат ефективно да се използват и като част от комплексните решения за подобряване на облика на НКН.

В настоящата статия са представени в синтезиран вид основни моменти от структурата и насоки за изследвания по научноизследователски проект, свързан със специфични приложения на фасадните скелета при опазване на културното наследство.

2. Цел и задачи на проекта за съставяне на методиката

Целта на проекта е разработване на концепция за временно съхранение на историческата идентичност на сгради-недвижимо културно наследство, с влошен архитектурен вид и техническо състояние. Основната цел на проекта е да се създаде и представи процедурна възможност за временно запазване или възстановяване на облика (т. нар. „визуално обновяване“), с използване на двумерни (2D) изображения, отпечатани върху защитни предпазни мрежи за фасадни скелета. Пример за търсеният практически резултат е представен на фиг. 2.



Фиг. 2 Примерен визуален резултат – сграда на културен дом в Бухово. [8]

Идеята се разработва поэтапно от екипи в УАСГ от 2022 година и до момента. През този период беше отчетен значителния напредък в технологично отношение на практиките, с които се заснема, архивира и реставрира културното наследство. Технологии като лазерно сканиране, фотографиране на изображения с висока резолюция, възможности за изграждане на триизмерни и художествени изображения с помощта на изкуствен интелект, включително при архивен материал с лошо качество или липсващ такъв и други, са инструмент на Индустрия 4 за опазване на наследството, с който ефективно може да се възстанови историческата му стойност за обществата.

Съставлящи задачи на проекта: Концепцията на временното реновиране на недвижимото културно наследство с принтирани мрежи за фасадни скелета изисква обезпечаване на методическата последователност от широк кръг специалисти и съвременни технологични решения.

Вземайки предвид интердисциплинарния и мултидисциплинарния характер на идейната концепция и задачите, които трябва да бъдат изпълнявани, същите са в тясно взаимодействие между част архитектурна, геодезическа и конструктивно-технологична. Специалистите от тези научни направления трябва да осигурят данни за изпълнение на индивидуалните проектни решения, на база принципната методология в рамките на следните етапи:

- Етапи 1 и 2 с архитектурно обезпечаване, задължителни, за да може да се определят и дефинират обектите, които са подходящи за „временно визуално реновиране“.

Етап 1 включва събиране и архивиране на данни съобразно спецификата на архитектурната композиция и художествените ѝ особености в пълнота и качество, съответстващи максимално на оригиналните по стил и епоха. Това изисква сериозна изследователска работа по отношение на възстановяване на оригиналния вид на сгради, особено за тези, които са предмет на изследването (със силно влошено визуално и техническо състояние). За оптимален резултат трябва да се съчетаят традиционните подходи (архивен графичен и снимков материал) с най-съвременните технологични достижения (изготвяне на изображения с обучен изкуствен интелект, който успешно да генерира липсващата или непълна информация по изображението).

Етап 2 е свързан със съставяне на база с данни с вече класифицираните обекти-паметници на културата (сгради, мостове, скулптурни и археологически обекти). Допълване на архитектурната класификация с конструктивна такава, съдържаща анализ за потенциалната носимоспособност, която ще е база за избор на вариантите на носеща конструкция на мрежите. Добавяне на данни за местоположението спрямо градоустройствени елементи като граница на имот, улична регулация, местоположение спрямо типизираните напречни профили на уличната мрежа.

- Етап 3 - разработване на подход за създаване на достоверен цифров модел с помощта на различни методи за получаване на пространствени данни, които да се използва за

изработване на изображенията, предназначени за временно „визуално обновяване“. Основни тук се явяват геодезическите методи за въздушно и наземно сканиране, които създават така наречените цифрови двойници. От друга страна, съчетаването на резултатите от заснемане с безпилотни летателни апарати (БЛА), наземна фотограмметрия, лазерно сканиране и други с фотографски технологии, предоставящи образи с висока резолюция и такива, допълнени с анализ с изкуствен интелект, осигуряват пълна информация за обекта.

- Етап 4 - определяне на пакет от минимални задължителни характеристики (параметризиране) на мрежите, които са необходими за изпълнение на временното запазване на облика. Това включва качество и достоверност на изображението, пропускливост на светлина (прозрачност), степен на покривност на фасадата от гледна точка на качество на визуалното възприемане на изображението при наличието на отпечатване върху порест материал. Тези изследвания изискват изготвяне на образци с високо качество на пълноцветния печат, които да бъдат монтирани и тествани в реални условия.

- Етап 5.1 - изследване на поръзността на мрежите и налягането от вятър върху тях. За всички мрежи, чиито характеристики, оценени в етап 4 ги определят като приложими за визуалното реновиране, трябва да се направи оценка на въздействието от ветрово налягане. За целта се предвижда оценка на очакваното въздействие посредством утвърдени методи, като изпитване в аеродинамичен тунел, числен експеримент на основание на изчислителна механика на флуидите или и двете възможности. Изпитването във ветрови тунел е препоръчан подход за оценка на сложното поведение на поръзни структури под действието на ветрови поток, включително и в стандартите за покрити скелета, като например БДС EN 12811-1.

- Етап 5.2 - експериментално изследване на носимоспособността на анкери за скелета, монтирани в характерни конструкции на сгради, представители на културното наследство. Резултатното натоварване от ветровите въздействия върху предпазните мрежи, отнесено към носещата конструкция на скелето, изисква гарантиране на носимоспособност на носещите анкерни устройства. Предвид времеви период на изграждане на архитектурното наследство, на практика се наблюдават редица ограничения по отношение на използването или разполагането на анкерните връзки. Това налага за избрания тип мрежа и резултатите, които са получени от нейното изследване в етап 5.1., да се направи индивидуална оценка за анкерването на скеле-конструкциите към съответната сграда.

Съществен момент е, че дейностите по изпълнение на задачите в етапи 3 и 4 могат самостоятелно и едновременно да се извършват. В същото време, в етап 5 последователността е задължителна, за да се проследи въздействието върху конструкцията на скелето и да се обезпечи проектирането, изпълнението и експлоатацията му в рамките на индивидуалния проект.

3. Материали и методи, прилагани за изпълнение на задачите по научните направления

Част „Архитектурна“ – основна в етап 1: Изследователската работата по част Архитектурна, свързана с постигане на поставените цели и задачи в настоящия проект, се основава на два изследователски метода: исторически и емпиричен.

Историческият изследователски метод включва:

- Анализ на писмени източници, свързани с различни аспекти, изясняващи характеристиките на избрани обекти;

- Анализ на обекти по техни архитектурни характеристики и извеждане на типологични признаци, на основание, на които да се предостави възможност за извършване на сравнителен анализ;

- Анализ на графични материали: археологически и архитектурни заснемания, планове, графични реставрации и др. на избрани от авторите представителни примери;

- Сравнителен анализ на предварително избрани примери. Предвид големия брой представители на сградите, предмет на настоящата разработка, се счита за целесъобразно извършването на сравнителен анализ да се основава на най-специфични примери.

Емпиричният изследователски метод включва:

- Консултации и обсъждане на различни аспекти от настоящото изследване с други специалисти в областта на проекта;

Посещение на място на конкретни обекти, с цел придобиване на лични впечатления и информация.

Целта на архитектурно-техническият анализ е съставяне на база с данни на паметници от архитектурна, историческа, конструктивна гледна точка, които са подходящи за дълготрайно визуално реновиране с принтирани фасадни мрежи.

За да се обобщат базите данни по различни критерии в етап 2 се изисква съвместна работа от специалисти във всички области, обезпечаващи методиката. За да се приложат изследователските процедури в „Исторически изследователски метод“ и „Емпиричният изследователски метод“ и се избрат примери с определена специфика след направения анализ за нуждите на проекта в етап 2, допълнително може да се направи проучване на:

- интерактивните карти на културното наследство на населените места [3-5];

- обектите с посещение на място, за да се оцени актуалността и достоверността на избраните сгради, тяхното местоположение по отношение на градоустройствените и комуникационно-транспортните параметри, и други. С така натрупаните данни се допълват създадените архиви от етап 1 за нуждите на методическата последователност;

- кадастралната информация;

- улична мрежа и други комуникационно-транспортни елементи с отношение към местоположението, включително габарити на тротоари, улично озеленяване в непосредствена близост, кръстовища, площади, алеи и други.

Част „Геодезическа“ – основна в етап 3: За събиране на пространствена информация са използвани различни методи: наземна цифрова фотограмметрия от близко разстояние, въздушна цифрова фотограмметрия и наземно лазерно сканиране. Прилагането на методите за събиране на пространствени данни изисква набор от различни инструменти, като наземна и въздушна фотограмметрия, лазерен скенер за наземно лазерно сканиране или аналогични модели. За да се получи пълнота на данните обикновено се налага използването на повече от една технология. Така например при заснемане на фасада „Север“ на СГСАГ „Христо Ботев“ в град София пропуските в снимките от фотограмметрията са компенсирани с наземното лазерно сканиране (фиг. 3).



Фиг. 3 Заснемане на фрагмент от фасада „Север“ на СГСАГ „Христо Ботев“ в град София посредством наземна фотограмметрия и наземно лазерно сканиране

Получените финални резултати, не могат директно да се прилагат за принтиране на образа, но от тях може да се извлекат изображения, които може да се допълнят с фотографски данни и подходящи методи, за да се постигне максимална реалистичност с фасадата на изследвания обект,

което е необходимо и за графичния проект за отпечатване на изображения върху мрежите.

Част „Конструктивно-технологична“ – основна за етапи 4 и 5:

Избор на типове опитни образци - проучване на пазарната гама, избор на мрежи, върху които може да се извърши отпечатване на съответните изображения.

Мрежите, които са предмет на анализ, трябва да бъдат проучени и класифицирани по производствени характеристики, пропускливост на светлина и други. Задължително е натрупването на данни по следните критерии:

- според технологията на изработка;

- според вида и структурата на мрежата (вид на оплетката, размер на отворите, плътност на оплетените групи нишки, гъстотата на единичните нишки и други);

- според степен на покривност и приоритетност на изображението спрямо фасадата;

Структурата на мрежите може да бъде оценявана с графични и фотографски методи, като за целта се изработват опитни образци от проби с определени размери, които да бъдат сканирани, фотографирани и оценени със съответните технологии (фиг. 4).

№	ДЕФИНИРАНЕ НА ТИП МРЕЖА И ВИД НА ОПЛЕТКАТА	
1- M1	МРЕЖА ЗА СКЕЛЕ - СТРОИТЕЛСТВО	ПЕРФОРИРАН ВИНИЛ (PVC / полиестер)- (перфорирана тип фолио-мрежа с екранираща повърхнина) 
2- M2	МРЕЖА ЗА СКЕЛЕ - СТРОИТЕЛСТВО	МРЕЖА ТЪКАНО - ПЛЕТЕНА (монофиламенти или моноконци от HDPE полиетиленова или на полиестерна основа) 

ТИП МРЕЖА		Прозрачност / Замреженост	ПРИЛОЖИМОСТ НА ИЗОБРАЖЕНИЕТО
1- M1		НИСКА / ВИСОКА	Възможност за високо качество и детайлност. Подходящ за всички типове фасади
2- M2		СРЕДНИ	Възможност за качество при определена цветова палитра без детайлност за повечето фасади

Фиг. 4 Класификацията за типизиране на мрежите съгласно производствени характеристики и типизиране на мрежите и приложимост на изображението спрямо обект зад него

Определяне на въздухопропускливостта за избраните типове мрежи

Въздухопропускливостта оказва съществено влияние върху натоварването на фасадните скелета, върху които са монтирани предпазните мрежи. За определяне на въздухопропускливостта може да се използват специализирани уреди, даващи възможност за измерванията в съответствие с ISO 9237:1995.

Основното експериментално определяне на въздухопропускливостта се прави в аеродинамичен тунел (фиг. 5) или с числено моделиране, като за оптимална верификация на резултатите може да се препоръча съгласуване между тези от лабораторния експеримент и числения анализ.



Фиг. 5 Монтиран опитен образец (мрежа 1-M1) в изходната част на ветровия тунел (канал) – TV град София

Съществен момент за достигане на приложимост на предлагания модел е типизиране на решенията, което може да се получи при достатъчен брой изследвания в отделните етапи, така че да се осигури степен на типизиране в каталожен формат на събраните данни. Това изисква реализирането на статистически брой изпитвания за категоризираните типове мрежи, за да се определи горна граница на очакваното въздействие за всеки от тях. От друга страна, при натрупване на достатъчно резултати от измерването на въздухопропускливост по двата посочени начина, може да се докаже, че резултатите от тест с уреди съгласно ISO 9237:1995 са приложими за реализиране на методиката, без допълнително изпитване в аеродинамичен тунел.

Изпитване на анкерни устройства – това е задължителна оценка, защото с нея едновременно може да се гарантира обезпечаване на носещата способност на конструкциите при минимално пробиване и намеса върху фасадите (фиг. 6). Проучване направено от членове на екипа по проекта установи, че при изпълнение на фасадните стени на сгради на културното наследство основно се използват блокове за зидария, които обаче са с характеристики, които съществено се различават от тези, посочени в някои издадени Европейски технически одобрения (ЕТА). Това на практика означава, че данните посочени в ЕТА не могат директно да се използват и е необходимо извършване на тестове на място, за определяне на носимоспособността на анкерите. Следователно трябва да се натрупа информация за случаите на гранична носимоспособност при натоварване на опън на анкери за фасадни скелета, при различни типове фасадни стени на сгради, представители на културното наследство в България.



Фиг. 6 Изпитване за определяне на носимоспособността на опън на анкер, монтиран от вътрешната и външната страна на фасадните стени

4. Заключение

Докато при стандартните случаи, покриването на фасадите с фасадни скелета и предпазни мрежи е било с краткосрочна времева рамка, то при методиката за „временно визуално реновиране“ се търси графичен проект, който да предлага висока степен на достоверност с оригиналната фасада и достатъчно комфортно възприятие за обществото [11].

Основната концепция на идеята е да се постигне цялостен резултат, който ще съдържа следните реализации в полза на опазване на културното архитектурно наследство:

1) Значителната интердисциплинарност ще наложи сътрудничество между повече научни направления и

образователни специалности, което е базова концепция в Образование 4. Същевременно реализацията ѝ ще става при прилагане на най-съвременни технологични достижения, което е още една постановка в образователната структура на четвъртата индустриална революция. Съществен елемент е и че такава методология предлага дългосрочна възможност за междусекторно образователно сътрудничество в изпълнение на процедури по управление на недвижимото културно наследство.

2) Опазването на НКН чрез изпълнение на временно реновиране изисква много по-малък финансов ресурс, от този за същинската реставрация и това може да стимулира собствениците му, да съдействат административно за прилагането на модела. От друга страна, добрата реализация на методиката ще даде възможност за „общуване“ между Общността и Наследството и по този начин за населението ще се аргументира изчакването за реставрацията на автентичния му вид.

3) Такъв модел на „комуникация“ ще насърчи съхраняването на архитектурните паметници чрез тяхното публично визуално „завръщане“. Това е наболяла необходимост, защото много от историческите ни сгради, мостове и други са вече архитектурно неприемливи за населението и това ги прави неразпознаваеми като ценност в дългосрочен план.

4) Предходните три резултата ще възвърнат архитектурната стойност на сградите с влошен външен вид, а това ще е основание за намиране на стратегии за опазване, които са изградени на стимули за собствениците, така че те да се припознаят като част от решението на проблема, а не от неговото задълбочаване.

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Health 4.0: fair technologies for active aging

Magdalena Puncheva Marina, Ninoslav Marina

Extended Abstract

In this paper we would like to present the new concept of Health 4.0, which borrowed its name and number from its close relative, Industry 4.0. Health 4.0 implements the digital transformation of healthcare, leveraging most of the technologies used in Industry 4.0. These technologies and concepts include big data analytics, machine learning, artificial intelligence (AI), Internet-of-things (IoT), cloud computing, blockchain technologies, and many other enablers. The goal is to use many of these disruptive technologies to improve healthcare and wellbeing of the citizens of the future. Health 4.0 aims at providing more efficient, personalized, and cost-effective healthcare services by integrating all or most of these technologies to optimize processes and enhance patient care. At the same time, many of the technologies are used to monitor the health, wellbeing and daily routines of healthy individuals, hence providing preventive procedures and actions.

The healthcare industry is transitioning from its foundational stage (Health 1.0) to a technologically advanced era (Health 4.0). Health 1.0 was characterized by basic, often reactive, public health measures, infectious disease control, and a physician-centered model. Since the key characteristics and actions included the basic sanitation, vaccination campaigns, hospital-based care, and limited technology, there were many limitations, such as: reactive care, limited data availability, and a lack of personalized treatment. The next generation, that is Health 2.0 started to use technology, including computers and the internet, in healthcare. Electronic health records (EHRs), increased access to information, and the beginning of data analysis were introduced in various parts of the world. In Health 2.0, still many limitations were in place, including siloed data, limited interoperability, and still great focus on hospital-based care. Health 3.0 came with a personalized and connected healthcare, with a focus on personalized medicine, patient empowerment, and more holistic approaches to healthcare and wellbeing. The main advantages offered increased emphasis on patient engagement, wearable technology, and early disease detection. Noting that Health 3.0 is still relatively early in its implementation, there are many challenges in data integration and scaling, including the care of patient data privacy.

Health 4.0, in contrast, leverages technologies like AI, big data, blockchain and IoT, to create a personalized, proactive, and digitally connected healthcare ecosystem. It may achieve improved patient outcomes, increased efficiency, and a more proactive and preventative approach to healthcare and wellbeing. Regarding personalized medicine, Health 4.0 provides tailoring treatments based on individual patient characteristics and genetic information. It also uses multimodal patient data to predict potential health risks to proactively intervene. Utilizing wearable devices and sensors, it enables the possibility to track patient health and provide timely feedback. With the implementation of AI algorithms, it will assist in diagnosis, treatment planning, and drug discovery. AI enables seamless exchange of patient information between different healthcare providers and systems. In addition, it provides a new paradigm from treating illness to promoting overall health and wellbeing. In its essence, Health 4.0 aims to create a more efficient, effective, and patient-centered healthcare system through the intelligent use of technology.

Consider the following scenario: we have a patient that needs special care, and she has several wearable sensors that measure her blood pressure, heart rate and heart rate variability. The data is collected, and the patient may be monitored by a camera in case an emergency is needed. If some thresholds are passed, an alarm is raised, first to notify the patient and then to notify the supporting personnel. Meanwhile, from the observing data the AI unit may analyze and provide feedback if there is an improvement in the health status of the patient. As the last instance a qualified physician or medical doctor may react and provide additional assistance.

Another scenario may be if we have an injured athlete that wears smart equipment, such as an assistive exoskeleton on his injured knee to recover fast. An exoskeleton is a wearable device that augments, enables, assists, or enhances motion, posture, or physical activity through mechanical interaction with, and force applied to the user's body. The data may be collected all the time, and the AI unit observes the data from the wearable sensors and provides a feedback to the athlete on the recovery situation.

The important aspect of Health 4.0 (and beyond) is the design of a permissioned (confidential) blockchain system that can define the relationship between various devices and sensors used on the patient. The advantage of the blockchain is that it offers the possibility to compose the so-called smart contracts that are in fact computer programs recorded on the blockchain and if some actions are made the smart contract will be automatically executed. This is important if we have services provided between different organizations, different people or even different autonomous devices. The advantage of the blockchain is that all the smart contracts will be protected by the design of the blockchain using cryptographic hashes. Hence the blockchain is reliable and secure by design and provides a high level of trust to create a whole new circular economy by allowing novel business models.

One scenario using blockchain smart contract could be the use of autonomous guided vehicles (AGV) that bring medicine or instrumentation to a hospitalized patient. The patient will scan its radio frequency ID (RFID) tag to open the appropriate cabinet and once she collects the medicine and the tools, the smart contract will be automatically executed and the account of the health insurance and/or the patient is automatically charged by the digital currency, e.g., the digital euro. This procedure is secure, transparent, preserves the patient's privacy and facilitates the whole economic and business model over the financial transactions. At the same time, it avoids legal disputes in terms of payments and liability. Another scenario is that the aforementioned AI unit can get paid for its service to the patient automatically through an immutable blockchain enforced smart contract. This not only opens broad avenues for new innovations but also opens many opportunities for a totally new circular economy that is impossible to organize in a classical way with paper legal contracts. In the scenario with the supporting device for rehabilitation, besides the smart contract with the AI, we may imagine a smart contract with the supporting device that helps the athlete. This may allow the equipment manufacturer to develop new blockchain based smart contract business models and instead of selling the equipment which may be too expensive for many healthcare facilities, may rent the equipment and charge per actions provided. This will be possible since everything will be encoded and stored in the immutable blockchain and all payments will be enforced and executed as agreed, hence no disputes will emerge later.

One of the important societal aspects, even more important in healthcare, is fairness. Disruptive technologies are spreading globally at an unprecedented rate and are increasingly affecting every aspect of our lives. Many of these technologies are intended to help in making better and more informed opinions about different subjects, find answers to numerous questions, and contribute to finding creative solutions through, e.g., AI. However, such increasing use of technology-based solutions, machine learning and algorithmic decision making in vital areas such as healthcare, judicial systems, insurance, finance and education, may significantly affect human lives. For such applications it is of critical importance that similar individuals will be classified and recognized similarly. The accuracy of the classification depends both on the machine learning model and the quality and the quantity of the training dataset. However, in situations where bias is present, for example in the training data set, it will be also reflected in the classification outcome. Such situations require either human intervention when making the final decision upon which actions will be taken, or implementation of machine learning algorithms for fair classification. In this paper, we would like to summarize several examples and case studies where such situations arise and discuss possible solutions such that a fair use of technology is provided to every citizen. Fairness in healthcare technology refers to various attempts to correct algorithmic bias in automated decision processes based on the automated models. Decisions made by such models after a learning process may be considered unfair if they were based on variables considered sensitive (e.g., gender, ethnicity, sexual orientation, or disability). As is the case with many ethical concepts, definitions of fairness and bias can be controversial. In general, fairness and bias are considered relevant when the decision process impacts people's lives. Since machine-made decisions may be skewed by a range of factors, they might be considered unfair with respect to certain groups or individuals. To avoid unfair and asymmetrical healthcare treatment, we must properly define the concept of fairness. It will not only provide a better society of healthy and active aging individuals, but it will improve healthcare and wellbeing in total by cutting many unnecessary additional expenses. With the increase of the senior population not only in the developed industrialized countries but also in the emerging economies of the developing world, we have to take urgent measures by implementing all the technology, data and knowledge to provide a healthy and happy future to humanity.

In conclusion, Health 4.0 uses the new disruptive technologies to provide active and healthy aging with the implementation of personalized medical treatment and the focus on prevention rather than intervention. Future challenges will include the education of the population to use the equipment and procedures of Health 4.0, as well as the treatment of the confidential patient data to respect the patient's privacy. Don't forget that healthy aging starts at birth rather than after 65 years of age.

Photoluminescence properties of coatings on A356 containing Al_2O_3 , Sm_2O_3 and ZrO_2 synthesized by sol-gel technology

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Abstract: Thin coatings of aluminum oxide (Al_2O_3), zirconium oxide (ZrO_2) and samarium oxide (Sm_2O_3) on aluminum alloy Al7SiMg (A356) were prepared by sol-gel method and immersion technique. The materials were characterized in detail by X-ray diffraction. The luminescent properties at room temperature were also investigated. Luminescence analysis showed that the Al_2O_3 coating containing ZrO_2 exhibits broad excitation and emission bands, peaking at 328 nm and 392 nm, respectively. Photoluminescence data for the Al_2O_3 coating containing ZrO_2 and Sm_2O_3 indicated effective excitation at 404 nm and strong broadband emission, which is due to the co-emission of ZrO_2 and Sm_2O_3 . Chromaticity coordinate analysis revealed that Al_2O_3 coating containing ZrO_2 and Al_2O_3 coating containing ZrO_2 and Sm_2O_3 emit in the blue-purple and pale pink regions, respectively. The chromaticity coordinates, color purity and CIE (Commission Internationale de L'Eclairage) color-correlated temperature were determined.

Keywords: A356, LUMINESCENCE, SOL GEL, COATINGS, Al_2O_3 , ZrO_2 , Sm_2O_3

1. Introduction

The development of multifunctional coatings for light metal alloys has received considerable attention due to their potential applications in aerospace, automotive, and energy sectors. Aluminum alloys, especially the A356 alloy, are widely used because of their low density, good mechanical properties, and excellent castability. However, their relatively poor corrosion and wear resistance limit their long-term performance in aggressive environments [1].

In this article, the surface of a 70/70 current terminal coated by the sol-gel method is investigated. It is an assembly of two parts made of AlSi7Mg alloy, used in the power grid (Figure. 1).

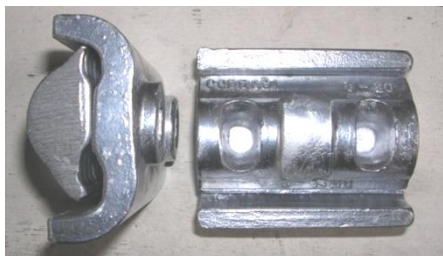


Figure 1.

Metal molds (tools) are used to obtain the castings. Before work, the tool is used to obtain a good surface, orientate directional crystallization and provide good feeding of the casting. For the actual part of the casting, Wolfraco coating is used.

Sol-gel technology has emerged as a versatile and cost-effective method for the fabrication of oxide-based thin films and coatings on metallic substrates [5]. This method allows for low-temperature processing, compositional control, and homogeneous distribution of dopants at the molecular level [6, 7].

Luminescent properties of Sm^{3+} ions show sharp emission peaks around 560–650 nm when excited in the UV region. The intensity and profile of the emission bands are sensitive to the local environment, defect states, and thermal history /Figure 2/.

As it is well known, the luminescent properties of ZrO_2 appear to be highly influenced by the methods used for its preparation. For instance, tetragonal ZrO_2 nanoparticles produced via microwave irradiation exhibit emission peaks at 402, 420, and 459 nm when excited at 254 nm, and a broad band at 608 nm at 412 nm excitation. In contrast, colloidal zirconia nanocrystals synthesized through a two-phase process display a broad emission centered around 365 nm when exposed to 250 nm UV excitation.

Therefore, exploring alternative methods to synthesize ZrO_2 would be both valuable and meaningful for investigating the luminescent properties.

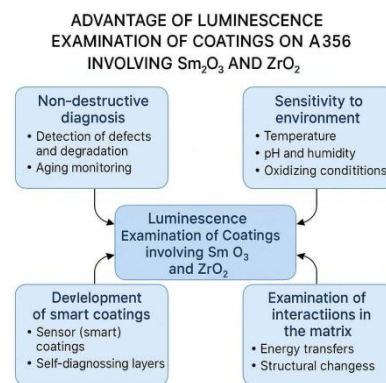


Figure 2.

In this work, we investigate the photoluminescence properties of Sm_2O_3 - Al_2O_3 -doped- ZrO_2 coatings synthesized via sol-gel technique and deposited on A356 aluminum alloy. The influence of samarium concentration on the structural and optical characteristics of the coatings is systematically examined.

2. Experimental procedures

2.1. Materials

Commercially available A356 aluminum alloy castings (nominal composition: 7.0% Si, 0.3% Mg, balance Al) were used as substrates. The substrates were cut into rectangular shapes ($20 \times 10 \times 5 \text{ mm}^3$), mechanically polished with silicon carbide paper to 1200 grit, degreased in ethanol and ultrasonically cleaned in deionized water.

The materials used for sol-gel synthesis included aluminum nitrate [$\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$], zirconium oxychloride [$\text{ZrOCl}_2 \cdot 8\text{H}_2\text{O}$] and samarium [Sm_2O_3], all obtained from AGC Glass Europe with a purity of >98%. 99.9% ethanol ($\text{C}_2\text{H}_5\text{OH}$) and nitric acid HNO_3 were used as solvents and stabilizing agents, respectively.

2.2. Sol Preparation

Two separate compositions were prepared based on the following compositions:

1. Al_2O_3 and ZrO_2 . 2. Al_2O_3 , ZrO_2 , and Sm_2O_3

The sol-gel solutions were prepared by hydrolytic condensation. Initially, aluminum nitrate was dissolved in deionized

water and absolute ethanol under vigorous stirring at room temperature. Nitric acid was added dropwise to stabilize the solution and control the rate of hydrolysis. Separately, $\text{ZrOCl}_2 \cdot 8\text{H}_2\text{O}$ was diluted in ethanol and added to the aluminum sol under continuous stirring. In the second composition involving Al_2O_3 , ZrO_2 , and Sm_2O_3 - nitric acid was added dropwise to the samarium oxide and introduced into the mixture containing Al_2O_3 and ZrO_2 to obtain the desired rare earth element content (0.5–2.0 mol%). The final two sols were stirred for 8 hours to ensure homogeneity and aged for 72 hours before coating.

2.3. Coating

The prepared sols were coated onto A356 substrates using the dip-coating technique at a draw speed of 5 cm/min. After deposition, the wet films were dried at 120°C for 1 hour to remove residual solvents. The coating process was repeated 1–3 times to achieve the desired thickness (~20 nm). The coated samples were subsequently heat-treated in air at temperatures of 420°C for 2 hours to promote densification and crystallization.

2.4. Characterization Techniques

Photoluminescence (PL) measurements were performed at room temperature using a fluorescence spectrometer (Horiba Jobin Yvon Fluorolog) with an excitation wavelength of 405 nm. Emission spectra were recorded in the range of 400–750 nm to evaluate the characteristic transitions of Sm^{3+} and Zr^{2+} ions.

3. Results and Discussion

Photoluminescence (PL) spectroscopy is essential for studying the optical characteristics of newly synthesized materials. Al_2O_3 does not possess luminescent properties. The PLE spectra of Al_2O_3 - ZrO_2 coating was recorded at room temperature by monitoring the most intensive characteristic emission of ZrO_2 ions at 392 nm wavelength, as shown in Figure 3.

Photoluminescence (PL) spectra

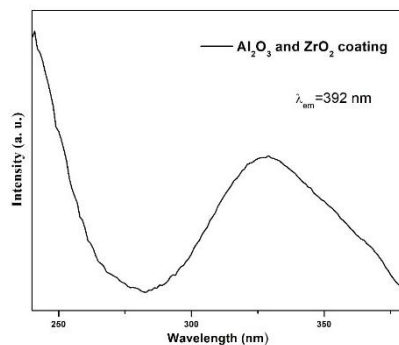


Figure 3. Excitation spectrum of the Al_2O_3 - ZrO_2 coating

The Figure 4 shows PLE spectrum containing two continuous strong broad bands with spanning wavelengths below 280 nm and from 280 nm to up to above 350 nm, with a prominent peak centered at 241 and 328 nm, respectively. The second peak was chosen for recording the emission spectrum.

Up to now, the origin of ZrO_2 luminescence is not clear and there are several different proposed mechanisms [8]. More precisely, since Zr^{4+} ions do not inherently exhibit luminescence, the emission observed in ZrO_2 is likely attributed to defects and/or impurities within the system, as has been noted in similar manuscripts [9, 10]

The luminescence characteristics of our Al_2O_3 - ZrO_2 coating, such as excitation and emission wavelengths positions, clearly differ from those reported for samples synthesized by other methods discussed in the Introduction section. Moreover, the excitation spectrum is shifted by about 10 nm and the emission spectrum by about 30 nm compared to our previous study on ZrO_2 coatings on glass. This effect may be due to the fact that in this case

the coating is deposited on an aluminum alloy. This indicates that various synthesis techniques introduce distinct types of defects and/or impurities in ZrO_2 , which significantly influence its luminescent behavior.

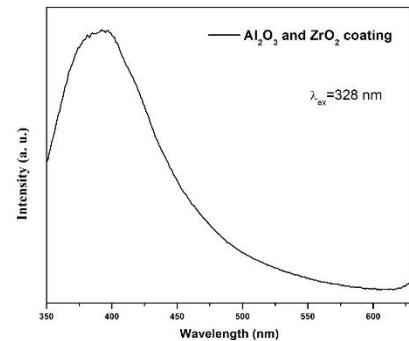


Figure 4. Emission spectrum of the Al_2O_3 - ZrO_2 coating

The photoluminescence behavior of ZrO_2 coating containing both Al_2O_3 and Sm_2O_3 was studied using the excitation wavelength of 404 nm and is shown in Figure 4. The obtained coating is characterized by strong broad band luminescence, which is due to the co-emission of ZrO_2 and Sm_2O_3 . The emission peak at 468 nm corresponds to the ZrO_2 emission. The incorporation of Sm_2O_3 has resulted in the appearance of new emissions in the visible range, which are clearly observed as bands at about 534 nm, 600 nm and 688 nm due to its characteristic intra-configurational f-transition $^5\text{G}_{5/2} \rightarrow ^7\text{H}_J$, where $J = 5/2, 7/2$ and $11/2$, respectively [11,12].

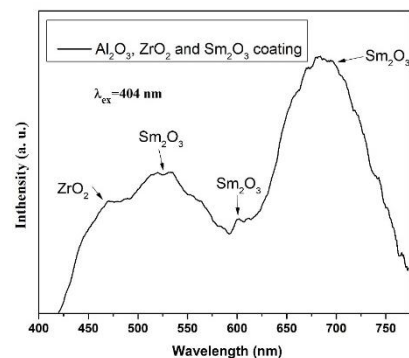


Figure 4. Visible emission spectra of the Al_2O_3 - ZrO_2 - Sm_2O_3 coating

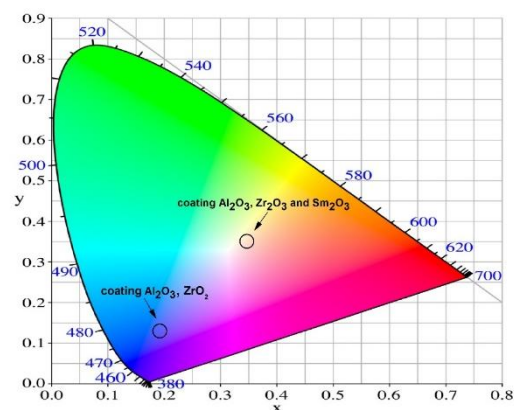


Figure 4. CIE chromaticity diagram of Al_2O_3 - ZrO_2 and Al_2O_3 - ZrO_2 - Sm_2O_3 coatings

To determine the precise emission colors, the CIE 1931 chromaticity diagram was used (Figure 4) [13]. The chromaticity coordinates were calculated from the emission spectra using the SpectraChroma software (Version 1.0.1), a CIE coordinate

calculator [14]. The obtained values for Al_2O_3 - ZrO_2 coating are 0.19:0.142 and correspond to blue-purple color of emission, while for Al_2O_3 - ZrO_2 - Sm_2O_3 coating are 0.344:0.363 corresponding to pale pink color.

The correlated color temperature (CCT) was determined using McCamy's empirical formula:

$$\text{CCT} = -449n^3 + 3525n^2 - 6823n + 5520.33 \quad [15]$$

where $n = (x - x_e)/(y - y_e)$ is the reciprocal slope, ($x_e=0.332$, $y_e=0.186$) are epicenter of convergence and x and y are the chromaticity coordinates.

Phosphors with CCT values under 3200 K are typically classified as warm light sources, whereas those exceeding 4000 K are regarded as cool light sources. The Al_2O_3 - ZrO_2 coating has a calculated CCT of 6263.08 and for Al_2O_3 - ZrO_2 - Sm_2O_3 coating is 5086.43 indicating that they function as cold light-emitting materials.

4. Conclusion:

In conclusion, innovative Al_2O_3 - ZrO_2 coating and Al_2O_3 - ZrO_2 - Sm_2O_3 coating were successfully fabricated on aluminum alloy castings using the sol-gel method combined with dip coating.

Luminescence analysis showed that the Al_2O_3 - ZrO_2 coating exhibits broad excitation and emission bands, peaking at 328 nm and 392 nm, respectively. Photoluminescence data for the Al_2O_3 - ZrO_2 - Sm_2O_3 coating indicated effective excitation at 404 nm and strong broadband emission, which is due to the co-emission of ZrO_2 and Sm_2O_3 . Chromaticity coordinate analysis revealed that Al_2O_3 - ZrO_2 and Al_2O_3 - ZrO_2 - Sm_2O_3 coatings emit in the blue-purple and pale pink regions, respectively.

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МЕТАЛЛОГРАФИЧЕСКИЕ ИССЛЕДОВАНИЯ ВЛИЯНИЯ КОМБИНИРОВАННОЙ ТЕХНОЛОГИИ, ВКЛЮЧАЮЩЕЙ ТЕРМОМЕХАНИЧЕСКУЮ И ПОСТДЕФОРМАЦИОННУЮ УЛЬТРАЗВУКОВУЮ ОБРАБОТКУ, НА ЭВОЛЮЦИЮ СТРУКТУРЫ ЛАТУНИ МАРКИ ЛЖМц59-1-1

METALLOGRAPHIC STUDIES OF THE INFLUENCE OF COMBINED TECHNOLOGY, INCLUDING THERMOMECHANICAL AND POST-DEFORMATION ULTRASONIC TREATMENT, ON THE STRUCTURE EVOLUTION OF THE LZHMTS59-1-1 BRASS

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Abstract. The purpose of this work is to establish patterns of the effect of post-deformation ultrasonic treatment on the structures of ultrafine-grained brass of the LZHMTS59-1-1 brand, obtained during its processing at a radial shear rolling mill with preliminary heat treatment. The structure of brass of the LZHMTS59-1-1 brand has been studied by X-ray diffraction analysis and light microscopy. In the course of the research, the relationship between the parameters of ultrasonic action and the microstructure of ultrafine-grained brass of the LZHMTS59-1-1 brand was established and it was shown that ultrasonic action on this material after radial shear rolling at certain amplitudes of mechanical stresses promotes relaxation of the nonequilibrium structure of grain boundaries and, thus, relieves internal stresses.

Keywords: COMBINED TECHNOLOGY, BRASS, PRE-HEAT TREATMENT, RADIAL-SHEAR ROLLING, POST-DEFORMATION ULTRASONIC TREATMENT, STRUCTURE

1. Введение

Если рассматривать все существующие способы получения ультрамелкозернистой структуры, как дискретные, так и для получения длинномерных изделий, то в большинстве они трудно исполнимы на практике, поэтому не находят особого применения в промышленных условиях, не то, что средне-, крупносерийном или массовом производстве, но даже и в мелкосерийном производстве. Исключение на наш взгляд может только составлять один из видов поперечно-винтовой прокатки, авторами работы [1] его выделяют в отдельный способ деформирования, называемый «радиально-сдвиговая прокатка» (РСП). Основное отличие радиально-сдвиговой прокатки от обычной винтовой прокатки, которая применяется, например, при прошивке труб, заключается в том, что в этом случае идет прокатка сплошного прутка по трехвалковой схеме с большими значениями углов подачи.

С помощью радиально-сдвиговой прокатки возможно получение высококачественных прутков с грандинойной ультрамелкозернистой структурой из широкого спектра материалов вплоть до сложнолегированных труднодеформируемых специальных сплавов черных и цветных металлов, что подтверждается в целом ряде научных работ, в том числе в работах [2-7].

Как известно формирование ультрамелкозернистой и нанокристаллической структур методами интенсивного пластического деформирования оказывает значительное, а иногда коренное влияние на деформационное поведение и механические свойства, как черных, так и цветных металлов и сплавов, что позволяет считать ИПД весьма перспективным методом управления структурой и свойствами. Но в силу того, что ультрамелкозернистые и нанокристаллические материалы появились сравнительно недавно, их устойчивость к внешним воздействиям, в частности, нагреву изучено пока слабо, как и мало исследованы возможности управления структурой ультрамелкозернистых и нанокристаллических материалов и их физико-механическими свойствами.

Белорусскими учеными из ГНУ «Институт технической акустики Национальной академии наук Беларуси» было предложено использовать дополнительную ультразвуковую обработку (УЗО) объемного металла в процессе и после интенсивной пластической деформации, что позволяет

эффективно снизить плотность нестабильных дефектов кристаллов. Ими доказано, что по сравнению с неполным отжигом, ультразвуковая обработка имеет ряд преимуществ, например, дает возможность обрабатывать материалы при комнатной температуре и контролировать воздействие акустической энергии. В целом ряде своих научных работах, в том числе в работах [8-12] они доказали, что ультразвуковая обработка является эффективным способом релаксации структуры сильно деформированных материалов, в том числе УМЗ материалов, полученных деформационными методами, которая приводит к повышению доли большеугловых границ зерен, релаксации неравновесных границ и тройных стыков зерен, не приводя при этом к значительному росту зерен, при этом эффект релаксации структуры зависит от амплитуды ультразвука, т.е. существуют некоторые оптимальные амплитуды напряжений, при которых он максимален.

Не всегда на практике возможно совместить в единый процесс пластического деформирования и ультразвуковой обработки. Но анализ целого ряда научных работ, вот некоторые из них [13-16], доказывает, что постдеформационная ультразвуковая обработка представляет собой перспективный метод обработки, который, в сочетании с другими методами (обработкой давлением, термической обработкой), позволяет значительно варьировать свойства металлов. Это связано с множеством эффектов, возникающих под воздействием ультразвука на материалы: улучшение структуры, снятие внутренних напряжений в деформированных металлах, повышение характеристик пластичности (акустопластический эффект) и другие. В зависимости от частоты, амплитуды и локальности воздействия, можно добиться как упрочнения материала, так и его разупрочнения и пластификации.

Анализ литературных источников в области получения УМЗ материалов различными способами обработки давлением, реализующими интенсивные пластические деформации, показал, что на данный момент в мировой практике не известны работы, связанные с получением УМЗ материалов радиально-сдвиговой прокаткой с дополнительным воздействием на эти УМЗ материалы ультразвуковых колебаний. При этом проанализировав конструкцию стана радиально-сдвиговой прокатки и известных устройств для наложения ультразвуковых колебаний на заготовку был сделан вывод, что совместить в единый процесс радиально-сдвиговую

прокатку и УЗО на практике очень трудно. Поэтому концепция, проводимых далее исследований, будет заключаться в получении в меди с помощью термомеханической обработки: предварительная термическая обработка + радиально-сдвиговая прокатка ультрамелкозернистой структуры, и последующее управление их структурой и физико-механическими свойствами с помощью ультразвуковой обработки.

Поэтому целью данной работы является изучение влияния комбинированной технологии, включающей термомеханическую обработку (предварительная термическая обработка (ПТО) + радиально-сдвиговая прокатка (РСП)) и постдеформационную ультразвуковую обработку, на эволюцию микроструктуры латуни марки ЛЖМц59-1-1.

2. Материалы и методика

Для достижения поставленной цели, а именно изучение влияния комбинированной технологии, совмещающей радиально-сдвиговую прокатку и ультразвуковую обработку, на эволюцию микроструктуры латуни марки ЛЖМц59-1-1, из предварительно подвергнутых предварительной термической обработке (отжигу при температуре 500°C) и деформированию на стане радиально-сдвиговой прокатки РСП 10-30 по схеме $\varnothing 25 \rightarrow \varnothing 23 \rightarrow \varnothing 21 \rightarrow \varnothing 19 \rightarrow \varnothing 17 \rightarrow \varnothing 15$ мм (температура деформирования 500°C) прутков, были подготовлены две партии образцов:

- первая партия образцов представляла собой диски диаметром 15 мм и толщиной 0,45-0,6 мм;
- вторая партия образцов была выполнена в виде цилиндрических стержней диаметром 15 мм и длиной 155 мм, которые и являлись сразу волноводами акустической системы.

На первом этапе исследований ультразвуковой обработке подвергали диски по схеме, представленной на рисунке 1.

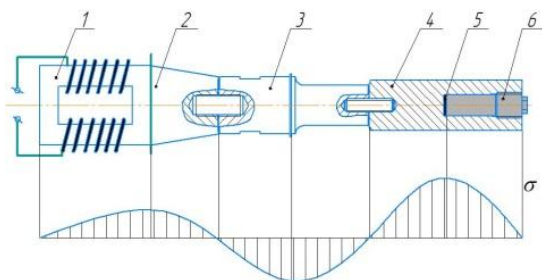


Рис. 1. Схема ультразвуковой обработки УМЗ образцов в виде дисков: 1 – ультразвуковой преобразователь, 2 – концентратор, 3 – бустер, 4 – волновод, 5 – обрабатываемый образец, 6 – поджимной винт

Для этого обрабатываемый образец в виде диска закрепляли внутри полости волновода в пучности механических напряжений с помощью специального винта, обеспечивая надежный акустический контакт между волноводом и обрабатываемым образцом. Затягивающий момент винта при этом составлял 90 Н*м.

Ультразвуковую обработку образцов проводили с амплитудой знакопеременных напряжений в образцах 40 и 70 МПа. Маркировка образцов в зависимости от режимов УЗО приведена в таблице 1.

Питание преобразователя ПМС15А-18 осуществляли от ультразвукового генераторов УЗГ2-4М с рабочей частотой 16,8 – 19,2 кГц и выходной мощностью 4,5±0,5 кВт и УЗГ2-1М с рабочей частотой 22±1,65 кГц и выходной мощностью 1±0,2 кВт.

При проведении ультразвуковой обработки образцов контролировали температуру волновода, которая при максимальных значениях знакопеременных напряжений не превышала 450С. Измерение амплитуды ультразвуковых смещений на торце волновода осуществлялось бесконтактным виброметром, погрешность измерения 2% + 0,1 мкм.

На втором этапе исследований ультразвуковой обработке подвергали диски по схеме, представленной на рисунке 2.

Для реализации данной схемы УЗО (рис. 2) из цилиндрических стержней диаметром 15 мм и длиной 155 мм были подготовлены образцы-волноводы, в соответствии с чертежом, представленном на рисунке 3. На торцевой поверхности образцов было выполнено отверстие с резьбой под шпильку М8, с помощью которой осуществлялось крепление к бустеру.

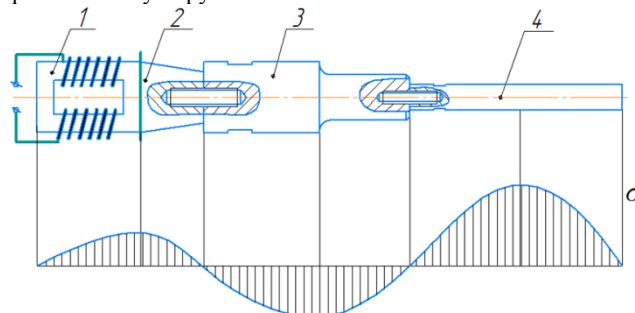


Рис. 2. Схема ультразвуковой обработки УЗО длинномерных образцов: 1 – ультразвуковой преобразователь, 2 – концентратор, 3 – бустер, 4 – волновод

Во всем остальном методика проведения УЗО цилиндрических образцов не отличалась от методики проведения УЗО образцов в виде дисков.

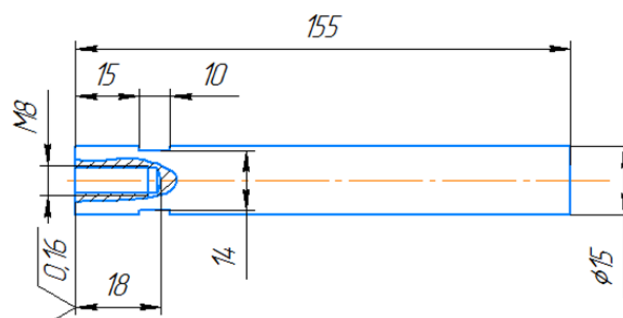


Рис. 3. Чертеж длинномерных образцов-волноводов

Для определения количественных параметров структуры ультрамелкозернистых материалов широко применяется метод рентгеноструктурного анализа (РСА). Рентгеноструктурные исследования, проводившиеся на образцах различных металлов, полученных методами интенсивной пластической деформации, показывают наличие искажений решетки, значительных микронапряжений, которые вызывают уширение рентгеновских пиков [10-12]. Также обнаруживается, что размер областей когерентного рассеяния, полученный методом РСА, заметно меньше размера зерен, рассчитанного из электронно-микроскопических снимков, для всех рассмотренных случаев деформационной обработки. Это может быть связано, во-первых, с допущениями в самих методиках расчета. Во-вторых, такая очевидная разница, которая наблюдается практически всегда для УМЗ металлов, может являться следствием наличия неравновесных границ зерен в структуре. Метод РСА позволяет определять размеры областей когерентного рассеяния (ОКР), соответствующих внутренней области зерен, однако не включающих в себя приграничные сильно искаженные области, образующиеся в материалах при ИПД. И, в-третьих, структура, формирующаяся при ИПД, является весьма неоднородной, внутренние объемы зерен могут включать в себя субструктурные фрагменты, которые методом РСА определяются как отдельные ОКР.

РСА структуры образцов латуни марки ЛЖМц 59-1-1 после ультразвуковой обработки проводился на рентгеновских дифрактометрах типа ДРОН-2 (CuKα излучение). Расшифровка рентгенограмм производилась при помощи программного обеспечения Crystallographica Search-Match. Рентгеновская съемка осуществлялась с фокусировкой по Бреггу-Брентано в режиме сканирования.

Полученная дифрактограмма исследуемых образцов приведена на рисунках 4. Исследование структуры латуни марки ЛЖМц59-1-1 и определение размера зерна проводилось

на световом микроскопе «MeF-3» фирмы «Reichert» (Австрия) при увеличении $\times 100$.

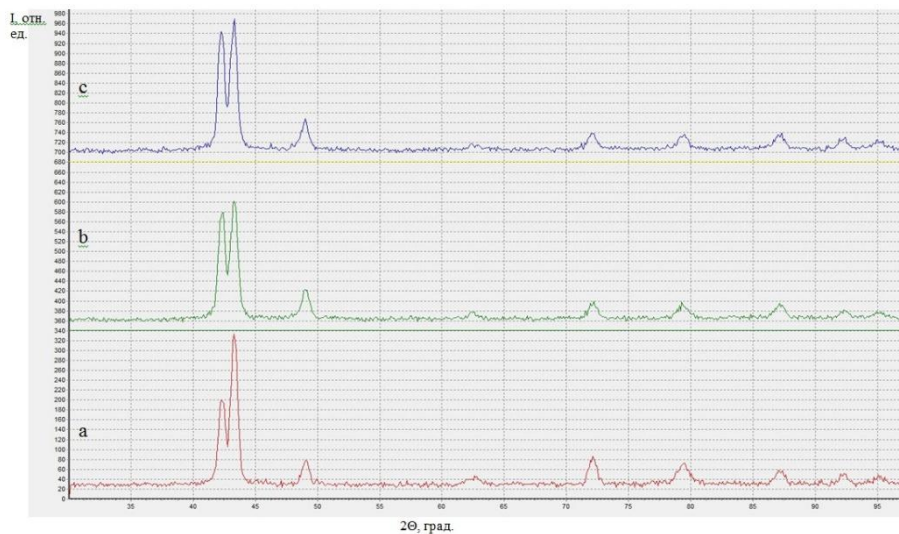


Рис. 4. Дифрактограмма (CuKα) образца латуни марки ЛЖМц59-1-1 после ПТО+РСП (а – без УЗО; б – УЗО 40 МПа; в – УЗО 70 МПа)

Обсуждение полученных результатов

Снижение уширения рентгеновских линий свидетельствует об уменьшении микронапряжений в исследуемом образце после УЗО, так и о некотором росте областей когерентного рассеяния (ОКР). Размер ОКР, как правило, отождествляют со средним размером кристаллитов, определив который, можно судить о характере изменения размера кристаллитов в материале в зависимости от условий обработки. По результатам РСА проведена оценка размеров ОКР образцов по уширению рефлексов на полученных дифрактограммах по формуле Шеррера–Селякова:

$$D = \lambda_{Cu} / B \cdot \cos \Theta,$$

где λ_{Cu} – длина волны излучения медного анода (0,1540 нм),

Θ – угол рассеяния ($^{\circ}$),

B – физическое уширение в ($^{\circ}$)* $\pi/180$.

Размер ОКР, как правило, отождествляют со средним размером кристаллитов, определив который, можно судить о характере изменения размера кристаллитов в материале в зависимости от условий обработки. Проведение УЗО привело к росту ОКР у всех образцов от 8 % до 20 %. Также методом РСА установлено, что латунь марки ЛЖМц59-1-1 представляют собой смесь двух основных фаз в соответствии с равновесной диаграммой состояния системы Cu – Zn. Основными фазами являются фазы CuZn (β -фаза) и твердый раствор цинка в меди (α -фаза). Медь с цинком образуют кроме основного альфа – раствора ряд фаз электронного типа бета, гамма, эпсилон. Наиболее часто структура латуней состоит из альфа – или альфа+ бета' – фаз: альфа-фаза – твердый раствор цинка в меди с кристаллическим решеткой меди ГЦК, а бета' – фаза – упорядоченный твердый раствор на базе электронного соединения Cu_5Zn_8 с решеткой ОЦК.

Как показал ДСК анализ (рис. 5), в образцах латунь марки ЛЖМц59-1-1 наблюдается один экзотермический пик. Пик обусловлен фазовым переходом $\alpha \rightarrow \beta$ в диапазоне температур 430-467 °С. Также после УЗО происходит увеличение площади пика, что связано с изменением уровня внутренних напряжений [17].

На рисунке 6 показаны фотографии микроструктуры латуни марки ЛЖМц59-1-1 после ПТО+РСП без и после УЗО.

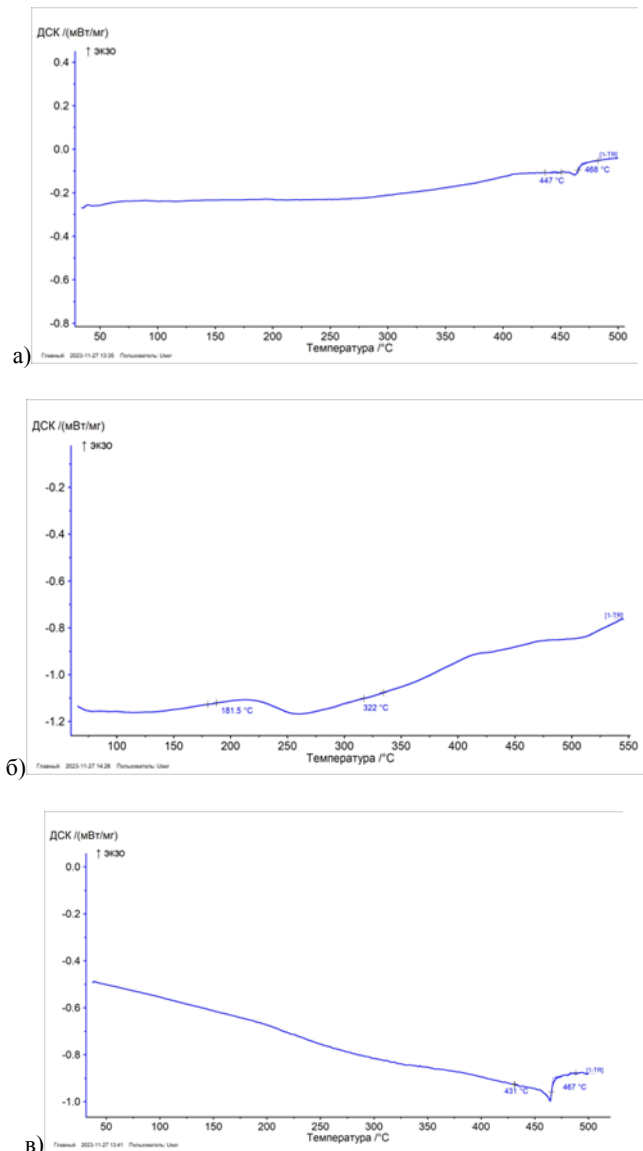


Рис. 5. ДСК-кривые образцов латуни марки ЛЖМц59-1-1 (а – без УЗО; б – УЗО 40 МПа; в – УЗО 70 МПа)

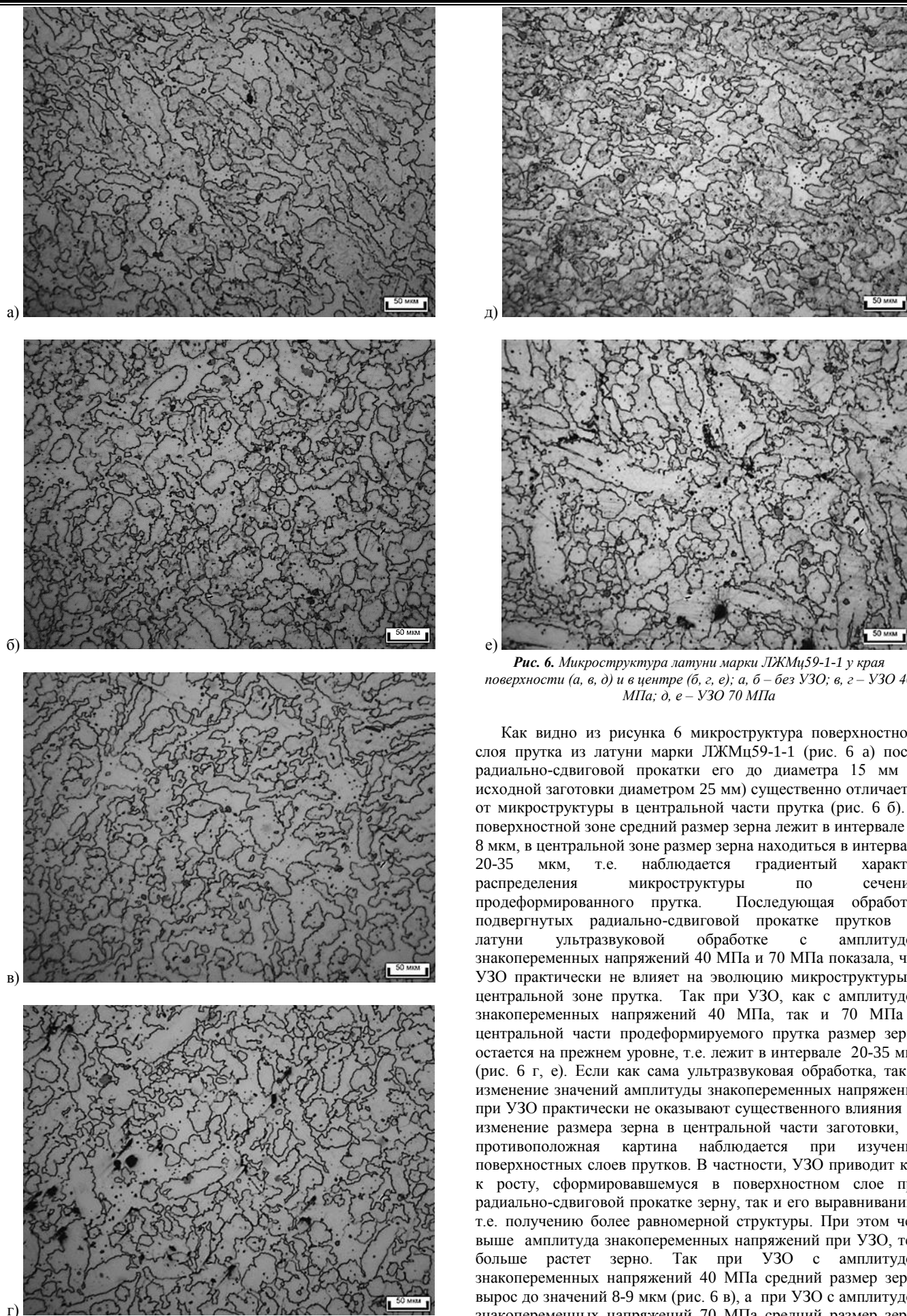


Рис. 6. Микроструктура латуни марки ЛЖМц59-1-1 у края поверхности (а, в, д) и в центре (б, з, е); а, б – без УЗО; в, з – УЗО 40 МПа; д, е – УЗО 70 МПа

Как видно из рисунка 6 микроструктура поверхностного слоя прутка из латуни марки ЛЖМц59-1-1 (рис. 6 а) после радиально-сдвиговой прокатки его до диаметра 15 мм (с исходной заготовки диаметром 25 мм) существенно отличается от микроструктуры в центральной части прутка (рис. 6 б). В поверхностной зоне средний размер зерна лежит в интервале 5-8 мкм, в центральной зоне размер зерна находится в интервале 20-35 мкм, т.е. наблюдается градиентный характер распределения микроструктуры по сечению продеформированного прутка. Последующая обработка подвергнутых радиально-сдвиговой прокатке прутков из латуни ультразвуковой обработке с амплитудой знакопеременных напряжений 40 МПа и 70 МПа показала, что УЗО практически не влияет на эволюцию микроструктуры в центральной зоне прутка. Так при УЗО, как с амплитудой знакопеременных напряжений 40 МПа, так и 70 МПа в центральной части продеформируемого прутка размер зерна остается на прежнем уровне, т.е. лежит в интервале 20-35 мкм (рис. 6 г, е). Если как сама ультразвуковая обработка, так и изменение значений амплитуды знакопеременных напряжений при УЗО практически не оказывают существенного влияния на изменение размера зерна в центральной части заготовки, то противоположная картина наблюдается при изучении поверхностных слоев прутков. В частности, УЗО приводит как к росту, сформировавшемуся в поверхностном слое при радиально-сдвиговой прокатке зерну, так и его выравниванию, т.е. получению более равномерной структуры. При этом чем выше амплитуда знакопеременных напряжений при УЗО, тем больше растет зерно. Так при УЗО с амплитудой знакопеременных напряжений 40 МПа средний размер зерна вырос до значений 8-9 мкм (рис. 6 в), а при УЗО с амплитудой знакопеременных напряжений 70 МПа средний размер зерна стал лежать в интервале 13-14 мкм (рис. 6 д). То есть

проведенные исследования свидетельствуют, что хотя УЗО не оказывает существенного влияния на эволюцию микроструктуры в центральной части прутка, но она позволяет снизить градиентный характер распределения структуры по сечению деформируемого на стане радиально-сдвиговой прокатки прутка за счет роста размера в его поверхностной зоне, и при этом чем выше амплитуда знакопеременных напряжений при УЗО, тем этот градиент меньше. Также УЗО способствует получению более равномерной структуры (с более меньшим разбросом размера зерна) в поверхностной зоне деформируемого прутка (рис. 6 в, д).

Заключение

В ходе данной работы была установлена наличие зависимости микроструктуры латуни марки ЛЖМц59-1-1, полученной после термомеханической обработки, включающей предварительную термическую обработку (отжиг) и деформирование на стане радиально-сдвиговой прокатки от параметров постдеформационного ультразвукового воздействия. Показано, что постдеформационное ультразвуковое воздействие на структуру латуни марки ЛЖМц59-1-1, полученной после термомеханической обработки, при определенных амплитудах механических напряжений способствует релаксации неравновесной структуры границ зерен и снятию, таким образом, внутренних напряжений. Полученные в данной работе данные позволяют расширить научные представления о механизме и закономерностях формирования структуры в различных ультрамелкозернистых черных и цветных металлах и сплавах при ультразвуковом воздействии на них.

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ИССЛЕДОВАНИЕ ВЛИЯНИЯ ДОБАВОК ОКСИДА ИТТРИЯ НА СТРУКТУРУ И СВОЙСТВА СТАЛИ AISI 304, ОТЛИТОЙ СПОСОБОМ ЦЕНТРОБЕЖНОГО ЛИТЬЯ

INVESTIGATION OF THE EFFECT OF YTTRIUM OXIDE ADDITIVES ON THE STRUCTURE AND PROPERTIES OF AISI 304 STEEL CAST BY CENTRIFUGAL CASTING

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Abstract. A comprehensive study of the issue related to the possibility of obtaining AISI 304 steel with increased resistance to radiation has been conducted. The thermodynamic interactions of yttrium with a liquid melt of AISI 304 grade steel have been studied. The possibility of introducing yttrium oxide into a liquid metal matrix has been evaluated. Experiments have been conducted to obtain prototypes of AISI 304 grade corrosion-resistant steel with the introduction of yttrium oxide into the liquid melt. The blanks were obtained by casting on a horizontal centrifugal casting machine. Studies of the microhardness of the samples showed that the samples obtained with the introduction of yttrium oxide have a lower hardness index gradient across the cross section. Microstructures allowing to identify inclusions formed by yttrium oxide in the casting body are presented.

Keywords: YTTRIUM OXIDE, CENTRIFUGAL CASTING, MICROSTRUCTURE, MICROHARDNESS, HARDENING, CASTING, HOLLOW BILLET, DISPERSED PARTICLES, CHEMICAL COMPOSITION, STRUCTURE

1. Введение

В условиях развивающегося рынка промышленности сталкивается не только с задачами, касающимися повышения качества продукта, но и с вопросами снижения себестоимости. Себестоимость различных продуктов неотъемлемо связана с затратами электроэнергии. Атомная энергетика остается на данный момент самым эффективным способом получения электроэнергии [1]. Данная отрасль включает в себя множество промышленных процессов, которые невозможно выполнить без использования материалов с соответствующими требованиями [2]. Повышение функциональных свойств металлических материалов с повышенной радиационной стойкостью, коррозионной стойкостью, равномерностью структуры, является важной задачей перед металлургией и машиностроением [3-4]. Одной из основных проблем в ходе эксплуатации деталей из стали марки AISI 304 под воздействием радиоактивного облучения и высоких температур, выступает появление такого дефекта как распухание [5].

Процесс получения деталей методом литья вызывает наибольший интерес в связи с простотой реализации технологии. Так же литейное производство позволяет получать заготовки близкие к конечному продукту, что снижает затраты на металлообработку детали [6-7]. В тоже время активно ведутся разработки по поиску новых материалов, объединяющих высоко пластичные металлические матрицы и высокопрочные тугоплавкие наполнители [8-11]. Сочетание различных фаз позволяет повысить основные функциональные показатели материалов, такие как износостойкость и стойкость к абразивному износу [12]. Введение наполнителей позволяет создать армирующий слой в теле самой матрицы. Кроме расширения диапазона нагрузок получаемой детали, упрочняющие частицы можно рассматривать как дополнительный барьер для проникания радиоактивного излучения, что повышает стойкости детали. Повышение радиационной стойкости происходит в ходе торможения армирующим слоем активных ионов, что в свою очередь приводит к снижению движения дислокаций.

Основными механизмами упрочнения стали и других металлических материалов являются: упрочнение раствора, упрочнение дислокаций, уменьшение зернистости и усиление фазового превращения [13]. Измельчение зерна – это единственный способ одновременно улучшить прочность и

сопротивляемость металла к ионизирующему воздействию. Упрочнение вторичной фазой может как улучшить прочность металла, так и снизить. Причиной является образование неметаллических включений являющихся концентраторами напряжения. Тем не менее, мелкодисперсные частицы вторичной фазы зачастую имеют эффект измельчения структуры и укрепления границ зерен, что может повысить стойкость стали к ионизирующему воздействию. Таким образом, кроме измельчения зерна, дисперсное упрочнение является наиболее предпочтительным методом.

Для реализации процесса измельчения зерна и усиления вторичной фазой необходима принципиально новая технология. Вторичная фаза может быть введена в стальную матрицу путем механического легирования. Способ введения мелкодисперсных частиц в стальную матрицу является сложной задачей, в связи с вопросами связанных со смачиваемостью вводимой фазы.

Введение тугоплавких наполнителей должно быть контролируемым процессом, для обеспечения создания армирующего слоя в определенной зоне заготовки. Объединение таких технологий как литейное производство и введение упрочняющих частиц при разливе на машину центробежного литья позволит не только добиться минимальной себестоимости конечного изделия, но и сделать процесс введения частиц более или менее контролируемым [14].

2. Технология введения дисперсных частиц

Сегодня проблема решается только с переходом на метод – технология механического легирования (МЛ). Технология МЛ была хорошо описана в работе [15]. При МЛ, технология предполагает, что смесь порошков различных металлов подвергается совместному высокоэнергетическому помолу с преобладающим механизмом трения. В процессе такого помола происходит измельчение частиц порошка (вплоть до нанокластерного размера) и взаимная твердофазная диффузия металлов друг в друга. В нанокластерах, термодинамически наиболее выгодным соединением становится твердый раствор, в который переходят имеющиеся в металле соединения типа интерметаллидов, силицидов и карбидов [16]. При последующем нагреве скомпактированных порошков эти соединения выпадают из раствора в виде наноразмерных частиц (преципитатов).

В работе [17] было установлено, что МЛ в твердом металле может растворяться и такой термодинамически прочный оксид, как Y_2O_3 с последующим выделением его нанокластерных преципитатов. При этом возможно укрупнение (коалесценция) нанопреципитатов в результате растворения мелких частиц и роста более крупных, что в конечном итоге сводит на нет все достоинства технологии МЛ.

В тоже время, существует технология повышения механических свойств металлических материалов за счёт введения дисперсных частиц в жидкий расплав при разливке с использованием машины центробежного литья. Данная технология, при достаточной простоте её реализации, позволяет получать стабильные результаты с использованием дисперсных частицы различной плотности получать градиентные материалы [18].

Центробежное литье является оптимальным методом получения заготовок ввиду большой скорости кристаллизации, обеспечивающей мелкозернистую структуру. При первом контакте жидкого металла с относительно холодной подложкой образуется мелкозернистая корка застывшего металла. Упрочняющие частицы подаются в процессе разливки в виде порошка практически сразу после начала разливки в разливочный носок во избежание оседания в разливочном ковше. Вращение изложницы заставляет частицы быстрее оседать и распределяться в теле металла при кристаллизации более равномерно благодаря воздействию сил Архимеда и центробежных сил. Кристаллизация идет по стандартной схеме – от периферии к центру, обеспечивая образование мелкозернистой структуры на поверхности заготовки. Наружная корка имеет мелкозернистую структуру и состоит в основном из молекул стали. Под коркой скрывается наружный рабочий слой заготовки, в котором сконцентрировались наиболее крупные частицы карбидов. При этом более мелкие частицы карбидов находятся между крупными частицами, но преобладают уже в периферийной зоне относительно границы раздела «подложка-металл», а также их концентрация постепенно снижается при удалении от границы раздела фаз к центру заготовки, образуя градиентную текстуру [19].

Для обеспечения надежной молекулярной связи карбидов и основного металла необходимо наличие высокой межфазной адгезии, т.е. частицы карбидов должны обладать оптимальной смачиваемостью жидкой сталью для образования надежного межфазного соединения.

Определение смачиваемости материалов по большей части происходит эмпирическими методами на основе натуральных опытов. Для прогнозирования характера распределения упрочняющих частиц в теле металла, толщины образующегося слоя, возможных физических характеристик заготовки, а также снижения материальных затрат на проведения натуральных испытаний принято решение о создании математических моделей для проведения анализа в САЕ-системах.

Неравномерное внедрение упрочняющих частиц приводит к их неравномерному распределению в теле закристаллизовавшегося расплава, выражающееся в появлении скоплений, которые могут быть обнаружены в ходе анализа отливок разрушающим методом, несмотря на то, что при центробежном литье на упрочняющие частицы воздействует поле гравитационных сил, которое ускоряет проникновение дисперсных частиц вглубь кристаллизующегося расплава [20].

Ввиду того, что процесс разливки при центробежном литье довольно скоротечный составляет не более 30-60 секунд до полной кристаллизации отливки из стали массой до 10-20 килограмм, неточное дозирование порошка нарушает необходимую удельную концентрацию дисперсных частиц в удельном объеме струи расплава. Следовательно, может возникнуть ситуация полного отсутствия упрочняющих частиц в наружных слоях заготовки по причине мгновенной кристаллизации при контакте с относительно холодной изложницей или на некоторой глубине от поверхности, которая выходит за необходимый допуск при механической обработке, в

результате чего расчетный диаметр готового изделия получится совсем или недостаточно упрочненным, несмотря на воздействие центробежных сил.

Аналогично может возникнуть иная ситуация. Если при разливке расплава начать внедрять частицы слишком рано, то весь упрочняющий порошок рискует оказаться в мелкозернистой корке, подлежащей удалению. Вдобавок это событие будет простимулировано воздействием поля гравитационных сил.

Владение сведениями о процессе разливки и возможностью управлять самим процессом с достаточной точностью позволяет минимизировать риски неравномерного распределения упрочняющих частиц, а также позволит производить оперативную разливку слоями из одного или нескольких видов дисперсных частиц [21].

В результате возникновения возможности слоистой дозированной разливки можно достигнуть материальной экономии за счет использования более распространенных и дешевых материалов, а также сократить повсеместное влияние гравитационных сил.

Схема, иллюстрирующая результат процесса разливки с внедрением дисперсных частиц разной плотности для упрочнения внутренней и внешней поверхностей кольцевой заготовки представлена на рисунке 1. Здесь изображена половина кольцеобразной заготовки, в которой легковесные частицы стремятся к ее оси вращения.

В данном случае при использовании традиционных методов центробежного литья без дозирования и контроля времени введения частиц мы вынуждены использовать частицы, обладающие разной плотностью, относительно матричного расплава. Как уже было сказано ранее, иногда могут быть использованы порошки из редких или дорогостоящих материалов, например карбидов титана TiC и карбидов вольфрама WC или оксида иттрия Y_2O_3 . Дополнительно к этому имеется еще одно ограничение, связанное с концентрацией упрочняющего материала. В результате чего мы будем вынуждены снизить размер товарной партии изделий, или завязать конечную стоимость изделий, или снизить качество изделий, выражающееся с снижением концентрации упрочняющих карбидов в теле заготовки на единицу объема для сохранения минимальной цены товарной партии. F_m – направление силы тяжести, вызванной скоростным вращением изложницы.

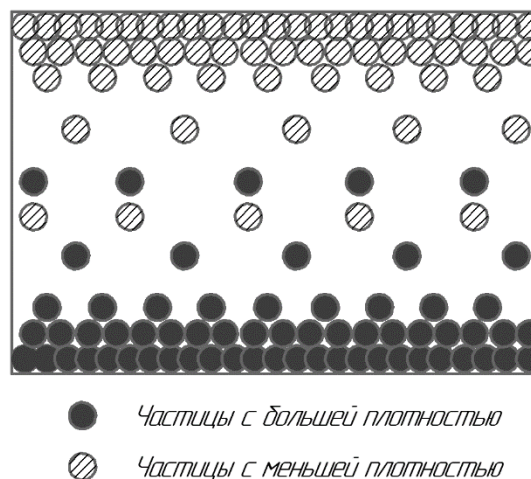


Рис. 1. Распределение упрочняющих частиц разной плотности в стальной матрице

На рисунке 2 изображен вариант слоистой разливки, являющийся результатом контроля дозирования порошка и матричного расплава, а также контроль времени разливки с введением некоторой временной выдержки, обеспечивающей достаточный уровень кристаллизации первого слоя, наполненного более легковесными частицами взамен тяжеловесных.

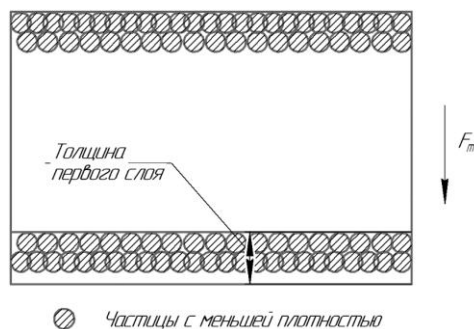


Рис. 2. Литие с использованием частиц меньшей плотности с формированием слоев

Естественно, что данная схема является практически идеальным исходом от процесса центробежного лития слоями. Однако не исключается, что в момент контакта горячего расплава некоторая часть зафиксировавшихся упрочняющих частиц в первом слое будет перемещена во второй слой, тем самым, снижая необходимую концентрацию упрочняющих частиц в наружном слое.

Для получения данного результата необходим точный контроль сведений о температурах первого слоя, который уже подвергнулся кристаллизации, а также температура расплава. Если разница температур будет слишком низкой, то существует риск возникновения полной рекристаллизации первого слоя при соприкосновении с расплавом, внедренным для формирования второго слоя. Следовательно, все частицы, зафиксированные в первом слое, могут быть вытеснены матричным расплавом, так как в данном случае упрочняющие частицы являются легковесными и менее плотными, относительно стального расплава.

Определение температуры расплава перед разливкой может производиться с помощью приборов, однако для контроля температуры закристаллизовавшегося слоя при достаточно быстром темпе разливки и трудоемкости определения температуры оптическим методом с достаточной точностью затруднительно. Здесь необходимо использовать математический аппарат, а именно законы термодинамики кристаллизации стального расплава с учетом влияния внедренных дисперсных частиц, воздушных потоков и процесса непрерывного центробежного вращения изложницы.

Проведен анализ литературы на предмет наличия существующих достижений и результатов исследований на тему изучения поведения тугоплавких частиц в теле кристаллизующегося металла при центробежном литие заготовок. Для реализации технологии по признаку наиболее близкого сходства были приняты математические модели представленные в работах [22, 23].

Оксид иттрия обладает плотностью близкой к плотности металлических материалов на основе железа $5,046 \text{ г/см}^3$. Следовательно, при реализации технологической схемы представленной в работе, оксид иттрия должен находиться на внешней (рабочей) стороне цилиндрической отливки. При небольшой толщине стенки заготовки, возможно, его распределение и на внутренней поверхности.

Усилить эффект от введения дисперсных частиц (более высокие значения механических свойств, более 300 МПа при 970K, более высокая радиационная стойкость к нейтронному облучению, более высокая сопротивляемость коррозии по отношению к теплоносителям, при повышенных температурах) возможно при использовании дополнительной внутренней механической раскатки, т.е. термомеханическое упрочнение.

3. Моделирование взаимодействия Y_2O_3 с металлическим расплавом

Как показали предварительные исследования, в качестве термодинамически неметаллических дисперсных частиц наиболее стабильным является Y_2O_3 [24]. Свойства оксида

иттрия как соединения рассмотрены в работе [25]. Однако, работы по введению Y_2O_3 в чистую металлическую фазу не дали положительного результата. Создание армирующего слоя в чистой металлической фазе невозможно в связи с плохой смачиваемостью данного типа частиц [26]. В тоже время упрочнение металлической фазы Y_2O_3 возможно в случае повышения содержания никеля в основной металлической фазе [27-29].

Разработка наиболее эффективной технологии создания металлических материалов на основе железной матрицы дисперсно-упрочненной оксидом иттрия необходимо создание сквозных технологических схем и инновационных технологий, включающих в себя как литейные технологии с введением упрочняющей фазы, так и термомеханическое упрочнение. Для чего необходимо экспериментально изучить влияние различных параметров (температуры, концентрации, скорости разлики и вращения печи, усилия раскатки, режимы термической обработки и др.) на ход процесса и его результаты. Для термодинамического моделирования высокотемпературных процессов, происходящих в системе оксид иттрия – металлическая матрица (расплав), и температур рекристаллизации целесообразно использовать программный комплекс FactSage [30]. Программное обеспечение FactSage 7.0 обозначает возможные направления процессов, протекающих при реализации разрабатываемых в ходе исследований технологических процессов.

Для моделирования использовался состав – 0,1% C, 1,5% Mn, 0,5% Si, 18,0% Cr, 10,0% Ni, 0,5% Ti, 69,25% Fe. Добавка Y_2O_3 – 1 гр. на 100 гр. массы металлического расплава. Результаты моделирования равновесных фазовых составов металла с добавкой оксида иттрия в зависимости от температуры и моделирования неравновесной кристаллизации (модель Шейла-Гулливера) металла с добавкой оксида иттрия представлены на рисунке 3. Расчёты велись с учётом возможности существования фаз переменного состава (твёрдых и жидких растворов), и с учётом отклонения, в такого рода фазах от идеальности.

В построении зависимости изменения фазового состава сплава и неравновесной кристаллизации от температуры, основной акцент делался на оксидной фазе сплава. Моделирование проводилось для температур, при которых осуществляется центробежная отливка заготовок, что позволяет с большей или меньшей точностью предполагать фазовый состав изучаемого сплава. Данное обстоятельство позволяет прогнозировать поведение дисперсных оксидов.

Наибольший практический интерес представляет центральная часть графика, где прямой линией через диаграмму проходит линия, характеризующая массу оксида иттрия системе. Исследуемая фаза почти не взаимодействует с компонентами сплава, не диссоциирует и не претерпевает аллотропических превращений

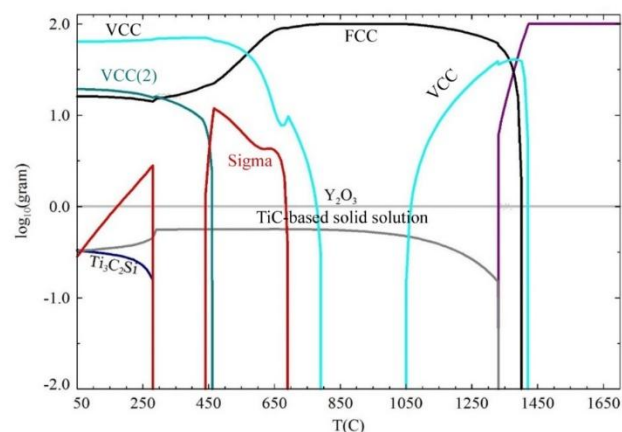


Рис. 3. Результаты моделирования равновесных фазовых составов металла с добавкой оксида иттрия в зависимости от температуры

На рисунках 4а и 4б представлены результаты расчёта модели неравновесной кристаллизации (модели Шейла-Гулливера) для исходного расплава без добавок оксида иттрия и с ним эталонным составом. Линия, соответствующая определённой фазе, в месте пересечения с осью температуры, отмечает точку начала кристаллизации фазы.

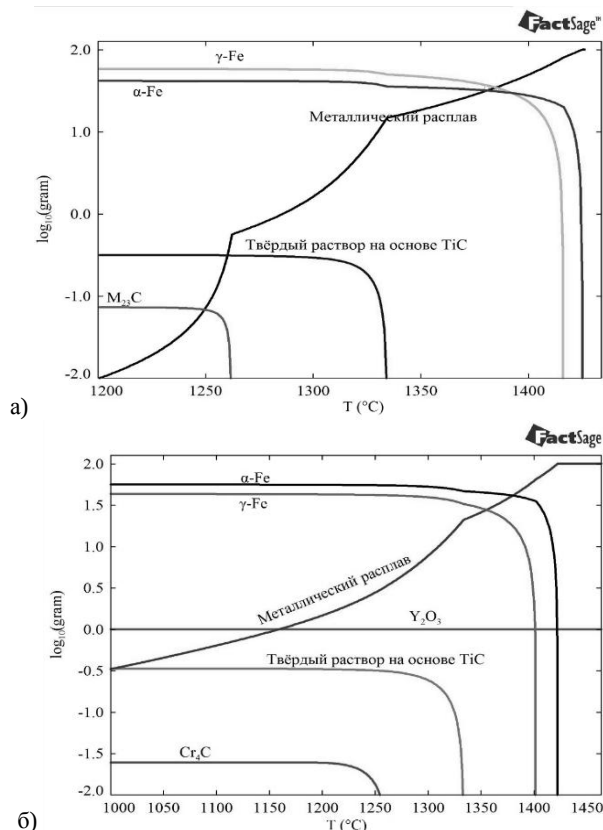


Рис. 4. Результаты моделирования неравновесной кристаллизации фазового состава стали марки 12Х18Н10Т в зависимости от температуры (модель Шейла-Гулливера): а - исходного расплава; б - металла с добавкой оксида иттрия в количестве 1 гр на 100 гр

Сравнительный анализ рисунков 4а и 4б позволяет сделать вывод, что оксид иттрия присутствует в расплаве в виде кристаллической фазы. При этом увеличивает содержание α -Fe (ОЦК фазы) в сравнении с моделью для расплава без присадки оксида иттрия.

Анализ данных моделирования показал, что в процессе получения металломатричных материалов методом центробежного литья не происходит взаимодействия оксида иттрия с металлическим расплавом. Установлена диссоциации соединений при условиях рассматриваемых процессов. Из чего можно сделать заключение о целесообразности проведения экспериментов по получению отливок центробежного литья с применением оксида иттрия как упрочняющей фазы с целью возможного повышения радиационной стойкости.

4. Эксперимент и обсуждение результатов

В качестве жидкого металлического расплава использована AISI 304. Данная марка стали имеет широко используется для производства деталей атомной промышленности. Содержание в ней никеля 9 – 11 % должно обеспечить смачиваемость упрочняющих частиц жидкой фазой и создание упрочняющего слоя.

Для получения партии опытных образцов использовалась печь СЭЛТ-001-40/12-Т, разливка осуществлялась в машину центробежного литья. Скорость вращения изложницы составляла 650 об/мин. Выпуск жидкого расплава производился в предварительно прогретую до 600 °С изложницу. Инжекционная подача частиц на струю металла осуществлялась весь период разливки. В ходе эксперимента

получено три полых заготовки с удовлетворяющим качеством поверхности. Заготовки имели внешний диаметр 156 мм, длину 180 мм, а толщина стенки составляла 30 мм. Заготовки имели удовлетворительное качество поверхности. Первая заготовка получена без введения дисперсных частиц. Количество частиц во вторых заготовках составляло 30 г. (Образец №1) и 39 г. (Образец №2). После получения заготовок, отбирались образцы для исследований.

Для отливок центробежного литья, данное литье отличается выраженной послойной кристаллизацией в направлении от внешней стороны отливки к центральной (внутренней) части. Отливки плотные без пор, трещин и каких-либо других дефектов усадочного характера. Микроструктура исследуемых отливок представлена литыми дендритными кристаллами альфа-Fe. Рост кристаллов имеет четкую направленность в центр отливки. Травление выявило внутредендритную ликвацию, что является логичным следствием сложного химического состава металлической фазы.

У полученных образцов измерялась микротвердость. Измерения проводились от внешней к внутренней области сформировавшейся заготовки. Показатели твердости заготовки введением Y_2O_3 в количестве 30 г. снизились относительно эталона, в свою очередь заготовка, полученная с введением 39 г. имеет более высокие значения твердости. Стоит отметить, что обе заготовки упрочненные Y_2O_3 имеют меньший градиент данного показателя. Это свидетельствует о том, что частицы выступили в роли микрохолодильников, данный фактор повлек за собой измельчение структуры. Результаты представлены на рисунке 5. Синими линиями представлены показатели твердости эталонного образца, оранжевыми показателями образцов с введением упрочняющих частиц.

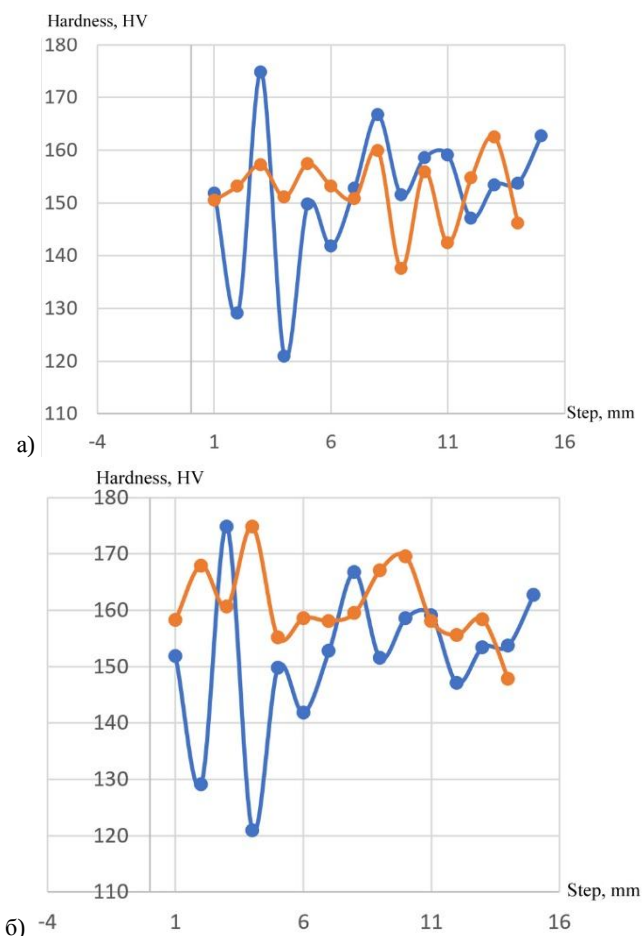
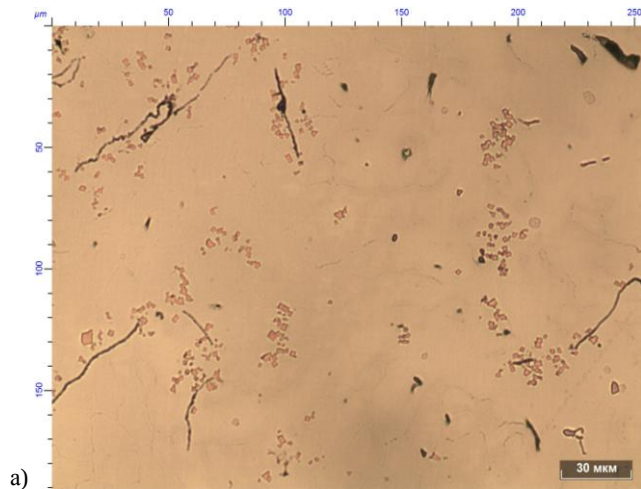
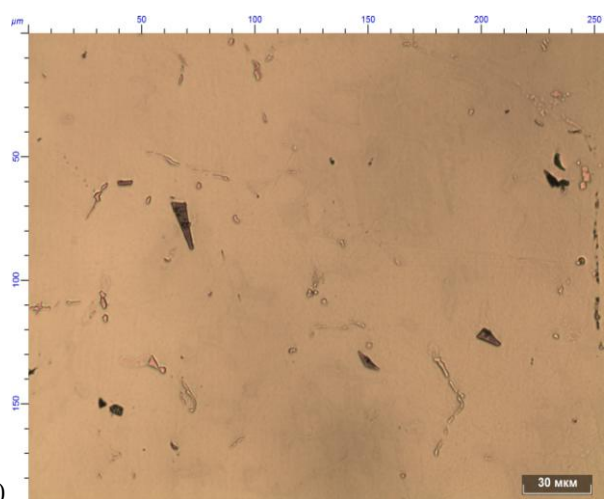


Рис. 5. Значения микротвердости от края к центру по сечению образца (синей линией отображены значения эталонного образца): а - с введенным количеством частиц равным 30 г; б - образца с введенным количеством частиц равным 39 г

Проведенные металлографические исследования показали, что неметаллическая фаза активно представлена нитридами титана (Рисунок 6а). Так же в структуре наблюдаются нитриды алюминия и карбонитриды титана (Рисунок 6б). Наличие данного вида включений также подтверждают исследования проведенные на электронном микроскопе (рисунок 7). Представлены спектрограммы неметаллической фазы по определенным химическим элементам. Обнаружены локализованные включения на основе Y. Химический состав выявленных включений представлен в таблице 1.

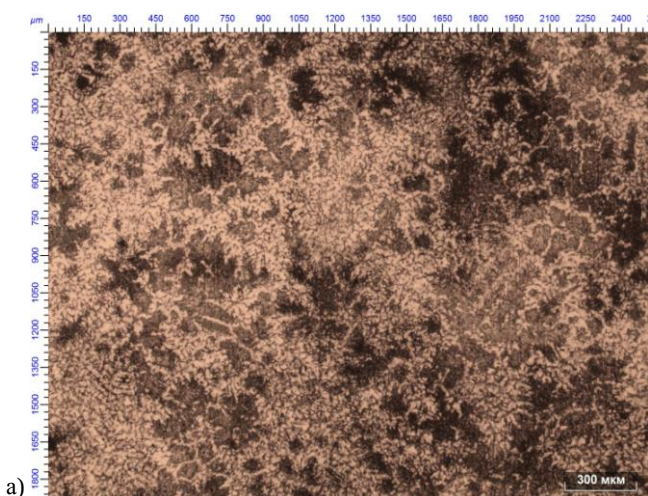


а)

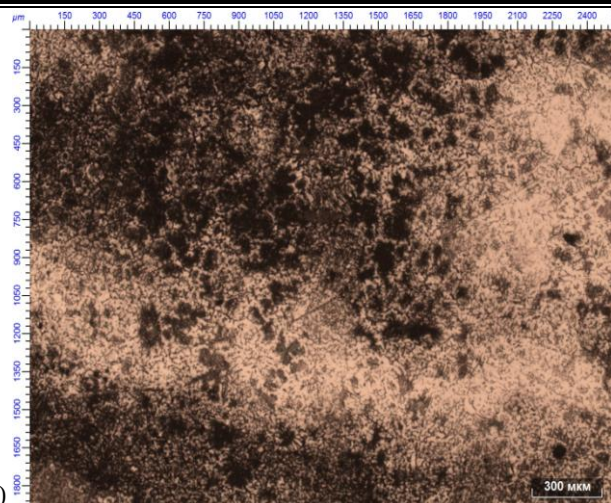


б)

Рис. 6. Фотографии микроструктур: а – нитриды титана; б – нитриды алюминия и карбонитриды титана



а)



б)

Рис. 7. Микроструктура образцов, увеличение $\times 65$: а – с введением 30 г Y_2O_3 ; б – с введением 39 г Y_2O_3

С учетом термодинамической стабильности соединения Y_2O_3 , можно предположить, что данный вид включений и есть вводимые тугоплавкие дисперсные частицы Y_2O_3 . Вводимые оксиды выступили в качестве подложки для кристаллизации алюмосиликатных и нитридных включений, образовав сплошные керамические включения.

Таблица 1 – Химический состав включений

Al	Si	Ti	Cr	Mn	Fe	Ni	Cu	Y	W
1.43	0.89	4.00	16.25	0.64	60.15	9.10	0.13	7.33	0.08

Вывод: Оценивая влияние введения Y_2O_3 на структуру отливки AISI 304 можно сделать следующие выводы. Технологически возможно усвоение Y_2O_3 при центробежном литье заготовок. Однако термодинамическая стабильность Y_2O_3 не вызвала изменения фазового состояния расплава. Исходя из полученных результатов, можно предполагать, что более целесообразным является введение оксида иттрия в стали типа AISI 304 имеющими большую концентрацию никеля в составе.

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Thermodynamic evaluation of a 250 mw three-cylinder steam turbine from ccpp

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Abstract: In this paper are presented isentropic analysis results of a steam turbine, their cylinders and cylinder parts which nominal power is equal to 250 MW. The analyzed steam turbine is a complex three-cylinder turbine which operates in a CCPP (Combined Cycle Power Plant). Considering all cylinders, the dominant mechanical power producer in the observed turbine is LPC (Low Pressure Cylinder) which produces 111.80 MW of mechanical power in real (polytropic) steam expansion process (almost half of the real mechanical power produced in the whole turbine). Developed mechanical power in turbine cylinders and isentropic losses are directly proportional – higher produced mechanical power will result in higher isentropic losses and vice versa. Whole analyzed steam turbine, their cylinders and cylinder parts show very good isentropic performance and high isentropic efficiencies of around 90%. The isentropic performance of the whole analyzed steam turbine, their cylinders and cylinder parts is in the range of the steam turbines (and their cylinders) from supercritical and ultra-supercritical power plants which are proven to be the best steam turbines from isentropic point of view.

KEYWORDS: THERMODYNAMIC (ISENTROPIC) EVALUATION, THREE-CYLINDER STEAM TURBINE, CCPP (COMBINED CYCLE POWER PLANT)

1. Introduction

The majority of electrical power worldwide today is produced by steam turbines [1, 2]. Steam turbines can operate in various kinds of power plants: conventional, nuclear, cogeneration, marine, etc. [3-7]. Steam turbines are also constitutive components of the combined cycle power plants where steam is produced by using combustion gases from gas turbine [8, 9]. Heat utilization in combined cycle power plants, along with mechanical power production in both gas and steam turbines, results in very high plant efficiency [10].

Steam turbines are usually composed of several cylinders connected to the same shaft which drives an electric generator [11, 12]. However, in many power plants and systems can be found low power steam turbines composed of one cylinder only [13, 14]. One cylinder steam turbines are usually auxiliary steam turbines which can be used for the drive of various mechanical power consumers [15]. Each turbine cylinder is dominantly composed of several turbine stages [16], but exceptions can be found in, for example, marine steam power plants where one-cylinder one stage steam turbine (Curtis stage) is used for the main feedwater pump drive [17].

Steam turbine cylinders can be single flow and dual flow cylinders, while dual flow cylinders can be symmetrical and dissymmetrical [18]. In a single flow cylinder, steam expands in one direction from the inlet until the outlet, while in dual flow cylinders steam enters in the cylinder and simultaneously expands in two opposite directions. Symmetrical dual flow steam turbine cylinder has identical left and right part, while dissymmetrical cylinder did not have identical both its parts (left and right parts) [19-21].

In this paper is analyzed one complex steam turbine composed of three cylinders which operates in CCPP (Combined Cycle Power Plant) and has a nominal power equal to 250 MW. Two cylinders of the observed turbine are single flow, while one cylinder is a symmetrical dual flow cylinder. The whole turbine is used for the electric generator drive. It is very interesting that analyzed steam turbine, their cylinders and cylinder parts show very high isentropic performance, comparable to the turbines (and their cylinders) from supercritical and ultra-supercritical steam power plants which are proven to be the best from isentropic point of view.

2. Description and characteristics of the analyzed turbine and their cylinders

As presented in Fig. 1, the turbine is composed of three cylinders – High Pressure Cylinder (HPC), Intermediate Pressure Cylinder (IPC) and Low Pressure Cylinder (LPC). All cylinders are connected to the same shaft which drives an electric generator (EG). Neither one cylinder from the observed turbine did not possess steam extraction [22], therefore the entire produced steam mass flow rate is used for mechanical power production only. Also, all cylinders get a steam mass flow rate produced in the Heat Recovery

Steam Generator (HRSG). HRSG uses heat contained in combustion gases from the gas turbine for producing steam at several pressure levels. Produced steam in HRSG is delivered to each steam turbine cylinder by using complex pipeline network. The nominal power of this steam turbine is equal to 250 MW [23].

HPC get steam of the highest possible pressure and temperature from High Pressure SuperHeater (HPSH). The steam expands through HPC after which is returned back to HRSG and passes through ReHeater (RH). RH increases steam temperature before its expansion in IPC. In RH, additional intermediate pressure steam mass flow rate is added from Intermediate Pressure SuperHeater (IPSH) and cumulative steam mass flow rate from RH expands through IPC. After IPC, steam is not returned back to HRSG, but a certain mass flow rate of low pressure steam is added from Low Pressure SuperHeater (LPSH) – operating point 5, Fig. 1, before expansion in LPC. Cumulative low pressure steam mass flow rate expands through LPC which is a symmetrical dual flow cylinder (HPC and IPC are single flow cylinders). In dual flow cylinders cumulative steam mass flow rate at the cylinder inlet (operating point 6, Fig. 1) is divided into two identical parts – the first part of inlet steam mass flow rate expands through left cylinder part (LPC-L), while the second part of inlet steam mass flow rate expands through right cylinder part (LPC-R). LPC of the analyzed turbine is also a symmetrical cylinder because both LPC parts (left and right) are identical with identical steam operating parameters at the inlet and outlet. After expansion through both LPC parts, steam mass flow rate from each LPC part is delivered to the deaerating condenser for condensation. The analyzed steam turbine arrangement is identical to many steam turbines from various conventional steam power plants [24]. This steam turbine arrangement, among other benefits, ensures the best possible steam axial force self-balancing [25].

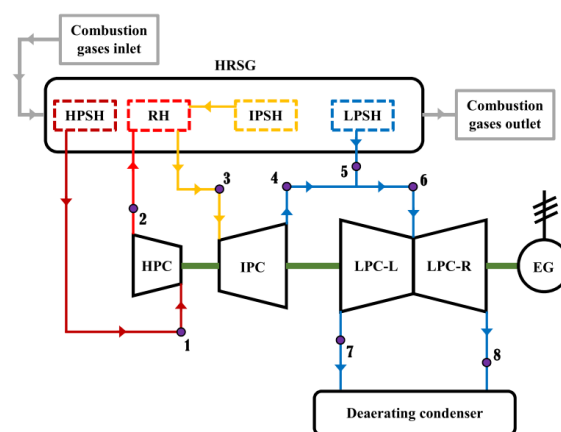


Fig. 1. General scheme and operating points required for the isentropic analysis of the whole turbine and their cylinders

Real (polytropic) and ideal (isentropic) steam expansion processes through each cylinder of the observed steam turbine are presented in specific enthalpy/specific entropy (h/s) diagram in Fig. 2.

In real (polytropic) steam expansion process through each cylinder is visible increase in steam specific entropy which is related to losses during expansion. Operating point's for real (polytropic) steam expansion process in each cylinder of the observed turbine are marked in Fig. 2 identically to operating points from Fig. 1.

Ideal (isentropic) steam expansion process is the best possible process which can occur in each turbine cylinder, and it did not consider any losses during the expansion (in ideal steam expansion process losses are equal to zero). Neglecting all the losses during expansion results with a fact that in ideal process steam specific entropy remains constant in each cylinder (and identical as at the cylinder inlet). Therefore, in ideal (isentropic) steam expansion process in each cylinder or cylinder part steam pressures and mass flow rates remain the same as in real (polytropic) process – the only difference in comparison to real process is retaining always the same steam specific entropy. In ideal expansion will always be developed the highest possible mechanical power (necessarily higher than in the real expansion process). Mechanical power developed in an ideal expansion process through each turbine cylinder cannot be obtained in real exploitation conditions, but it can be a guideline for losses reduction [26]. In ideal (isentropic) steam expansion processes operating points are marked in a same manner as presented in Fig. 1, but with the addition of index “is” along with the number.

In Fig. 2, ideal expansion process in HPC is marked with operating points 1 and 2is, in the IPC ideal process is marked with operating points 3 and 4is, while in each part of the LPC ideal steam expansion process occur between operating points 6 and 7is or between operating points 6 and 8is.

As noted before, LPC is composed of two identical parts with identical steam operating parameters – so steam expansion processes through both LPC parts (LPC-L and LPC-R) are identical.

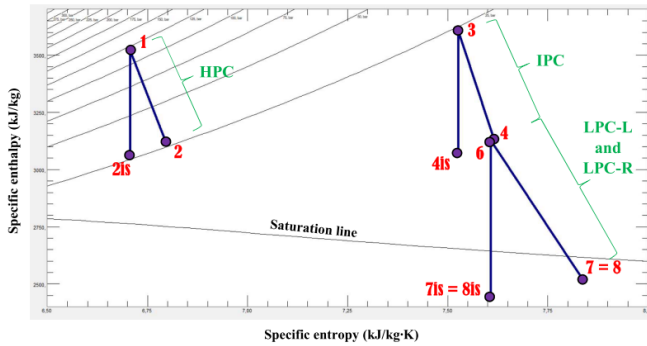


Fig. 2. Specific enthalpy/specific entropy diagram of steam expansion process (both ideal and real) through all three steam turbine cylinders

3. Isentropic analysis equations

Isentropic analysis is based on a comparison of ideal (isentropic) and real (polytropic) steam expansion processes. The essential element of comparison is produced ideal and real mechanical power in each cylinder, cylinder part and whole observed turbine [27]. Isentropic analysis equations presented in this paper part are based on the recommendations from available literature [28-30]. Also, it should be highlighted that isentropic analysis is a “black box” method because it did not require knowledge of the internal structure of any cylinder or cylinder part [31]. Markings in the following equations will be related to operating points from Fig. 1 and Fig. 2.

Real (polytropic) mechanical power of each cylinder, cylinder part and whole turbine is calculated according to the equations:

$$P_{re,HPC} = \dot{m}_1 \cdot (h_1 - h_2), \quad (1)$$

$$P_{re,IPC} = \dot{m}_3 \cdot (h_3 - h_4), \quad (2)$$

$$P_{re,LPC-L} = P_{re,LPC-R} = \frac{\dot{m}_6}{2} \cdot (h_6 - h_7), \text{ where } h_7 = h_8, \quad (3)$$

$$P_{re,Whole LPC} = P_{re,LPC-L} + P_{re,LPC-R} = 2 \cdot P_{re,LPC-L}, \quad (4)$$

$$P_{re,Whole Turbine} = P_{re,HPC} + P_{re,IPC} + P_{re,Whole LPC}. \quad (5)$$

Ideal (isentropic) mechanical power of each cylinder, cylinder part and whole turbine is calculated according to the equations:

$$P_{id,HPC} = \dot{m}_1 \cdot (h_1 - h_{2is}), \quad (6)$$

$$P_{id,IPC} = \dot{m}_3 \cdot (h_3 - h_{4is}), \quad (7)$$

$$P_{id,LPC-L} = P_{id,LPC-R} = \frac{\dot{m}_6}{2} \cdot (h_6 - h_{7is}), \text{ where } h_{7is} = h_{8is}, \quad (8)$$

$$P_{id,Whole LPC} = P_{id,LPC-L} + P_{id,LPC-R} = 2 \cdot P_{id,LPC-L}, \quad (9)$$

$$P_{id,Whole Turbine} = P_{id,HPC} + P_{id,IPC} + P_{id,Whole LPC}. \quad (10)$$

Isentropic loss is calculated according to the equation:

$$IS_{Loss,(i)} = P_{id,(i)} - P_{re,(i)}, \quad (11)$$

while isentropic efficiency is:

$$\eta_{IS,(i)} = \frac{P_{re,(i)}}{P_{id,(i)}}. \quad (12)$$

In Eq. 11 and Eq. 12 i is the index related to any cylinder, cylinder part and whole turbine (i = HPC; IPC; LPC-L; LPC-R; Whole LPC; Whole Turbine).

4. Steam operating parameters required for the isentropic analysis

Steam operating parameters of the real (polytropic) expansion process in each operating point from Fig. 1 are found in [23] and presented in Table 1. For the ideal (isentropic) steam expansion process, operating parameters in each operating point from Fig. 2 are calculated according to the previously described procedure by using NIST-Refprop 9.0 software [32] and they are presented in Table 2.

Table 1. Steam operating parameters of the real (polytropic) steam expansion process

O. P.*	Temp. (K)	Pressure (bar)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)	Quality**
1	838.06	118.90	149.65	3521.0	6.7067	Superh.
2	625.82	27.89	149.65	3126.9	6.7942	Superh.
3	837.74	23.89	166.36	3608.0	7.5265	Superh.
4	605.76	4.60	166.36	3132.9	7.6154	Superh.
5	583.28	4.75	17.95	3086.1	7.5221	Superh.
6	603.55	4.60	184.31	3128.3	7.6079	Superh.
7	324.18	0.13	92.16	2521.7	7.8368	0.97
8	324.18	0.13	92.16	2521.7	7.8368	0.97

* O. P. = Operating Point (in accordance to Fig. 1)

** Quality equal to 1 denotes saturated steam, while quality equal to 0 denotes water

Table 2. Steam operating parameters of the ideal (isentropic) steam expansion process

O. P.*	Pressure (bar)	Mass flow rate (kg/s)	Isentropic specific enthalpy (kJ/kg)
1	118.90	149.65	3521.0
2is	27.89	149.65	3073.2
3	23.89	166.36	3608.0
4is	4.60	166.36	3080.1
6	4.60	184.31	3128.3
7is = 8is	0.13	92.16	2447.5

* O. P. = Operating Point (in accordance to Fig. 2)

5. Isentropic analysis results and discussion

Mechanical power of each cylinder, cylinder part and whole turbine developed in real (polytropic) and ideal (isentropic) steam expansion processes is presented in Fig. 3. Due to neglecting all losses during expansion, mechanical power developed in the ideal process must always be higher than mechanical power developed in the real process, what can clearly be seen in Fig. 3.

According to the results presented in Fig. 3, considering all cylinders, the dominant mechanical power producer in the observed turbine is LPC which produces 111.80 MW of mechanical power in real (polytropic) steam expansion process. HPC is the cylinder which produces the lowest mechanical power (both ideal and real). Fig. 3 also confirms that LPC is a symmetrical cylinder because both of its parts (LPC-L and LPC-R) develop identical mechanical power equal to 55.90 MW in real and 62.74 MW in the ideal expansion process.

Whole observed steam turbine produces mechanical power equal to 249.82 MW in real (polytropic) steam expansion process what means that steam operating parameters presented in Table 1 are nominal load parameters. In ideal (isentropic) steam expansion process whole turbine can produce mechanical power equal to 280.31 MW what can be used as a guideline for the improvements and losses reduction.

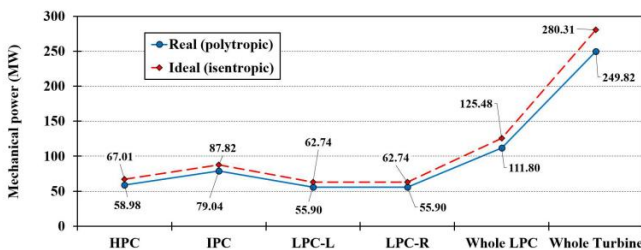


Fig. 3. Mechanical power (real and ideal) of each cylinder and whole observed turbine

Isentropic losses of each cylinder, cylinder part and whole analyzed turbine are presented in Fig. 4.

Comparison of Fig. 3 and Fig. 4 related to the turbine cylinders shows that developed mechanical power (both ideal and real) and isentropic losses are directly proportional – higher produced mechanical power will result in higher isentropic losses and vice versa. Therefore, the highest isentropic loss of all cylinders can be seen in LPC (equal to 13.68 MW), while the lowest isentropic loss of all cylinders has HPC (equal to 8.04 MW).

Whole observed steam turbine has isentropic loss equal to 30.50 MW. Any reducing the whole turbine isentropic loss will result with an increase in produced mechanical power and overall efficiency.

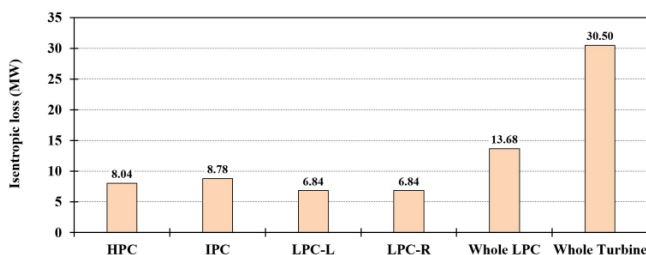


Fig. 4. Isentropic loss of each cylinder and whole observed turbine

Isentropic efficiency of each cylinder, cylinder part and whole observed turbine can clearly be seen in Fig. 5.

From Fig. 5 can easily be concluded that whole observed steam turbine, their cylinders and cylinder parts show very good isentropic performance and high isentropic efficiencies of around 90%. Observation of all cylinders leads to conclusion that HPC has the lowest isentropic efficiency (equal to 88.01%), while IPC has the highest isentropic efficiency (equal to 90.00%). Whole LPC as well as both of its parts (LPC-L and LPC-R) have identical isentropic efficiencies equal to 89.10%. The highest isentropic efficiency of

IPC can be explained with optimal operating conditions in which this cylinder operates. IPC is not influenced with a steam of the highest pressure and temperature in the plant (as HPC) and, simultaneously, what can clearly be seen in Fig. 2, neither one IPC stage did not operate by using wet steam as LPC (wet steam contains water droplets which increases losses). Therefore, as concluded for many other similar steam turbines, IPC performance is in the most of the cases better than the performance of any other cylinder inside the same steam turbine [33]. Whole observed steam turbine has a very high isentropic efficiency equal to 89.12%.

In comparison to isentropic efficiencies (for each cylinder and whole turbine) of various similar steam turbines from other power plants which can be found in the literature [34], it can be concluded that analyzed steam turbine and their cylinders have very high isentropic efficiencies. In the literature can be found that steam turbines from supercritical and ultra-supercritical steam power plants shows the best performance and the highest efficiencies (for each cylinder and whole turbine) [34]. It should be highlighted that an isentropic performance of the whole steam turbine and their cylinders analyzed in this paper is in the range of the steam turbines (and their cylinders) from supercritical and ultra-supercritical power plants.

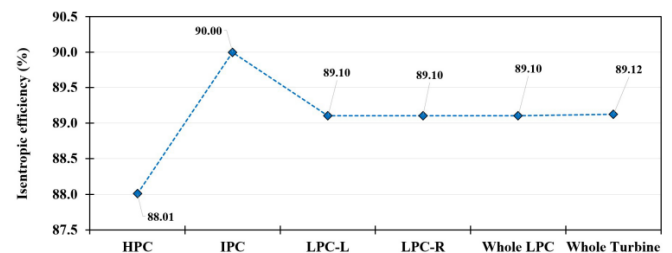


Fig. 5. Isentropic efficiency of each cylinder and whole observed turbine

Further analysis and possible optimization of the observed steam turbine will be based on the results obtained in this analysis. For that purpose, many conventional and artificial intelligence [35, 36] methods and processes can and will be used.

6. Conclusions

This paper presents isentropic analysis results of the complex three-cylinder steam turbine which operates in a CCPP. The nominal power of the observed steam turbine is equal to 250 MW, while entire steam mass flow rate used in the observed turbine is produced in HRSG which uses combustion gases from the gas turbine. The most important conclusions of the performed analysis are:

- The dominant mechanical power producer in the observed turbine is LPC which produces 111.80 MW of mechanical power in real (polytropic) steam expansion process. Real mechanical power produced in the LPC represents almost half of cumulative produced real mechanical power in the whole turbine.
- Developed mechanical power in turbine cylinders and isentropic losses are directly proportional – higher produced mechanical power will result in higher isentropic losses and vice versa.
- Whole observed steam turbine has isentropic loss equal to 30.50 MW. Any reducing the whole turbine isentropic loss will result with an increase in produced mechanical power and overall efficiency.
- Whole observed steam turbine, their cylinders and cylinder parts show very good isentropic performance and high isentropic efficiencies of around 90%.
- IPC of all cylinders has the highest isentropic efficiency (equal to 90.00%). The highest isentropic efficiency of IPC can be explained with optimal operating conditions in which this cylinder operates. IPC is not influenced with a steam of the highest pressure and temperature in the plant (as HPC) and, simultaneously, neither one IPC stage did not operate by using wet steam as LPC (wet steam contains water droplets which increases losses).
- It should be highlighted that an isentropic performance of the whole analyzed steam turbine and their cylinders is in the range of

the steam turbines (and their cylinders) from supercritical and ultra-supercritical power plants which are proven to be the best turbines from isentropic point of view.

7. Acknowledgment

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"Preparation, phase and optical characterization of $\text{Sm}_2\text{O}_3\text{-ZrO}_2$ coatings on glasses obtained by sol-gel technology using the Dip Coating method"

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Abstract: Obtained experimental self-cleaning coatings (based on compositions with the participation of Sm_2O_3), applied by the sol-gel method on glass slides. This study attempts to improve the overall efficiency of a photovoltaic solar panel by using a Sm_2O_3 doped ZrO_2 (SDZ)-based coating. The optical characterization and phase composition of the obtained experimental samples were investigated using UV-VIS-NIR, XRD and XRF methods. The coatings are nanocrystalline according to XRD and XRF analyzes and show transmittance close to that of pure glass when tested with a UV-VIS-NIR spectrophotometer. The experimental results represent a prerequisite for the development of a series of additional compositions and a detailed technological regime for obtaining various modifications of resistant, long-lasting self-cleaning coatings, potentially applicable to photovoltaic panels.

Keywords: SOL GEL, XRD, XRF, UV-VIS-NIR, DIP COATING, PHOTOVOLTAICS, ZrO_2 , Sm_2O_3

1. Introduction

Zirconium oxide is one of the most well studied transition-metal oxides with promising applications in the development of innovative materials, products with high operational reliability and components for high-tech devices [1-7].

Zirconium oxide thin films are characterized by the presence of a significant variety of functional properties [8-27]: high hardness, excellent mechanical properties, high melting point, corrosion resistance, low electrical conductivity, high dielectric constant, high refractive index, high transparency in the visible and near-infrared regions, large optical band gap, high laser-induced damage threshold, low optical loss, good thermal properties, chemical inertness, biocompatibility, good thermodynamic stability in contact with silicon, etc.

Due to their characteristics, various thin films obtained on the basis of ZrO_2 find application as wear resistance coatings, corrosion protective layers, thermal barriers [28], as well as in the production of various electronic components, biocompatible implants and a number of other products.

At the same time, due to their unique optical properties, thin films of ZrO_2 have significant potential for use in the field of optics and opto-electronics [15,19,29-31] for the development of broadband interference filters, selective reflection coatings, active electro-optical devices, including light emitting diodes, oxygen sensors, high power laser, passive and active waveguides, buffer layers in micro-electronic devices, scintillators, etc.

The operational properties of thin films are determined by their phase composition and structure, which depend on the components used, the presence of modifiers and the applied technological methods for coating deposition.

There are many different techniques for deposition thin films [3,15-19,29-38], such as chemical vapor deposition (CVD), physical vapour deposition (PVD), electrochemical deposition, hydrothermal processing, electron beam evaporation, magnetron sputtering, spray pyrolysis, plasma spraying, pulsed laser deposition, atomic layer deposition, liquid phase deposition method, ion-beam aid deposition and sol-gel method, etc.

Among them the sol-gel method [3,16,32-34,37] provides a number of significant technological advantages such as relatively low processing temperatures, high optical quality of the obtained coatings, capability of coating large surface areas, simplicity and comparative low cost, etc. In order to regulate the solvent evaporation rate, the formation of various cracks and crystal defects and to suppress of the process of the grains growth and unfavorable aggregation, appropriate low-volatility organic compounds are introduced to the used sol-gel precursors: polyvinyl alcohol, polyethylene glycol, hydroxypropyl cellulose, polyvinylpyrrolidone [19]. In addition, this technique is suitable to preparation almost any homogeneous and uniform single- or multi-component oxide coatings (ZrO_2 , SiO_2 , etc.) prepared by spin and dip coating method [31].

The ion Zr^{4+} does not exhibit pronounced photoluminescence properties, but this can be significantly affected by the formed local defects [20]. In most cases they represent oxygen vacancies, various types of impurities, free radicals, etc., which favor broad band PL emission [20].

The sol-gel deposition method is known to provokes the formation of large number of surface defects (for example-oxygen / Zr vacancies or interstitials) in the thin ZrO_2 coatings, which improves their photoluminescence characteristics [19].

Another technological method to activate the PL emission is incorporation of appropriate luminescent agents (including lanthanide ions and others) into the host lattice of ZrO_2 [20]. The existing low-phonon energy of ZrO_2 creates the possibility for the implementation of more efficient luminescence from the incorporated activator ions. The considered effect is determined by the fact that the lower the phonon energy of the specific host, the higher the probability of performing a radiative transitions of the introduced rare earth $3+$ ions [20].

In this aspect, a current technological interest is the study of the characteristics of modified Sm-doped ZrO_2 experimental samples and the possibilities for obtaining thin films of Sm_2O_3 .

Samarium-doped zirconia samples were prepared using two different technological approaches. By applying atomic layer deposition, thin crystalline films (doped by using ion implantation) with a predominantly monoclinic structure were prepared. While by skull-melting method, bulk polycrystalline experimental samples with presence of monoclinic and tetragonal phases of ZrO_2 were obtained [35]. Photoluminescence measurements of Sm emission in the prepared samples were performed by using pulsed laser excitation at 405, 320 and 230 nm. The obtained spectra may be interpreted as superpositions of two different sets of lines attributable to the presence of Sm^{3+} centers in different phases of ZrO_2 . The research of the fine structure in the observed luminescence spectra of Sm^{3+} ions in the experimental sample showed the existence of at minimum two different luminescence centers related to monoclinic and tetragonal phases of ZrO_2 [35]. Excitation at 405 nm provokes the direct excitation of Sm^{3+} , whereas the excitation at 230 nm is interpreted as host-sensitized excitation.

A samarium doped polycrystalline ZrO_2 experimental sample was studied for its phase composition and optical characteristics. From micro-Raman measurements performed the presence of tetragonal as well as monoclinic phase was confirmed [36]. The obtained emission spectrum of Sm^{3+} suggest a significant changes under excitation near the spectral region of fundamental absorption. Combined excitation-emission spectroscopy measurements shows three different sites for the used dopant ions to be present in the experimental sample [36].

Innovative thin films of zirconia oxide ZrO_2 and samarium oxide Sm_2O_3 on glass substrates have been obtained by applying

sol-gel technology and using dip coating method [37]. Excitation and emission spectra of ZrO₂ films consists of broad bands with maximum values of 318 and 365 nm. The photoluminescence measurements performed of the deposited Sm₂O₃ thin films reveals that can be efficiently excited with 700 nm and consist of emission bands centered at 567, 603, 639 and 707 nm, consistent with characteristic Sm³⁺ transitions [37]. The established values of the chromaticity coordinate points of the prepared Sm₂O₃ and ZrO₂ thin films are located in the orange and blue region. The obtained Sm₂O₃ thin films is characterized by a high color purity of 96% [37].

Samarium oxide Sm₂O₃ thin coatings were deposited on silicon substrates by using pulsed laser deposition method at a temperature range of 25, 200, 400 and 680°C [38]. The performed XRD analysis shows that the structure of Sm₂O₃ coating obtained at 25°C is amorphous, while the coating prepared at 200°C is a partially crystallized. Monoclinic structure was the established predominant phase for Sm₂O₃ coatings obtained at temperatures of 400°C and 680°C [38]. The polycrystalline Sm₂O₃ coating prepared at 680°C is very dense, while coatings obtained at lower temperatures (25, 200 and 400°C) have higher porosity. The established values of index of refraction *n* and extinction coefficient *k* (at $\lambda=633$ nm) are 1.867 and 0.0660 for the coating prepared at 680°C and are in a range of 1.5~1.6 and 0.01~0.04 respectively for films deposited at lower temperatures [38].

2. Experimental procedures

All of the chemicals were utilized exactly as they were supplied, in analytical grades. AGC Glass Europe chemicals were used for thin film coatings. Alfa Aesar Germany supplied the 99.9% ethanol C₂H₅OH), ZrOCl₂·8H₂O, and Sm₂O₃. Nitric acid (HNO₃) is used as a stabilizer. Getting the glass substrate ready. The slides were trimmed to size (20 mm × 70 mm × 2 mm) before to cleaning. In order to clean and remove submicron particles from the substrate surface, substrate cleaning is crucial before the deposition process. The quality of the sticky film on the base is determined by this. After being cleaned or washed for 15 minutes in 99.9% ethyl alcohol and 15 minutes in acetone, the glass substrates were dried at 60°C for 10 minutes. Cleaning the glass substrates helps the coating material stick to the substrate better and keeps the coating from being contaminated. The production technology is presented in the scheme. They used sol-gel technology. After dissolving ZrOCl₂·8H₂O in H₂O and pure alcohol, a 0.01–0.02 molar solution was produced. Sm₂O₃ was added 30 minutes later. It was vigorously stirred while Sm₂O₃ was added gradually. The ratio was 6.5 weight percent Sm₂O₃ to 93.5 weight percent ZrO₂. Nitric acid was added or agitated during the hydrolysis process until the solution turned clear, meaning it had been fully dissolved. The glass sample was coated with the resultant solution using the Dip Coating technique. The substrates were immersed in the prepared solutions for 30 s and then pulled out at a speed of 0.8 mm.s⁻¹ and dried to evaporate the organic solvents - the glass substrates were dried at 120°C for 30 minutes. The coating procedure was repeated three times. After that, the sample was treated at 420°C.

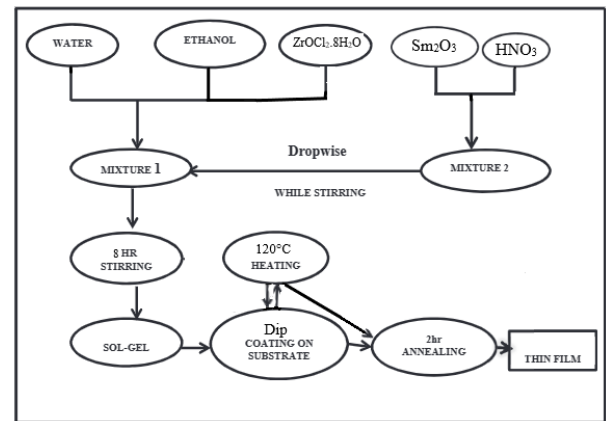
3. Results and Discussion

The samples were examined using a Philips X-ray diffractometer PW 1030, with an X-ray source of Cu K α radiation ($\lambda = 1.5406$ Å) and θ -2 θ Bragg-Brentano geometry. The scan step size was 0.025°, 10 s in the range 25–65° 2 θ . The diffractograms were analysed using the PDF-2 2022 database.

The thickness of the layer and its elemental composition were measured using energy-dispersive X-ray fluorescence spectrometry (EDXRF) with an EPSILON 1 spectrometer (PANalytical, Malvern, UK). The Omnian and Stratos software modules were used for quantitative and layer thickness analysis respectively.

The size of the crystallites is calculated according to the Scherrer formula:

Schematics of the process of obtaining a thin film of sol gel with ZrO₂ and Sm₂O₃



$$D = 0.9\lambda / B \cdot \cos\theta$$

D - average crystallite size / Average Crystallite size/

λ - wavelength (in angstroms) - 1.54178 Å / X-Ray wavelength/

θ - Bragg angle (degrees) - 2 θ /2 /Bragg angle/

B - line broadening FWHM (2 θ), /Line broadening/ must be of dimension radians (rad=2 θ * π /180)

Figures 1-3 present the results of XRD and XRF analyses of the surface of the glass samples. The SDZ3 /Figure 1/ layer is thinner and amorphous. X-ray diffraction (XRD) analysis confirmed the presence of zirconium and samarium oxides. The distinct peak at 31.91° 2 θ in the diffractogram of sample SDZ5 /Figure 3/ corresponds to the (120) plane of orthorhombic ZrO₂ [ref. code: 00-049-1746]. A broad, lower-intensity peak at 31.12° 2 θ suggests the crystallization of an additional phase on the surface. Weaker reflections at 34.92°, 50.21°, and 59.67° 2 θ correspond to the (111), (200), (220), and (311) planes of cubic ZrO₂ [ref. code: 00-089-9069]. The broadening of the main peak at 31.12° 2 θ (111) indicates the fine-grained nature of the coating, but it could also be related to the formation of monoclinic Sm₂O₃, whose peaks overlap with those of ZrO₂. The diffractogram of SDZ4 /Figure 2/ shows the formation of a cubic ZrO₂ layer, with samarium possibly present either as a dopant in the cubic zirconium oxide lattice or as monoclinic Sm₂O₃.

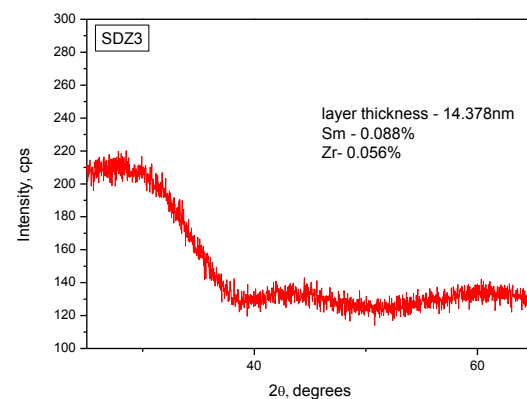


Figure 1. XRD and XRF analyses of the surface of the coating on glass / SDZ3 /

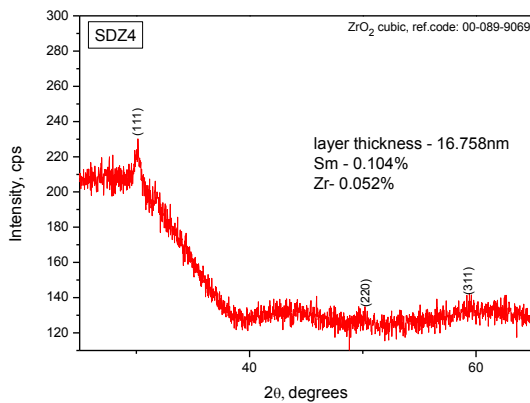


Figure 2. XRD and XRF analyses of the surface of the coating on glass / SDZ4 /

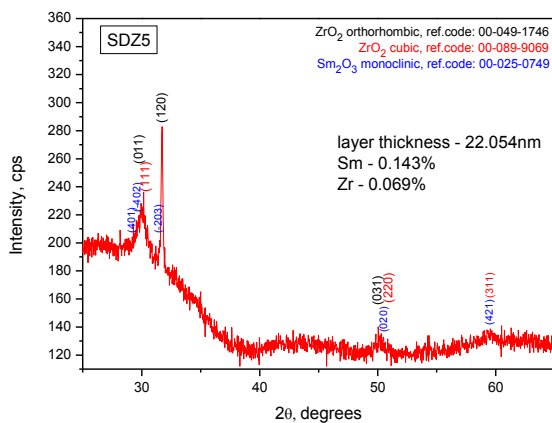


Figure 3. XRD and XRF analyses of the surface of the coating on glass / SDZ.5/

The figures show the percentage composition of ZrO_2 and Sm_2O_3 and the thickness of the coating on the modified glass surfaces. X-ray fluorescence analysis confirms the incorporation of Zr and Sm ions into the surface, forming a coating with a thickness of 14 to 22 nm.

The crystallite sizes (t) were calculated using Scherer's equation: $t = \kappa \lambda / B \cos \theta$. Here, κ is the shape factor ($\kappa = 0.9$ for spherical crystals with cubic symmetry); λ (in Å) is the wavelength; θ is the diffraction angle of the peak; and B (in radians) is the line broadening at the full width at half maximum (FWHM) values of the peaks. The crystallite sizes ranged from 9 to 76 nm for ZrO_2 and Sm_2O_3 (Table.1).

Table 1.

Samples	2θ	hkl	t (nm)
SDZ5	31.12	(111)	9
	31.91	(120)	76
SDZ4	31.12	(111)	10

Optical characterization was performed with UV-VIS-NIR Shimadzu 3600 double-beam spectrophotometer (Shimadzu Corporation, Kyoto, Japan) in the spectral region of 240-1800 nm. The transmittance spectra of the samples were taken against air. The reflectance spectra were measured by using the specular reflectance attachment (5° incidence angle) and Al coated mirror as reference. On the figures 4,5 present the results of optical characterization.

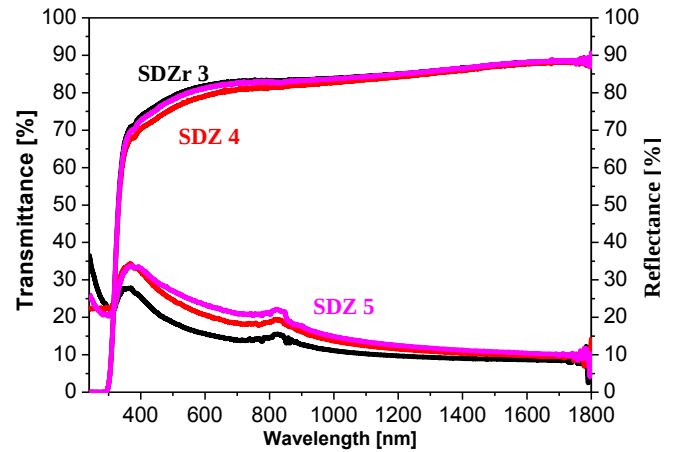


Figure 4. The figure shows the transmission and reflection spectrum of an experimental coating on a glass substrate in the region 400 - 1800 nm / SDZ.3, SDZ.4 and SDZ. 5 /

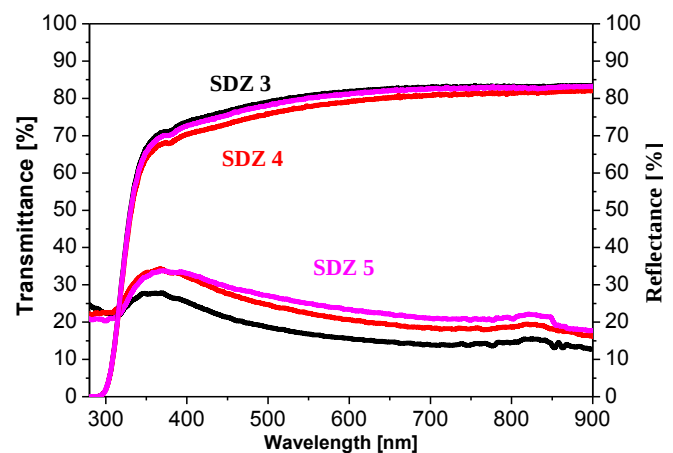


Figure 5. The figure shows the transmission and reflection spectrum of an experimental coating on a glass substrate in the region 300 - 900 nm / SDZ.3, SDZ.4 and SDZ.5 /

4. Conclusions

This study attempts to improve the overall efficiency of a photovoltaic solar panel by using a ZrO_2 -based coating, with Sm_2O_3 .

1. The coatings are prepared by sol gel method with Dip Coating.

2. The coatings are dense and nanocrystalline, according to XRD and XRF analyses.

3. The coatings of SDZ.3, SDZ.4 and SDZ.5 samples show good transmittance by UV-VIS-NIR spectrophotometer examination.

The experimental results represent a prerequisite for the development of a series of additional compositions and a detailed technological regime for obtaining various modifications of resistant, long-lasting self-cleaning coatings, potentially applicable to photovoltaic panels.

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Study of the influence of transition and rare earth oxide coatings on glasses for photovoltaic panels produced by the sol-gel method. A Review

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Abstract: The efficiency of photovoltaic (PV) systems is significantly influenced by surface contamination, which can reduce light transmission and energy conversion performance. In this study, self-cleaning nanostructured coatings based on titanium dioxide (TiO_2), zirconium dioxide (ZrO_2), and their doped and composite variants (with Y_2O_3 and Eu_2O_3) were synthesized using the sol-gel method and applied to photovoltaic glass substrates. The coatings were characterized in terms of their optical transmittance, surface morphology (AFM), wettability (contact angle), and crystallographic properties (XRD). Results indicate that TiO_2 coatings offer superior superhydrophilic behavior, while stabilized ZrO_2 -based composites show excellent transparency, surface homogeneity, and long-term durability. Eu_2O_3 -doped coatings exhibit additional luminescent functionalities, potentially useful for photonic enhancement. These findings highlight the potential of sol-gel coatings in improving PV panel performance via integrated passive cleaning mechanisms and multifunctional surface engineering.

KEYWORDS: SOL-GEL COATINGS, SELF-CLEANING FILMS, PHOTOVOLTAIC PANELS, TiO_2 , ZrO_2 , Y_2O_3 , Eu_2O_3 , NANOSTRUCTURES, AFM, UV-VIS-NIR, XRD

1. Introduction

Photovoltaic (PV) installations reached a global capacity of two terawatts (2 TW) by November 2024, with growth rates and cost reductions being remarkably high [1]. In 2022, a major milestone in renewable energy was reached: photovoltaics (PV) surpassed a global installed capacity of 1 TWdc. However, despite the significant growth and decreasing costs over time, PV still accounts for only a small portion of global electricity production (4 to 5% in 2022).

The number of PV systems installed worldwide has grown almost exponentially since 2010, leading to a cumulative installed photovoltaic capacity of approximately 1.5 terawatt-peak (TWp) by the end of 2023 [2], compared to only 39 GWp installed by the end of 2010. (1 TWp = 1000 GWp, and Wp refers to the maximum power a photovoltaic module can deliver when illuminated with a standardized solar spectrum AM1.5 at a module temperature of 25°C).

In 2023, approximately 300 GWp of photovoltaic modules were installed globally, and this annual installation rate is expected to grow rapidly over the next decade to reach 1–3 TWp per year.

For a high-efficiency photovoltaic module, light absorption in the absorber layer of solar cells must be maximized. To maximize absorption, first, reflection losses must be minimized—or conversely, the coupling of incident light into the solar cell must be maximized. Second, for weakly absorbing semiconductors such as silicon, absorption must be enhanced. This is the role of anti-reflective coatings.

Anti-reflective coatings, illustrated in Fig. 1, are applied to the surface of solar cells and cover the glass of photovoltaic modules to increase light absorption and its conversion into electricity. They reduce the reflection from the solar cell, allowing more light to enter the cell. The coating is designed to have a refractive index between that of air and the front material of the solar cell or photovoltaic module. Reflection is minimized when the thickness of the coating is one-quarter of the wavelength. In that case, the phase shift between the front and rear reflected rays is $\Delta\phi = \pi$. [3]

The global rise in PV installations underscores the need to optimize their performance and longevity. Surface soiling and optical losses reduce energy output, especially in dusty or industrial environments. A promising solution lies in applying self-cleaning, anti-reflective coatings. The sol-gel method allows cost-effective fabrication of such functional layers with nanoscale control.

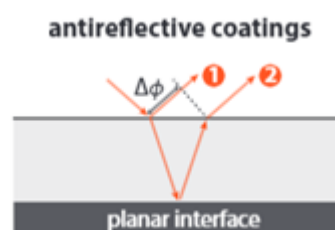


Figure 1. Optical concept used in photovoltaics. - In antireflective coatings, the strongest antireflective effect is achieved when the phase shift $\Delta\phi$ between the rays reflected from the front (1) and the back (2) is π , 3π , 5π . . In addition.

Photovoltaic (PV) systems represent a cornerstone of renewable energy infrastructure, yet their long-term efficiency is hindered by the accumulation of environmental contaminants on glass surfaces. These deposits, mainly composed of dust, organic residues, and pollutants, reduce light transmittance and deteriorate electrical output. Mechanical and automated cleaning systems are either cost-inefficient or impractical in remote installations, leading to interest in passive self-cleaning surface coatings. Sol-gel technology enables the production of nanostructured oxide layers with controllable properties, offering both transparency and surface functionality essential for photovoltaic performance enhancement.

The development of self-cleaning materials, especially in photovoltaic systems, began in the late 20th century as part of a broader movement to reduce maintenance costs and improve long-term efficiency in solar installations. Traditional coatings, while often transparent, lacked hydrophilicity or photocatalytic properties. TiO_2 -based films, introduced due to their photoreactive nature and superhydrophilic behavior, became a benchmark for self-cleaning surfaces. However, they also showed limitations in phase stability and wear resistance, especially in harsh outdoor environments. This has led to exploration of other oxides such as ZrO_2 , Y_2O_3 , and Eu_2O_3 that offer structural robustness and multifunctionality when combined through sol-gel methods.

The sol-gel method offers an economical and flexible approach for depositing anti-reflective and self-cleaning thin layers on glass surfaces of photovoltaic panels. Recent experimental research conducted at the Bulgarian Academy of Sciences focuses on the development of coatings based on TiO_2 , ZrO_2 , Y_2O_3 and Eu_2O_3 , applicable under real conditions. However, cleaning mechanisms vary widely between materials and are highly dependent on environmental exposure [7 – 19].

2. Experimental procedures

Thin film coatings were deposited on cleaned AGC glass substrates using a sol-gel dip-coating technique. Precursor solutions were prepared by dissolving titanium butoxide ($\text{Ti}(\text{OBU})_4$) and zirconium oxychloride ($\text{ZrOCl}_2 \cdot 8\text{H}_2\text{O}$) in ethanol with nitric acid (HNO_3) as a stabilizer. Yttrium nitrate ($\text{Y}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$) and Eu_2O_3 were added in controlled proportions to synthesize doped and composite systems. The solutions were stirred magnetically for 2 hours at room temperature.

The slides were trimmed to size (20 mm × 70 mm × 2 mm) before to cleaning. In order to clean and remove submicron particles from the substrate surface, substrate cleaning is crucial before the deposition process. The quality of the sticky film on the base is determined by this. After being cleaned or washed for 15 minutes in 99.9% ethyl alcohol and 15 minutes in acetone, the glass substrates were dried at 60°C for 30 minutes. Cleaning the glass substrates helps the coating material stick to the substrate better and keeps the coating from being contaminated. Dip-coating was performed at a withdrawal rate of 3 mm/s, with a 10-second immersion time. After each coating cycle, films were dried at 120°C degrees Celsius for 30 minutes. Final curing was carried out in a muffle furnace at 400 – 450°C for 2 hours with controlled temperature ramping (5 °C/min).

Optical characterization was performed with UV–VIS–NIR Shimadzu 3600 double-beam spectrophotometer (Shimadzu Corporation, Kyoto, Japan) in the spectral region of 240–1800 nm. The transmittance spectra of the samples were taken against air. The reflectance spectra were measured by using the specular reflectance attachment (5° incidence angle) and Al coated mirror as reference.

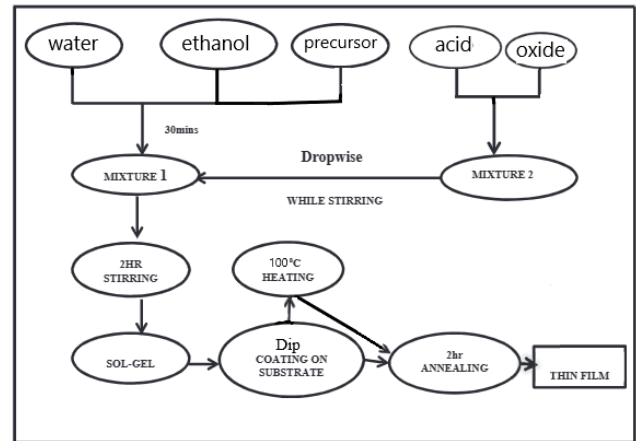
AFM imaging was performed on the NanoScope V system (Bruker Ltd, Germany) operating in tapping mode in air at a room temperature. We used silicon cantilevers (Tap 300Al-G, Budget Sensors, Innovative solutions Ltd. Bulgaria) with 30 nm thick aluminum reflex coatings. According to the producer's specifications the cantilever spring constant and the resonance frequency are in the range of 1.5 to 15 N/m and 150 ± 75 kHz, respectively. The radius of tip curvature was less than 10 nm. The scanning rate was set at 1 Hz and the images were taken in highest possible resolution mode of the AFM, 512×512 pixels in JPEG format. The NanoScope software was used for the section analysis and roughness of the all images.

This study utilised the DSA 100-Expert (Krüss GmbH, Germany) to measure contact angles on glass substrates. Contact angles were measured using the tilting table accessory of the DSA 100-Expert to identify both the advancing and receding contact angles. A droplet of deionised water was deposited onto the glass substrate, and the table was then tilted at a consistent rate of 5 degrees per minute, up to an angle of inclination of 90 degrees.

The synthesised materials were studied using an X-ray powder diffractometer (XRD), specifically a PANalytical Aeris, which uses $\text{CuK}\alpha$ radiation ($\lambda = 1.5406 \text{ \AA}$) in a θ - θ configuration following the Bragg-Brentano geometry. The 2θ scan range was set from 20° to 40° with a scan step of 0.02° for 60 seconds per step. The diffractograms were analysed using the PDF-2 2022 database.

The thickness of the layer and its elemental composition were measured using energy-dispersive X-ray fluorescence spectrometry (EDXRF) with an EPSILON 1 spectrometer (PANalytical, Malvern, UK). The Omnian and Stratos software modules were used for quantitative and layer thickness analysis respectively.

Schematics of the process of obtaining a thin film of sol gel



3. Results and Discussion

3.1 Optical Transmittance

All coatings demonstrated high optical transmittance in the 400–1800 nm range. TiO_2 and Eu_2O_3 -containing coatings achieved the highest transmittance, reaching up to 85%, with minimal spectral distortion. ZrO_2 and Y_2O_3 -doped systems also maintained transparency suitable for PV applications / Figure 1/.

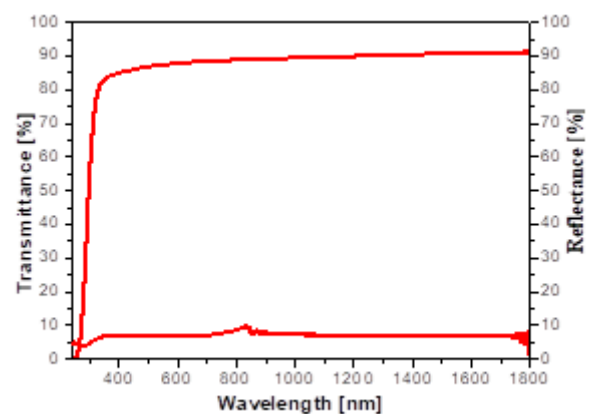


Figure 1. The figure shows the transmission and reflection spectrum of an experimental coating on a glass substrate in the region 400 - 1800 nm /the spectra are of the same type/

3.2 Surface Morphology (AFM)

AFM analysis revealed nanoscale surface roughness for all sol-gel coatings. TiO_2 coatings exhibited uniform surfaces with roughness average (Rq) of 5–14 nm. ZrO_2 -based coatings, particularly with Y_2O_3 or Eu_2O_3 additives, showed more structured but still even morphologies with Rq values of 10–15 nm, supporting favorable light-scattering and wetting properties / Figure 2/.

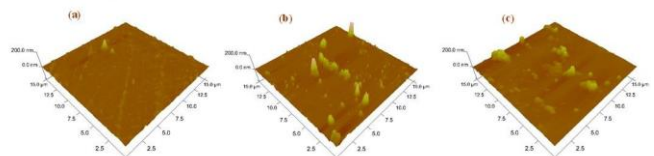


Figure 2. 3D AFM images of the surface of the samples (TiO_2) with scan area $5 \times 5 \mu\text{m}^2$ and z-range, $z = 100 \text{ nm}$ and $z = 200 \text{ nm}$

3.3 Wettability and Self-Cleaning Behavior

TiO₂ coatings showed superhydrophilic behavior, with contact angles as low as 8.3°, facilitating self-cleaning by allowing water to spread and remove contaminants. Y₂O₃-stabilized coatings displayed durable hydrophilicity under outdoor exposure. Eu₂O₃-doped coatings also exhibited moderate hydrophilicity, suggesting combined optical and cleaning functionality Figure. 3/.

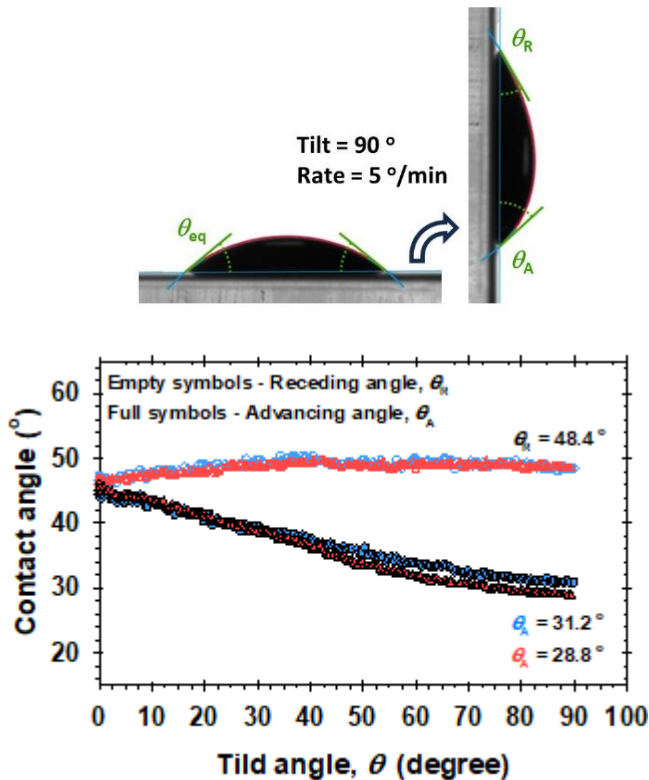


Figure. 3. Contact angle measurements on modified glass surfaces: A) Represents the procedure of determining dynamic contact angles by tilting the optical table of the apparatus to 90 degrees. B) Illustrates the advancing and receding contact angles of a water droplet on the samples with TiO₂. The values are calculated by taking the 2D profile of the droplet and applying the tangential method to both sides of the droplet concerning its midpoint.

3.4 Crystallinity and Structural Properties (XRD)

XRD patterns confirmed the presence of nanocrystalline phases. TiO₂ coatings showed mixed amorphous and anatase phases. ZrO₂ coatings exhibited dominant tetragonal structure, stabilized by Y₂O₃ additives, with average crystallite sizes around 31 nm. Eu₂O₃-doped systems revealed mixed monoclinic/tetragonal phases, offering a balance of structural integrity and photonic enhancement /Figure 4/.

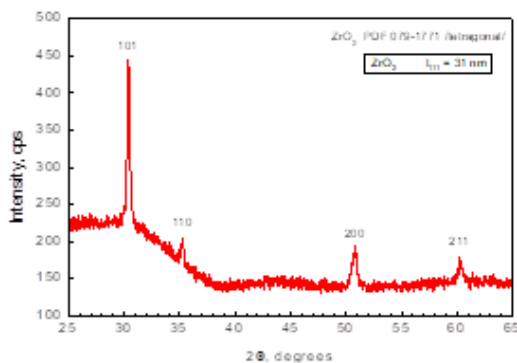


Figure 4. The figure shows the X-ray diffractometer of samples with Y₂O₃ and ZrO₂

3.5 Photoluminescence Enhancement (Eu₂O₃)

Photoluminescence measurements revealed strong red-orange emissions from Eu³⁺ transitions under UV excitation (~392 nm). This indicates that Eu₂O₃ doping may contribute to spectral down-conversion, redirecting unused UV light to the visible spectrum and enhancing photovoltaic output. These findings open avenues for multifunctional coatings combining self-cleaning and photoluminescent benefits / Figure 5/.

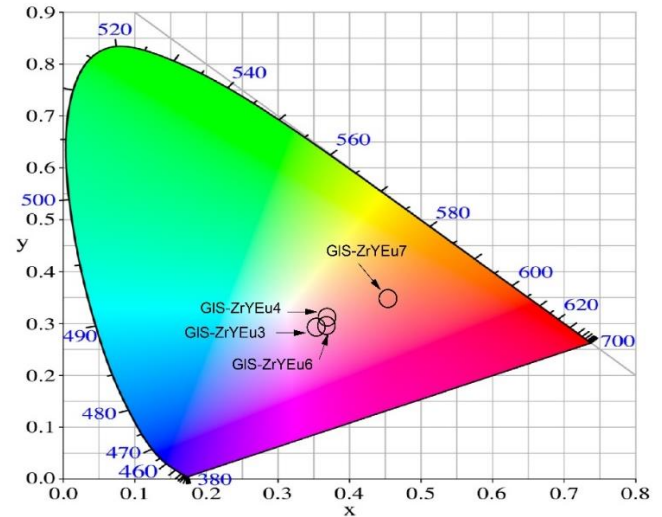


Figure 5. CIE chromaticity diagram of coatings (ZrO₂, Y₂O₃ and Eu₂O₃) on glasses

Summary of coating characteristics

Coating Comment

TiO₂ Classic choice with very good optical transmittance (~80%) and superhydrophilicity (contact angle ~8.3°), which is ideal for self-cleaning. Amorphous/anatase structure is typical for sol-gel synthesis.

ZrO₂ Similar transmittance (~79%), but no specified data on self-cleaning properties. Morphology shows moderate roughness. Crystal structure is tetragonal – stable phase.

ZrO₂ + Y₂O₃ Stabilized tetragonal phase with particles ~31 nm, good optical transmittance and pronounced self-cleaning. Uniform morphology is a positive factor for optical applications.

ZrO₂ + Eu₂O₃ Highest optical transmittance (~80–85%), with potential for luminescence – possibility of dual function (optical + photonic). Nano-roughness may be favorable for self-cleaning.

Y₂O₃ /ZrO₂ Composite coating with high permeability and long-term self-cleaning ability. Uniform morphology and stable tetragonal crystallinity make it suitable for long-term use.

Table 1: Summary of Key Coating Properties

Coating	Transmittance (%)	Contact Angle (°)	Crystallinity
TiO ₂	~80	8.3 (superhydrophilic)	Amorphous / Anatase
ZrO ₂	~79	Not specified	Tetragonal
ZrO ₂ + Y ₂ O ₃	~75–80	Hydrophilic (stable)	Tetragonal (~31 nm)
ZrO ₂ + Eu ₂ O ₃	~80–85	Moderately hydrophilic	Mixed Mono. / Tetra.
Y ₂ O ₃ /ZrO ₂	High	Durable hydrophilicity	Tetragonal

4. Application Potential and Durability

Real-world exposure tests confirmed the coatings' resistance to environmental wear. Functional properties were retained for over 30 days without degradation, suggesting long-term applicability in PV systems. Coatings exhibited resilience to common contaminants, and their transparency makes them suitable for coating on glasses both crystalline and thin-film PV technologies.

5. Conclusion

Sol-gel synthesized nanostructured coatings offer a viable solution for improving photovoltaic module performance. The reviewed studies confirm their potential in enhancing light absorption, resisting surface fouling, and withstanding environmental stressors. Future research should focus on multilayer systems, hybrid oxide formulations, and integration of rare-earth additives for advanced optical and self-cleaning functionalities.

Studies confirm the effectiveness of the sol-gel method for creating multifunctional thin-film coatings that improve:

- Light conversion efficiency
- Self-cleaning and durability
- Optical transmittance and resistance to contamination

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A review on the technological specificity of the synthesis of quartz ceramics

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Abstract: A survey of the prevailing trends in the field of quartz ceramics has been carried out. The article examines the main technological stages characteristic of the synthesis of quartz ceramics and the production of various product categories. The main technological stages characteristic of the synthesis of quartz ceramics and the production of various categories of products have been presented. The technological conditions applicable to the processing of raw materials, the preparation of suspensions with optimal characteristics, the molding of blanks and the heat treatment of semi-finished products have been examined. The role and influence of various technological factors in the formation of the structural characteristics and operational indicators of the products have been analyzed.

Keywords: QUARTZ CERAMICS, QUARTZ GLASS, SYNTHESIS,

1. Introduction

With the increasing operational requirements for equipment used in various technical fields, the need arises for the development and application of materials with adequate characteristics. Based on different technological schemes, special ceramic materials have been developed with specific functional properties, enhanced durability, and resistance in aggressive environments. In this regard, current interest is directed toward the existing technological possibilities for obtaining different modifications of quartz ceramics.

The present article aims to outline the prevailing trends in the development of quartz ceramic technology, examining the main stages and technological conditions applicable for the synthesis of quartz ceramics and the production of a range of items.

2. Fundamentals of quartz ceramic technology

Various raw materials are applicable in the synthesis of quartz ceramics: transparent quartz glass [1–4], opaque quartz glass [4,5], synthetic amorphous quartz [6], and crystalline quartz [7]. The choice of raw material depends on the intended performance characteristics of the final products, technological conditions, scale of production, and other factors.

A critical technological requirement is the high purity of raw materials due to the significant role of impurities in initiating crystallization processes. To minimize surface contaminants, various technological methods are applied: acid treatment (etching with hydrochloric [7] or hydrofluoric acid [2]), repeated washing with water, flame polishing, and more. This anti-crystallization approach enables the removal of deposited surface impurities that promote the formation of crystalline nuclei, thereby improving the crystallization resistance during subsequent technological steps. The preparation technology described in [8, 9] maintains high raw material purity, with impurity content in the sintered material increasing by only 0.008% compared to the original material (Table 1).

Table 1. Chemical composition of the material, %

	Source quartz glass	Baked or cast material
MgO	0.0004	0.001
Mn ₃ O ₄	0.00006	0.0002
Al ₂ O ₃	0.005	0.01
Fe ₂ O ₃	0.002	0.003
CuO	0.0002	0.0003
Na ₂ O	0.0015	0.0015
TiO ₂	0.0006	0.0008
CaO	0.001	0.002
Amount impurities	0.0107	0.0188
SiO ₂	99.989	99.981

2.1. Raw material grinding

A key production stage is obtaining a powdered fraction (from quartz raw material) with suitable particle size distribution, optimal dispersion, and required technological characteristics. The raw material is initially crushed. Processing can be carried out by dry [10, 11] or wet grinding, mainly in ball mills of various capacities. Some technological schemes use vibratory mills for dry grinding (up to 180 minutes) [10–12] with or without subsequent washing of the fractions.

Using ball mills with metal parts for grinding quartz glass is considered inappropriate due to contamination risks. High-purity grinding uses ball mills [13, 14] with appropriate linings (quartz, mullite, etc.) and grinding media (quartz mullite [6], corundum, etc.).

The recommended grinding duration is 40–80 hours, during which specific surface area increases significantly. Initially, particle sizes over 50 µm predominate; with continued grinding, fractions above 100 µm disappear. Powdered materials obtained within 15 hours contain significant amounts of particles over 0.1 mm. Fractions are grouped as fine (<10 µm), medium (10–60 µm and 60–100 µm), and coarse (>100 µm) (Fig. 1) [3].

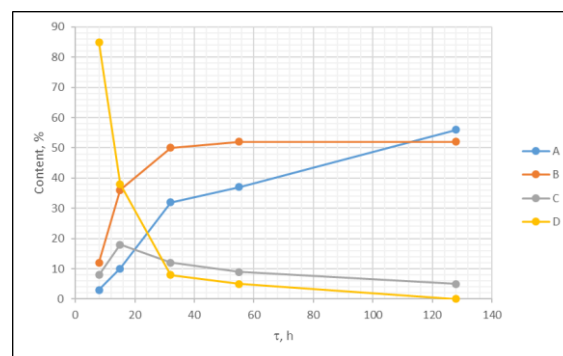


Fig. 1. Change in the content of different groups of fractions depending on the duration of grinding: A - to 10 µm; B - 10-50 µm; C - 50-100 µm; D - enlarges 100 µm

The dependence of bulk density on the applied grinding duration was studied. With a decrease in particle size, the contacts between them (per unit volume) increase, while the mass of each particle decreases. The bulk density of the resulting polydisperse powder mass is determined mainly by the content of small fractions. For finely dispersed powder masses, a bulk density of about 0.6-0.9 g/cm³ was established, while for relatively larger masses (even monofractions, 50-63 µm, 63-100 µm, 100-160 µm, 160-200 µm, 200-315 µm) the values are in the range of 1.30-1.32 g/cm³. For monofractions with larger sizes 1-1.2 mm, 1.2-1.5 mm, 1.5-2.5 mm, the bulk density increases to 1.38-1.40 g/cm³. The significant increase in bulk density in larger monofractions is due to the

relatively larger mass of the particles in the presence of more limited contacts between them per unit volume.

To significantly facilitate and shorten the total duration of the technological process of grinding and preparation of highly concentrated suspensions, the method of one-stage wet grinding of quartz glass is applicable. After the initial preliminary crushing of quartz glass, without conducting intermediate dry grinding, the raw material is directly subjected to wet grinding in a ball mill until a suspension is obtained. A characteristic technological specificity of the method is the combination in the volume of one milling unit (ball mill) of the processes of crushing and fine grinding in the conditions of an aqueous environment. The crushed fragments of quartz glass with an approximate size of 50-70 mm, introduced into the ball mill, are subjected to crushing (for 1 to 2 hours) to about 1-2 mm and subsequent fine grinding. In the process of grinding in the presence of water, the starting raw material gradually passes into a state of suspension with the planned technological characteristics.

An alternative technological approach is to apply a two-stage method for processing the raw material and preparing a suspension, using initial dry grinding and subsequent wet grinding to obtain a suspension.

Rheological properties are crucial in producing high-concentration, sedimentation-stable suspensions and forming semifinished and final products. Additives may enhance various process steps or modify quartz ceramics to improve performance—e.g., adding small amounts of Cr_2O_3 increases temperature resistance.

2.2. Forming semifinished products

Various methods are used to form semifinished products: slip casting from water suspensions, thermoplastic molding, pressing, thermoplastic pressing (using silicone resins and others), electrophoresis method, etc. This article focuses on slip casting, a widely used and cost-effective method for producing items with complex geometries and varied characteristics.

Despite the significant variety of suspensions applicable in ceramic technology, their main characteristic is the ratio of the solid component (disperse phase) and the liquid phase (disperse medium). An effective technological approach to minimize production waste in molded semi-finished products is the regulation of the grain size composition of the masses [9] and the characteristics of the suspensions used.

The characteristics of the prepared suspensions affect various aspects of the production process: technological indicators of the prepared slip masses, behavior of the casting masses when introducing the casting molds, resistance of the molded semi-finished products, conditions of the drying process, specificity of the sintering mode, operational properties of the resulting products. There are a number of technological requirements for suspensions applicable to the synthesis of quartz ceramic products: high concentration of solid phase, good sedimentation resistance, dispersibility, lack of air inclusions, lack of strongly expressed anomalous rheological behavior, appropriate granulometric composition, optimal viscosity, allowing free filling of the casting molds. In industrial conditions, an essential factor is the high resistance and technological reproducibility of the characteristics of the suspensions when preparing individual production batches, even with partial fluctuations in the ratio of components and chemical composition. When using the slip casting method, the use of suspensions with optimal viscosity values allows for an optimal growth rate of the collected (deposited) casting mass in the molds and the production of durable blanks. At the same time, the use of suspensions with appropriate viscosity ensures free removal of excess slip from the molds.

Higher rates of mass growth (in casting molds) complicate the effective regulation of the required thickness of the blanks and create a danger of clogging of the technological channels of the

molding equipment. Inexpediently low casting speed creates conditions for increased sedimentation of the solid phase, uneven thickness of the samples and significant adverse changes in the technological characteristics of the suspensions. In terms of production, an important technological factor is the residence time of the blanks in the casting molds before their extraction by dismantling the molds.

There are basic requirements for semi-finished products obtained by slip casting, namely the presence of appropriate density, sufficient mechanical resistance (allowing further implementation of the upcoming stages of the technological process), low shrinkage and absence of defects during drying. The formulated requirements are especially significant and relevant in the production of large-sized products, which, with low resistance of the blanks, exhibit a tendency to deformation and partial or complete destruction under the action of their own mass. Even insignificant shrinkage (up to 0.2-0.3%) in the drying process of large-sized samples creates prerequisites and potential conditions for the destruction of the samples.

The use of a polydisperse grain size composition with a significant presence of relatively large fractions allows the production of highly concentrated suspensions, ensuring the production of blanks with increased density and strength and low shrinkage during drying. At the same time, suspensions with similar indicators show an increased tendency to stratification. There may be a small volume of gas phase in unstabilized suspensions or in suspensions obtained by the methods of suspension or limited saturation to stabilization. Suspensions with typical thixotropic properties are characterized primarily by complete resistance to sedimentation, but the resulting semi-finished products have a lower density and the presence of air inclusions. The limiting concentration of the suspensions provides a sharp increase in their sedimentation resistance, which allows for accelerated mass gain during molding of the samples and obtaining castings with increased density. On the other hand, the pronounced dilatant behavior complicates the casting process and reduces its speed.

The increased degree of dispersion provides higher stability of the suspension, but leads to a decrease in the casting speed of the blanks and an increase in the shrinkage effect of the semi-finished products during drying. Due to the reverse effect of the impact of individual factors on the technological properties of the suspensions, the combination of all favorable characteristics in one composition is difficult to implement. The selection of technological indicators of the suspensions is carried out on the basis of certain priority characteristics (applied with optimal values), taking into account the specifics of the planned production process and the specific requirements for the final products. The determination of the values of the secondary indicators (for each individual case) is determined within the permissible fluctuation intervals.

The behavior and aging of the obtained suspensions (on quartz glass) during prolonged storage at rest under conditions preventing moisture loss and drying were studied. In suspensions with low and medium density, stratification was observed during storage with the formation of a stable precipitate and a layer of suspension with a low concentration. With increasing density, a tendency was observed to reach a state of complete stability of the precipitate and behavior characteristic of stabilized suspensions.

Rheological properties are influenced by concentration, particle dispersion, stabilization, coagulation, temperature, and preparation method. Intense stirring improves suspension stability and reduces viscosity.

The tendency of suspensions to settle is manifested primarily by their stratification and the formation of a visible sedimentary layer. From a technological and production point of view, settling is an unfavorable effect. In the casting process, with increasing dimensions and thickness of the blanks, the risk of settling processes increases due to the longer duration of the molding stage

and the coarser grain size composition of the fractions used (used mainly in the production of large-sized products).

To increase the sedimentation resistance of suspensions, an increase in the dispersity of the solid phase or an increase in the viscosity of the dispersion medium is applied. At the same time, this method does not represent a universal production technological solution. In the preparation of large-sized and some other categories of quartz ceramic products, the presence of a certain amount of coarse fraction in the compositions used is technologically necessary and expedient. On the other hand, an increase in the dispersity of particles and the viscosity of the dispersion medium leads to an increase in the porosity of semi-finished products during molding.

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The rate of mass increase during the molding of the samples to a significant extent determines the technological qualities of the suspensions. The porosity of the resulting castings is determined by a number of characteristics of the suspensions used: rheological properties, degree of stabilization, viscosity values, tendency to coagulation, dispersion of the solid phase, etc. The specificity of the gypsum molds used (porosity, moisture absorption, etc.) has a significant impact on the casting speed. When preparing the casting molds, the porosity and capillary size of the resulting gypsum molds are regulated by changing the water-gypsum ratio of the prepared solutions. As the water-gypsum ratio increases, the total porosity of the gypsum forms and the average capillary size increase.

The change in the nature of the rheological behavior of suspensions (the transition from Newtonian or dilatant to thixotropic or thixotropic-dilatant) with increasing the degree of dispersion has been studied. The transition of part of the bound water to a free state increases the mobility of the system. In suspensions with a limiting concentration, a slight increase in the content of the dispersed medium provokes a drastic decrease in the dilatant properties. The use of stabilized suspensions in the molding of semi-finished products allows the production of samples with lower porosity. In stabilized coarse-dispersed and medium-dispersed suspensions, behavior characteristic of dilatant or Newtonian liquids is observed. When the degree of dispersion of the solid phase increases below a certain limit, significant changes in the rheological behavior and thixotropic characteristics are recorded. It is assumed that in a number of cases the appearance of thixotropic properties of the suspension is due to an increase in the adhesion forces between the particles with an increase in the degree of dispersion and the occurrence of partial coagulation. At a degree of dispersion in the range between medium and high content of fine fractions in suspensions with increased density (e.g. $> 1.95 \text{ g/cm}^3$), a thixotropic-dilatant nature of behavior is possible.

In classic ceramics, pH is often adjusted with electrolytes. For quartz-glass-based suspensions, optimal performance is achievable without pH adjustment (optimal range: 4.0–6.0). Wet grinding forms silicic acid, lowering pH.

In a more acidic environment (when HCl is introduced), coagulation of the quartz glass suspension occurs, which leads to a decrease in the density of the molded samples. An increase in the concentration of H^+ ions shifts the direction of the reaction towards

the formation of undissociated silicic acid molecules on the surface of the particles and subsequent coagulation in the system. The isoelectric state of the suspension is recorded at pH values about 1–2. Moderate acidity of the suspension (from pH 5–6 to pH 4–5) favorably affects the rheological properties of high-density suspensions, reducing their dilatation properties and increasing the sedimentation resistance of the system.

2.3. Thermal treatment

An optimized thermal regime ensures high sintering rates without forming large amounts of cristobalite. Due to the narrow firing range of quartz ceramics, a homogeneous temperature field in furnaces is essential.

The density of the molded blanks and the purity of the raw materials used are the main technological factors influencing the characteristics of the ceramic samples during thermal treatment. The insufficient initial density of the obtained semi-finished products determines the lower density and mechanical resistance of the manufactured products due to the lower degree of sintering [15]. At the same time, the purity of the starting raw material has a significant impact on the kinetics of the crystallization processes.

Quartz glass and synthetic amorphous SiO_2 crystallize above 1000°C . Surface contamination (e.g., salts) affects crystal nucleation and growth. Cristobalite has a granular, spheroidal structure and forms along grain boundaries, with its size depending on firing conditions [16]. Non-glass-forming oxides (e.g., alkali, alkaline earth metals) enhance crystallization by disrupting Si–O bonds.

The role of the gas environment (Ar , N_2 , CO , CO_2 , O_2) on the degree of crystallization and formation of cristobalite in synthetic quartz glass (with impurities of Na_2O) under heat treatment conditions (1200 , 1300 , 1400°C) has been studied. A significant slowdown of the crystallization process in an Ar , N_2 , CO_2 environment has been established. It has been established that in the conditions of a gas environment of O_2 or H_2O vapors it does not directly affect the formation of crystallization centers, but accelerates the growth of cristobalite crystals, while reducing their content in the presence of a suitable atmosphere drastically reduces the growth rate of cristobalites.

The use of high-density semi-finished products made of high-purity transparent quartz glass allows the production of final products with increased complex performance characteristics. For samples with increased density, a sintering regime is applicable at relatively lower and cost-effective temperatures or with a shorter duration of the heat treatment used, while minimizing the risk of product crystallization.

Fast heating through crystallization-prone ranges is recommended. Cristobalite formation risks sample damage due to structural transitions ($\alpha \rightarrow \beta$) causing $\sim 5\%$ volume change at 160 – 270°C .

In experimental samples, an optimal sintering temperature of about 1200°C with an isothermal hold of 2 hours was established. At a sintering temperature of 1250°C , an increase in the values of individual indicators (density and others) was established and at the same time a significant decrease (approximately two times) in the thermal stability of quartz ceramics was recorded. With an increase in temperature to about 1300°C (and higher values), a more significant formation of cristobalite was recorded. In quartz ceramic samples, maximum strength resistance was established at sintering temperatures characteristic of the beginning of crystallization, allowing the formation of cristobalite up to 2–3%. When applying a temperature treatment regime causing a further increase in the cristobalite content, a significant decrease in the strength characteristics of the material was recorded.

Some studies have found an increase in porosity in samples obtained by sintering at temperatures exceeding the optimum values. This effect is interpreted as a consequence of the presence of

microcracks formed during cooling of partially crystallized samples. At the same time, other studies have not found similar changes in the porosity of the samples.

3. Conclusion

This publication examines the various technological stages characteristic of the synthesis of quartz ceramics and the production of a number of products, such as foundry vessels – pots [17], vessels for dental equipment, structural elements for innovative beehives [18] etc., and for each specific material for the product, modifiers can be added that improve some of its properties – mechanical, physicochemical and thermal. The technological regimes applicable to the processing of raw materials, preparation of suspensions, molding of semi-finished products and adequate thermal treatment of samples are presented. The role of technological conditions for the formation of the structure and operational properties of the products is studied, as well as the ability to crystallize quartz glass, which is significantly determined by the presence of impurities and the technological conditions of synthesis used (gas environment, thermal treatment regime, etc.).

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Design and study of the operation of a green waste composter with energy cogeneration

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Abstract: Nowadays, renewable bioenergy is considered as one of the ways to provide energy at the expense of fossil fuels. The possibility of obtaining energy from organic materials through bio-electrochemical systems attracts considerable interest. Green waste is organic plant-based materials generated from grass clippings, broken branches, fallen trees and others, the utilization of which is currently not very effective. In the present study, we constructed a composter based on bio-electrochemical systems for the utilization of green waste with cogeneration of energy. The composter showed good performance in terms of both the decomposition of organics and the generated energy.

Keywords: GREEN WASTE, GREEN ENERGY, WASTE MANAGEMENT, BIO-ELECTROCHEMICAL SYSTEMS

1. Introduction

In the current era of increasing energy demands and the urgent need to mitigate climate change, researchers and scientists are constantly searching for innovative and sustainable solutions to meet energy needs. Increasing industrialization and a growing population require a huge amount of electricity. Bioenergy from waste biomass is seeking a lot of attention nowadays due to the rapid depletion of fossil fuels. [1] One such solution for electricity generation is the development and use of microbial fuel cells using the conversion of waste biomass. Renewable energy, such as solar energy, wind energy, hydropower, and geothermal energy, are considered as sources of sustainable energy. They are clean energy compared to coal and nuclear energy, as coal power and nuclear power plants can pollute the air and release radioactive waste, potentially harmful to human health and the ecological environment. [2] Bioenergy from the organic fraction of municipal solid waste, food waste, agricultural organic waste, forestry wood waste, and others has the potential to produce electricity, methane, and hydrogen through combustion, microbial fuel cells, anaerobic digestion, microbial electrolysis cells, and fermentation. [3] Microbial fuel cells are believed to have the potential for environmental remediation and electricity generation from organic pollutants, biomass, and organic waste through microbial biodegradation.

The current linear economy assumes abundant, readily available and cost-effective natural resources. However, this assumption is unsustainable. In contrast, the circular economy reduces waste and improves resource efficiency, making it a more sustainable alternative to the dominant linear model. Biomass energy generated from agricultural residues, forest waste and municipal waste provides a renewable substitute for fossil fuels. This reduces greenhouse gas emissions and improves energy security. Proper waste management, including waste reduction, recycling and innovative waste-to-energy technologies, reduces the burden on landfills and incineration, and creates renewable energy from materials that would otherwise go to waste. [18]

Waste and by-products of plant origin, such as bark, leaves, grass, seeds and others, can be utilized by extracting valuable nutrients and converting them into soil fertilizers. Reducing plant waste not only benefits the environment, but also contributes to various social programs by reducing greenhouse gas emissions, improving ecosystem services and implementing sustainable resource management policies. [5] Using industrial plant waste for higher value-added purposes can save significant amounts of CO₂. Anaerobic digestion has been identified as the preferred option compared to incineration, offering the highest environmental benefit. Recycling and reuse of agricultural waste are promising options for sustainable waste management and energy production. Choosing the right approach to utilize plant waste is crucial for cost-effective resource management and conservation. The economic impact of plant waste is closely related to its valuation, the processes used, and the economic benefits that depend on the final product. [1]

The European Union Green Deal is a comprehensive set of policy initiatives aimed at improving the EU economy for sustainable development and reducing greenhouse gas emissions to net zero by 2050. It supports a circular economy model that aims to minimize waste, reusing materials and recycling products to reduce environmental impact. In the long term, plant waste and plant-based by-products are very important because they are valuable resources that can be reused to reduce environmental impact and improve resource efficiency. [6] Furthermore, converting these waste streams into energy supports efforts to combat climate change, reduce waste and optimize resource use.

Agricultural biowaste is obtained through various biological sources and industrial processing, which is a typical renewable energy source with abundant nutrients and easily biodegradable organic matter. These waste materials are capable of being degraded under aerobic and anaerobic conditions. The projected global population, urbanization, economic development and changing production and consumption behavior lead to abundant production of biowaste. These biowaste mainly contain starch, cellulose, proteins, hemicellulose and lipids, which can serve as low-cost raw materials for the development of new value-added products, as well as the production of bioenergy through bio-electrochemical systems. [7]

Biomass is an available and carbon-neutral energy source that can contribute to the efforts to meet the rapidly growing need for cost-effective energy materials for bioelectrochemical systems. However, the challenges and costs associated with finding specialized biomass could hinder its widespread application in bioelectrochemical systems. Waste-derived biomass could be a promising alternative to specialized biomass for energy production through bioelectrochemical systems. Therefore, the use of biomass wastes (e.g., grass, agricultural and forestry wastes, and others) is an attractive strategy for the commercialization of bioelectrochemical systems. Furthermore, the application of waste biomass resources as energy sources in bioelectrochemical systems can significantly reduce their environmental and health risks. [8]

A group of microorganisms use the organic matter for their growth and start releasing protons and electrons. *Clostridium acetobutylicum*, *Clostridium thermohydrosulfuricum*, *Saccharomyces cerevisiae*, *Lactobacillus* and others are very well-known examples of bacteria used to produce bioenergy in the form of electricity. Exoelectrogenic microorganisms, usually belonging to the *Geobacter* and *Shewanella* genera, can transfer electrons from organic materials to the anode surface, which leads to microbial metabolism and energy production. [9] Composting is a biological fermentation technology that converts agricultural and forestry waste into valuable resources. In the composting process, organic matter undergoes mineralization and humification under conditions controlled by microorganisms. [10] However, the optimal conditions under which microbial fuel cells can generate energy during the composting process have not been sufficiently studied. Conventional composting under aerobic conditions requires more energy for mixing and aeration, which can lead to huge amounts of leachate. Anaerobic composting, also known as

anaerobic digestion, can be an alternative solution for converting solid waste into reusable energy and biofuel. [11]

Microbial fuel cells are typically operated with a liquid organic phase because the ion transfer process is efficient in a liquid medium. However, some researchers have investigated the potential of operating microbial fuel cells with a solid organic phase (especially for solid waste treatment). This is promising if several important factors are optimized, such as the type and amount of substrate, the microbial community, the system configuration, and the type and number of electrodes, which increases the amount of electricity generated. [12] The critical factor that affects the performance of a microbial fuel cell is the efficiency of electron and proton transfer through the solid medium. However, this limitation can be overcome by improvements in the electrode system and regular mixing of the substrate. [13] Integrating microbial fuel cells with other conventional solid waste treatment methods can be used to produce sustainable green energy. Although microbial fuel cells produce relatively small amounts of energy compared to other waste-to-energy methods, bioelectrochemical systems still hold promise for achieving zero-emission treatment. [14]

Recently, it has been found that microbial fuel cells can be a technology for alternative treatment and generation of electricity from waste without intermediate treatment steps, since anaerobic digestion uses electrogenic microorganisms. The bioelectricity of microbial fuel cells depends on the electron transfer process and the efficiency of biodegradation of solid waste. [15] Many researchers use the term solid-phase microbial fuel cells for MFCs that convert solid waste into electricity. However, some researchers use the term compost microbial fuel cells. [16] Solid-phase microbial fuel cells (SMFCs) are one of the innovations in MFC technologies that can be applied to solid waste. They have been found to accelerate the anaerobic digestion process of waste, directly generate electricity, and produce mature compost from organic compounds. Solid-phase microbial fuel cells are cost-effective because they require inexpensive materials for their construction and operation. [17] Furthermore, their ability to generate electricity makes them a direct alternative source of renewable energy, which has attracted considerable attention from researchers. Also, solid-phase microbial fuel cells are an alternative method to overcome the problem of solid waste treatment, as it uses them as a substrate to provide an environmentally friendly and sustainable source of electricity. [18] Therefore, solid-phase microbial fuel cells are considered capable of addressing multi-sectoral problems, as they can be integrated with other waste treatment methods, such as aerobic composting or anaerobic digestion.

This study focuses on the development of a prototype composter with cogeneration of energy by integrating microbial fuel cells with a conventional plant biomass treatment method. The study also aims to establish the efficiency and performance of the constructed facility.

2. Materials and methods

Plant biomass

For the purpose of the study, plant biomass was taken from campus of University of mining and geology "St. Ivan Rilski", Sofia, Bulgaria (42.6604710456078, 23.35296900986125). The plant biomass consists mowed grass with a length of 10 - 15 centimeters. In plant biomass, ancestral species are *Cynodon dactylon*, *Capsella* and *Taraxacum*.

Construction of SMFC biosensor

The composter is a plastic container with a volume of 360 cm³. The composter consists of 24 PVC pipes arranged vertically. Each PVC pipe has a diameter of 110 mm and a height of 900 mm. The bottom of the pipes is closed with PVC plugs. At the bottom of the pipes are located stainless steel AISI 304 electrodes with an area of 414.48 cm² acting as an anode. At the top of the pipes is a second stainless steel AISI 304 electrode with an area of 414.48 cm² acting

as a cathode. Copper wires were used as conductors in the electrical circuit. Each of the 24 tubes represents a solid-phase microbial fuel cell (SMFC). Then the plant biomass was placed in the tubes and filled with water. The approximate volume of plant biomass in each tube is 7.5 dm³. The physicochemical characteristics of water was pH 7.12, Eh 352 mV and EC 73 $\mu\text{S cm}^{-1}$ measured by Vernier LabQuest Mini. On Figure 1 is shown a scheme of single segment (PVC pipe) of the composter.

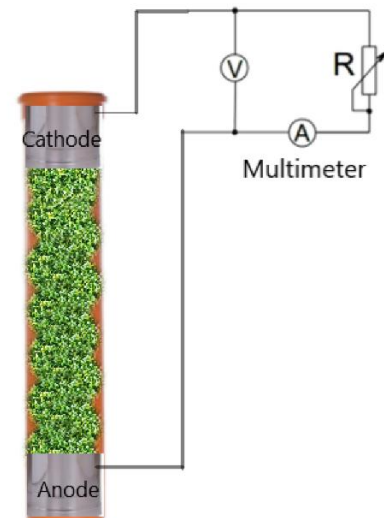


Fig. 1 The schematic diagram of single segment (SMFC) of the composter

The individual segments (SMFCs) (fig. 2) were stacked in the plastic container and after the segments reached a base voltage, the electrical parameters of the composter were measured. The electrical parameters were measured with the segments connected in series and in parallel. Then the segments were connected in series 12x12 and both pairs connected in parallel, and the electrical parameters were measured again.



Fig. 2 Photo of single segment of the composter

Electrochemical analysis

To determine the operation and effectiveness of the composter polarization and power curves were obtained by varying external

resistances sequentially from 10, 8, 6, 4, 2, 1.5, 1.3, 1, 0.7, 0.5, 0.3 to 0.1 K Ω using MCP lab electronics BXR-04 ResistorBox. The voltage dynamic were measured and recorded in real time with Vernier LabQuest Mini and Logger Lite software.

3. Results and discussion

After filling all segments of the composter with plant biomass, the dynamics of the open-circuit voltage of the individual segments was monitored. Figure 3 presents the averaged voltage data of the individual segments.

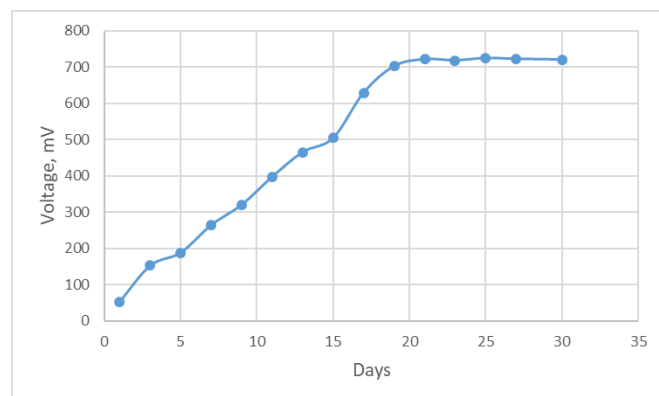


Fig. 3 Average open circuit voltage of individual segments of the composter

The graph shows that after filling the segments with plant biomass, a slow, smooth increase in the open circuit voltage begins. The voltage increases until the 19th day after filling with plant biomass, after which the segments begin to maintain an average base voltage of 725 mV.

The following experiments aimed to determine the electrical parameters of the composter with different connection schemes for the individual segments. They were carried out after the voltage on all segments had stabilized.

Figure 4 presents the electrical parameters of the composter when the individual segments are connected in series.

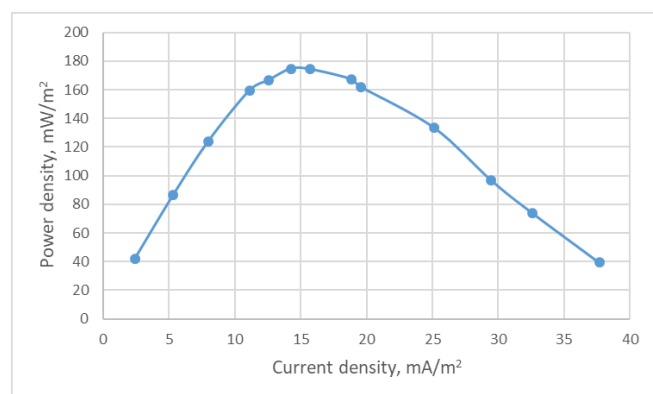


Fig. 4 Power density dynamics when connecting segments (SMFCs) in series

The graph shows that when connecting the individual segments of the composter in series, a maximum power density of 178 mW/m² is achieved at a current density of 14.7 mA/m². The maximum power density was achieved with an applied resistance of 1.5K Ω . When connecting the composter segments in series, a maximum open circuit voltage of 17.428 V was reached.

The next measurement aimed to determine the electrical parameters of the composter when the individual segments were connected in parallel. Figure 5 presents the results of this measurement.

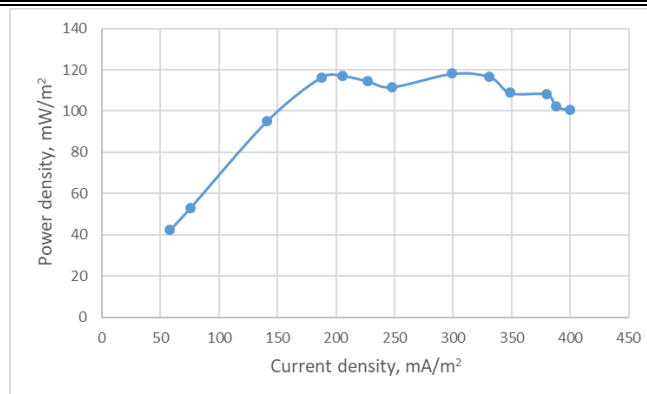


Fig. 5 Power density dynamics when connecting segments (SMFCs) in parallel

This connection achieved a lower power density than the series connection, but a significantly higher current density. The maximum power density of 119.56 mW/m² was measured at a current density of 299.82 mA/m² and an applied resistance of 1.1 K Ω .

The last experiment aimed to determine the electrical parameters of the composter when connecting 12x12 segments in series and connecting the two pairs in parallel. The results obtained are shown in figure 6.

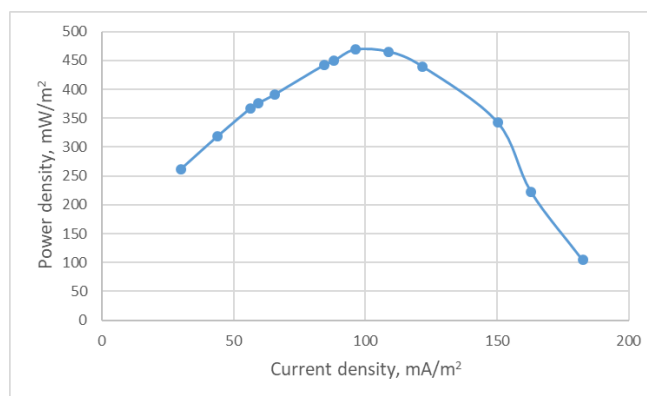


Fig. 6 Power density dynamics when connecting 12x12 segments (SMFCs) in series and connecting two pairs in parallel

With this connection, the composter achieved the best electrical parameters of the tested variants. A maximum power density of 474.6 mW/m² was recorded at a current density of 97.4 mA/m² and an applied resistance of 1.1 K Ω .

4. Conclusion

Climate change, the growing need of the population and the economy for energy sources and the international commitments made to environmental protection require the research and implementation of innovative renewable energy sources. Plant waste is a raw material that is currently not sufficiently utilized and even creates prerequisites for environmental problems. Through appropriate technology implemented in working devices, plant waste can be a valuable source of renewable energy and value-added products, such as soil fertilizers.

Solid-phase microbial fuel cells are a suitable technology for the utilization of plant waste with parallel energy production. Studies in laboratory conditions show reliable results for practical application of the technology. In the present study, we integrated the solid-phase microbial fuel cell technology into a composter with cogeneration of energy through 24 stacked segments (SMFCs). The study of the composter's operation showed that 19 days after filling with plant biomass, the individual segments reach their maximum base voltage of an average of 728 mV. In order to establish the efficiency of the composter, three variants of electrical connection

of the individual segments were studied. The results showed that a high power density of 474.6 mW/m² with a series connection of 12x12 segments and a parallel connection of the two pairs.

In order to turn the constructed composter into a commercial product, additional research is needed on its long-term operation, the possibilities for storing and utilizing the generated energy, the quality of the resulting compost, etc. However, the data obtained are a step towards the possibility of using plant waste as a sustainable energy source.

Acknowledgements

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Comprehensive Analysis of Laser Welding Advancements

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Abstract: Laser welding has become an indispensable manufacturing process, revolutionizing industries from automotive to medical devices with its precision, speed, and versatility. This advanced technique, which uses a high-intensity laser beam to melt and fuse materials, has seen significant technological advancements in recent years. These developments have expanded its applications, improved weld quality, and enhanced process control, making laser welding a cornerstone of modern manufacturing. This article provides an in-depth overview of the latest scientific developments in laser welding, including advancements in laser sources, process monitoring and control, material compatibility, applications, future directions, and challenges. It also integrates the most recent research from 2024 and 2025 to ensure the content reflects cutting-edge trends and innovations.

1. Introduction to Laser Welding

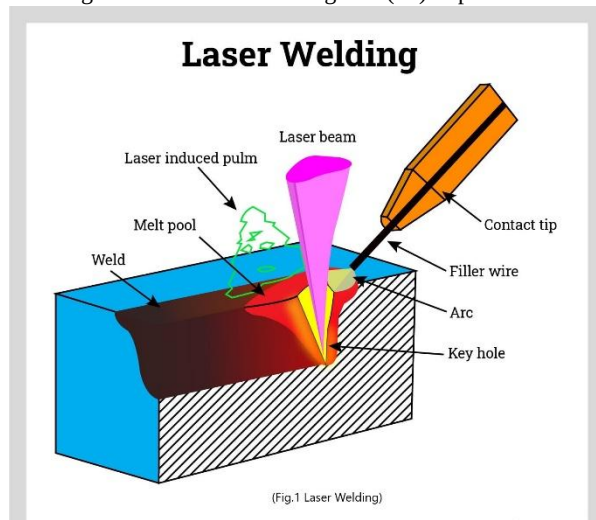
Laser welding is a high precision joining process that uses a focused laser beam to melt and fuse materials, creating strong, durable bonds with minimal thermal distortion. The process can be categorized into two main types: keyhole welding and conduction welding. In keyhole welding, the laser beam vaporizes the material at the focal point, creating a deep, narrow weld known as a "keyhole."

This method is ideal for thick materials requiring deep penetration. In conduction welding, the laser heats the surface of the material, causing it to melt and flow together without vaporization, making it suitable for thin materials or shallow welds.

Laser welding offers several advantages over traditional welding methods, including higher precision, lower heat input, reduced distortion, and the ability to automate the process. These benefits have made it a preferred choice for industries requiring high-quality, high-speed welding, such as automotive, aerospace, electronics, and medical device manufacturing.

Recent advancements in laser technology, particularly the development of high-power solid-state lasers in the 1990s, expanded their use to larger, more industrial applications. The transition from gas lasers to solid-state lasers marked a turning point, enabling higher power outputs and better beam quality.

Today, laser welding (Fig.1) is a critical process in modern manufacturing, with the global laser welding machine market projected to grow by USD 504.4 million between 2024 and 2028, driven by increased demand in electric vehicle (EV) production and the integration of artificial intelligence (AI) in process control [1].



2. Fiber Lasers

Fiber lasers have become the dominant laser source for welding due to their high efficiency, excellent beam quality, and flexibility.

These lasers use optical fibers doped with rare-earth elements (e.g., ytterbium) to generate the laser beam, allowing for higher power densities and deeper penetration at faster welding speeds. The light is guided through the fiber core, resulting in a tightly focused beam with a small spot size, which enhances precision. Fiber lasers also have a longer operational life (up to 100,000 hours) and require less maintenance compared to traditional CO₂ or Nd:YAG lasers, making them cost-effective for industrial use. Recent developments have focused on increasing the power output of fiber lasers while maintaining beam quality. High-power fiber lasers exceeding 10 kW are now available, enabling the welding of thick materials in industries such as shipbuilding and heavy machinery manufacturing.

These lasers have also proven effective for welding challenging materials like aluminum and copper, which have high reflectivity and thermal conductivity. For example, in 2024, IPG Photonics introduced a 20-kW fiber laser system specifically designed for deep penetration welding of thick steel plates, achieving weld depths of up to 20 mm in a single pass with a welding speed of 2 m/min (IPG Photonics, 2024). This system uses advanced beam shaping techniques to distribute energy evenly, reducing defects like spatter and porosity.

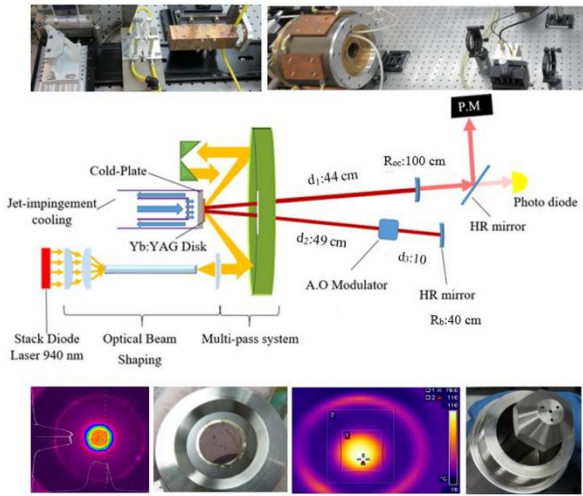
A notable trend in fiber laser technology is the rise of handheld fiber laser welders, which have democratized access to laser welding technology. These portable devices, such as the Bodor Pro 1500 launched in 2024, feature self-cooling systems and smart control knobs, making them ideal for small workshops and on-site repairs. The Bodor Pro 1500 has been tested for durability in extreme temperatures ranging from -20°C to +60°C and covers a welding area of 0.24 m², offering unprecedented flexibility for welders. It operates at a power range of 1.5 kW, with adjustable beam oscillation to improve weld seam quality [2]. This innovation has made laser welding accessible to smaller businesses, broadening its industrial impact.

3. Disk Lasers

Disk lasers are another type of solid-state laser that has gained traction in welding applications. These lasers use a thin disk of laser-active material (e.g., ytterbium-doped yttrium aluminum garnet, or Yb:YAG) to generate the beam, allowing for efficient heat dissipation and high-power scalability. The disk design minimizes thermal lensing—a distortion caused by heat in traditional rod lasers—enabling a unique combination of high beam quality and power. This makes disk lasers suitable for both fine and deep penetration welding.

Recent research has highlighted the effectiveness of disk lasers in welding high-strength steels and other challenging materials (Fig.2). For example, a 2024 study by Trumpf demonstrated that disk lasers could produce high-quality welds in advanced high-strength steels (AHSS) with minimal distortion, a critical requirement for automotive and aerospace applications. The study used a 16-kW disk laser with a beam parameter product (BPP) of 4 mm·mrad, achieving a weld depth of 12 mm at a speed of 5 m/min [3]. The

ability to scale power without compromising beam quality makes disk lasers particularly attractive for precision welding tasks, such as joining thin-walled aerospace components or automotive body panels.



(Fig.2 Disk Lasers Operational Testing)

4. Multi-Wavelength Lasers

One of the most significant recent advancements in laser sources is the development of multi-wavelength lasers, which combine different laser wavelengths to optimize energy absorption for specific materials. At the 2024 International Congress on Applications of Lasers & Electro-Optics (ICALEO), Okamoto et al. presented a hybrid system using blue (450 nm) and near-infrared (1080 nm) lasers to weld copper and aluminum. The blue laser, with its shorter wavelength, is more readily absorbed by copper (absorption rate ~65% compared to ~5% for infrared), while the near-infrared laser provides deeper penetration for aluminum. This combination resulted in higher-quality welds with fewer defects, such as porosity and cracks, compared to single-wavelength systems [4]. The experimental setup used a 2.5 kW near-infrared laser and an 800 W blue laser, achieving optimal results at a scanning speed of 240 mm/s and a weld strength of 95 MPa in cross-tensile tests.

Multi-wavelength lasers are particularly promising for welding dissimilar materials, which are increasingly used in lightweight, multi-material designs in industries like aerospace and electronics. By tailoring the laser's energy absorption to each material, these systems reduce the risk of weak bonds and intermetallic compounds, which are common challenges in dissimilar welding. This technology is still in its early stages but holds immense potential for future applications.

5. Material Compatibility and Weldability

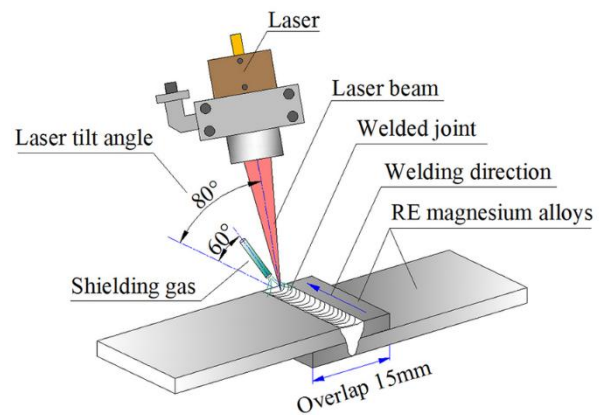
Laser welding is a versatile process capable of joining a wide range of materials, including metals, plastics, and composites. However, the weldability of different materials varies, and recent research has focused on expanding the range of materials that can be successfully welded using lasers, particularly dissimilar materials and advanced composites.

6. Welding Dissimilar Materials

One of the most significant challenges in laser welding is joining dissimilar materials, such as aluminum to steel or copper to titanium. These materials have different thermal properties (e.g., aluminum's thermal conductivity is 237 W/m·K vs. steel's 50 W/m·K), melting points (660°C for aluminum vs. 1,538°C for steel), and expansion coefficients, which can lead to defects like

cracks, weak bonds, and brittle intermetallic compounds. Recent advancements have addressed these challenges through optimized process parameters, new filler materials, and innovative laser technologies.

For example, the 2024 ICALEO paper by Okamoto et al. demonstrated high-quality welding of copper and aluminum using a multi-wavelength laser system and nickel mesh inserts. The nickel mesh, with a thickness of 0.1 mm, acted as an interlayer, reducing the formation of brittle Cu-Al intermetallic compounds (e.g., CuAl_2) and improving the bond strength. Experimental results showed that the breaking strength of the welds doubled when using nickel mesh at minimized penetration depths, achieving up to 95 MPa in cross-tensile tests compared to 45 MPa without the mesh [4]. This approach has significant implications for industries like electronics and automotive, where copper-aluminum joints are increasingly used in battery systems and power electronics (Fig.3). Another promising development is the use of ultrashort pulse lasers for welding dissimilar materials. These lasers deliver extremely short pulses (in the picosecond or femtosecond range), minimizing heat input (e.g., heat-affected zone < 10 μm) and reducing the risk of thermal damage. A 2025 study by the University of Stuttgart found that ultrashort pulse lasers could successfully weld glass to metal (e.g., borosilicate glass to stainless steel) without causing cracks or delamination, achieving a shear strength of 20 MPa. The process used a 500 fs pulse duration and a 1030 nm wavelength, with a repetition rate of 1 MHz [5]. This breakthrough opens new possibilities for applications in optics, microfluidics, and electronics.



(Fig.3 Overlapping Laser Welding)

7. Plastic and Composite Welding

Laser welding of plastics and composites has also seen significant advancements.

Traditionally, welding plastics required additives like carbon black to absorb laser energy, as most polymers are transparent to infrared wavelengths. However, new laser technologies, such as diode lasers with tailored wavelengths, can now weld clear or transparent plastics without additives.

This development is particularly important for medical device manufacturing, where material purity is critical.

For example, in 2024, Coherent Inc. introduced a diode laser system specifically designed for welding transparent polymers like polycarbonate and PMMA (polymethyl methacrylate) used in medical tubing and diagnostic devices. The system uses a 980 nm wavelength, which is absorbed by the polymer's molecular structure (absorption coefficient $\sim 0.1 \text{ cm}^{-1}$), ensuring a clean, biocompatible weld with a tensile strength of 30 MPa [6].

Composite materials, which consist of a matrix (e.g., epoxy) reinforced with fibers (e.g., carbon or glass), are widely used in aerospace and automotive applications due to their high strength-to-weight ratio (e.g., CFRP tensile strength $\sim 3,500$ MPa).

However, laser welding of composites is challenging due to the differences in thermal expansion between the matrix (CTE ~ 50 $\mu\text{m/m}\cdot\text{K}$) and the fibers (CTE ~ 1 $\mu\text{m/m}\cdot\text{K}$). Recent research has focused on optimizing laser parameters to minimize these effects.

A 2025 study by the National Institute for Materials Science [7] in Japan demonstrated that using a pulsed laser with a pulse duration of 10 ns and a frequency of 50 kHz could reduce thermal damage in carbon fiber-reinforced polymers (CFRP), resulting in stronger, defect-free welds with a shear strength of 25 MPa [7].

This approach minimizes fiber degradation and matrix vaporization, enhancing composite weldability.

8. Conclusion

Laser welding has firmly established itself as a transformative technology in modern manufacturing, offering unparalleled precision, speed, and versatility. The latest advancements in laser sources, such as handheld fiber lasers and multi-wavelength systems, have expanded their accessibility and capabilities, while innovations in process monitoring, including event cameras and AI-driven control systems, have enhanced weld quality and reliability. The ability to weld a wide range of materials, including dissimilar metals and composites, has opened new possibilities in industries like automotive, aerospace, electronics, and medical devices. As laser welding continues to evolve, its integration with additive manufacturing and smart technologies promises to drive further innovation, ensuring its central role in the future of manufacturing.

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Behavior of a centrifugal fan for industrial applications – expedient practical tests

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Abstract: Paper deals with testing of a specific centrifugal fan under different conditions – changes in supply voltage and flow rate regulation by throttling, as well as the application of frequency control. A digital portable multifunctional device has been used for measuring and analyzing three-phase electrical circuits. Some intrinsic electrical variables have been measured and recorded, and others have been subsequently calculated. Comments, conclusions and recommendations have been done. The results obtained would be interesting for specialists dealing with this technical equipment.

Keywords: INDUCTION MOTORS, ELECTRIC DRIVE, CENTRIFUGAL FAN, ELECTRIC VARIABLES MEASUREMENT, TOTAL HARMONIC DISTORTION, VARIABLE SPEED DRIVES

1. Introduction

The energy base of production, which is the electric drive (ED), determines the technical level of efficiency of the equipment's functioning. The development of the ED is moving along the path of increasing economy and safety. The technical level, operating mode, and operating conditions of electrical equipment determine the productivity, quality, and cost of production, i.e. all the main indicators characterizing the efficiency of work, both of individual workshops and of entire enterprises [1].

Electric motors (EMs) are used to provide forces and torques to generate motion in countless industrial applications [2]. According to a number of estimates, electromechanical systems powered by EMs consume over 2/3 of all electricity generated in countries such as the USA, Japan and the European Union. In Bulgaria, the situation is similar, but the difference is that the use of energy-efficient EDs and technologies is not yet widespread.

The development of industrial technologies leads to an increase in the number of EMs used. In production units and mechanisms, alternating current EMs are most often used, while at the same time, the widespread use of induction motors (IMs) as part of the EDs of various production machines, mechanisms and processes is well known due to their undeniable advantages.

Induction motors account for about 90% of all EMs and consume about 40% of the electrical energy produced [2]. This versatile application is explained by the extremely skillful combination of operational and design characteristics of these motors: relatively simple and inexpensive design, simple and rugged structure, high operational reliability, minimal maintenance, high efficiency, economy of operation, good overload capacity [3, 4]. In fact, the IM is the workhorse of many industrial applications [2].

In this regard, the issue of appropriate control of IMs is relevant. The ultimate goal is to reduce the individual types of their losses. [2]. A wide range of IM speed control strategies exist, including voltage control, voltage and current-fed variable-frequency inverters, cycloconverters, and slip-energy recovery. However, within the application areas being considered, the use of voltage- and current-fed inverters predominates [3]. Variable speed drives (VSDs) are currently being actively implemented. In them frequency control is implemented using autonomous voltage inverters, which allows solving a number of problems related to the imperfection of existing ED systems. In a vector controller, the magnitude and the phase of the supply currents must be controlled in real time, in response to changes in both the speed and the torque demands.

It has been found that about 55% of IMs are used to drive fans and pumps. [5]. Centrifugal fans are the most common type [6].

The main goal of this paper is to test a specific centrifugal fan under different conditions (changes in supply voltage and flow rate regulation by throttling, application of frequency control).

2. Some technical considerations

Historically speaking – George Westinghouse acquired in July 1888 Nikola Tesla's patents from April 1888 for alternating current induction motors, transformers and a distribution system and began to manufacture and sell the world's first small electrical appliance – a fan powered by a 125 W AC motor. Otherwise, the first three-phase EM was invented in 1889 by Mikhail Osipovich Dolivo-Dobrovolsky, a Russian engineer working as a chief electrician at the German company AEG.

Fans are machines used to transport gases and gas mixtures. They are used for ventilation of domestic, industrial and other premises, for heating systems (air-conditioning installations), for cooling motors, for exhausting flue gases. They provide air flow in combustion and other technological processes. They are used in refrigeration and drying equipment. They can transport granular and powdery products such as flour, grain, cement, sawdust, shavings, etc. Their division into groups depends on the pressure of the gases at the outlet and their purpose. The fans create a pressure difference between the outlet and inlet of 0.001 to 0.01 MPa. A special feature is that for fans the torque needed varies roughly with the square of the speed [4].

The need for a good ventilation system that provides a sufficient amount of fresh air in the premises and, accordingly, removes the exhaust air is well known. However, regardless of the damage caused to people's health by prolonged stay in rooms with stagnant air, in modern construction the emphasis is mainly on good insulation of buildings and limiting the infiltration of outside air into the premises. The organization of good ventilation is often overlooked. The only solution to ensure sufficient fresh air is the implementation of good ventilation. Controlling the quality of air in the home and work environment is of great importance and for this reason a European standard regulates the requirements for the design and assessment of the energy efficiency of buildings, focused on indoor air quality. In fresh air processing systems, options for natural organized ventilation, night ventilation or forced ventilation are first sought.

Depending on the way the air movement is organized, ventilation systems are mainly of two types – natural and forced (mechanical) ventilation. Natural ventilation relies mainly on air infiltration through the joints of windows and doors. The supply and removal of air from the premises is carried out under the influence of the difference in temperature of the internal and external air (thermal pressure) and under the influence of the wind on the building (wind pressure). In mechanical ventilation, the supply and exhaust of air is implemented with the help of fans or through a pre-built ventilation system. It also allows for pre-treatment of the air supplied and extracted from the premises. A number of specialists advocate the opinion that mechanical ventilation is the only solution for ventilating modern, well-insulated buildings, in which the possibilities of natural ventilation are severely limited.

In order to comply with modern requirements for energy efficiency of installations and reduce the amount of energy required, a number of measures are being taken aimed at reducing energy costs and increasing the efficiency of mechanical ventilation.

Electric motors in general in driven fans are a source of energy losses. One possibility to limit these losses and increase the efficiency of the system is the use of frequency converters, which allow for fan speed control [5]. They make it possible, by reducing the motor speed when the load and the required amount of air are reduced, to reduce electricity consumption.

3. Results

As a first part of the measurements carried out, the operation of the tested centrifugal fan without any control applied to it was affected. Below is a description of the object for study.

The tested IM is a driving component of a specific industrial centrifugal fan. It is offered in Bulgaria by the company VIKIWAT Ltd. [7].

Parameters of industrial centrifugal fan considered

Brand: VEMARK (own commercial brand of VIKIWAT Ltd.)

Fan type: centrifugal V-4D-300QD

Flow rate: 3200 [m³/h]

Rated power: 1250 [W]

Supply voltage: 400 [V AC]

Rated current: 2.5 [A]

Rotational frequency: 1360 [rpm]

Noise level: 68 [dB]

Operational temperature: -10~60 [°C]



Fig. 1 General view of an industrial centrifugal fan V-4D-300QD.

The centrifugal fan is used when it is necessary to achieve a high air flow rate. The low noise level during operation is an advantage when installing it in ventilation systems or air ducts in industrial halls or public buildings. The advantages of this fan are: high efficiency, low vibrations, low noise level, high flow rate, small dimensions and easy installation. It is possible to regulate the fan flow rate by the motor speed with a properly selected frequency converter. The fan cannot be powered by a modified sine wave inverter – this will damage it.

To measure the electrical variables, the METREL MI 2292 power quality analyzer was used, which is a digital portable multifunctional device for measuring and analyzing three-phase electrical circuits. In recording mode, the measured values are stored in memory for further analysis [8].

Using the METREL MI 2292, voltage and current values have been measured at the input of the EM driving the centrifugal fan at different throttle valve positions and supply voltage values set with a three-phase autotransformer Goldsource 9 kVA/12 A. As is known, the value of the supply voltage can vary within certain limits in the upward and downward direction. This was simulated by supplying an autotransformer, for which it turns out that in the upward direction it is possible to reach an increased value of only +3%U_N. The supply voltage values set one after another were 103%, 100%, 95% and 90% of the nominal voltage value. The throttle valve has been set to different values of open position – 100%, 50% and 25%.

Below are presented the results obtained in graphical and tabular form – Figures 2~13 and Table 1. Some of the results shown are for a supply voltage of 90% from the rated voltage value, since voltage fluctuations and deviations of the order of decreases up to 10% often occur in power supply lines. This is when the largest harmonic distortions of current and voltage are observed.

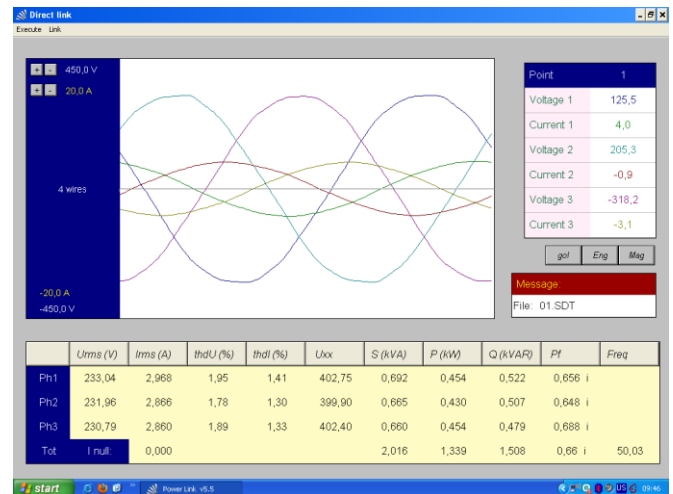


Fig. 2 Characteristics at a supply voltage value of 400 V (100% from the rated voltage value) at 100% open throttle valve.

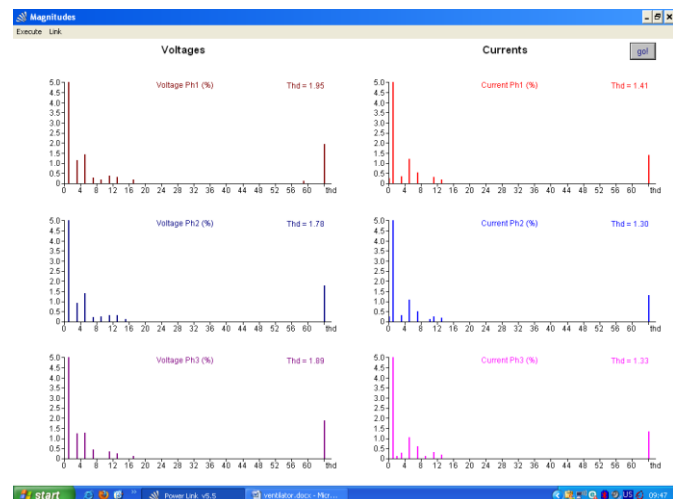


Fig. 3 Voltage and current harmonics at a supply voltage value of 400 V (100% from the rated voltage value) at 100% open throttle valve.

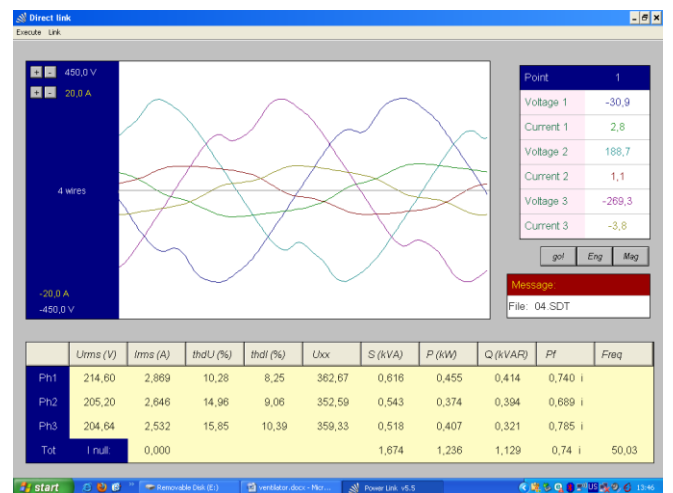


Fig. 4 Characteristics at a supply voltage value of 360 V (90% from the rated voltage value) at 100% open throttle valve.

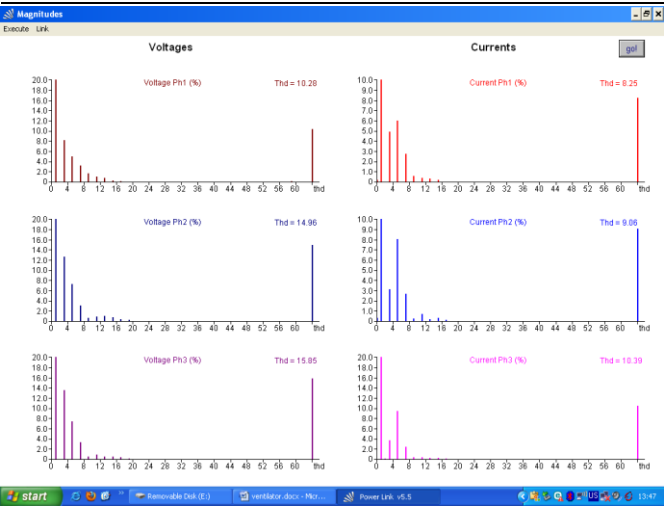


Fig. 5 Voltage and current harmonics at a supply voltage value of 360 V (90% from the rated voltage value) at 100% open throttle valve.

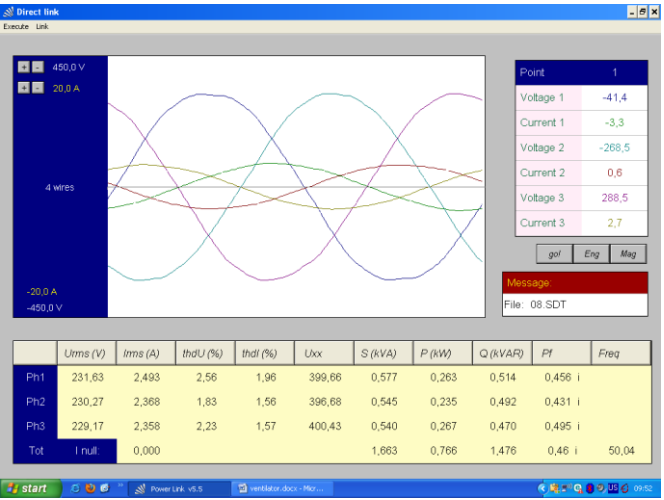


Fig. 6 Characteristics at a supply voltage value of 400 V (100% from the rated voltage value) at 50% open throttle valve.

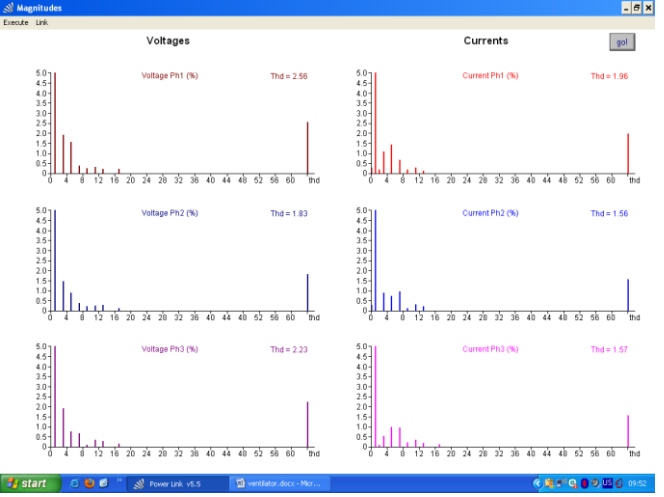


Fig. 7 Voltage and current harmonics at a supply voltage value of 400 V (100% from the rated voltage value) at 50% open throttle valve.

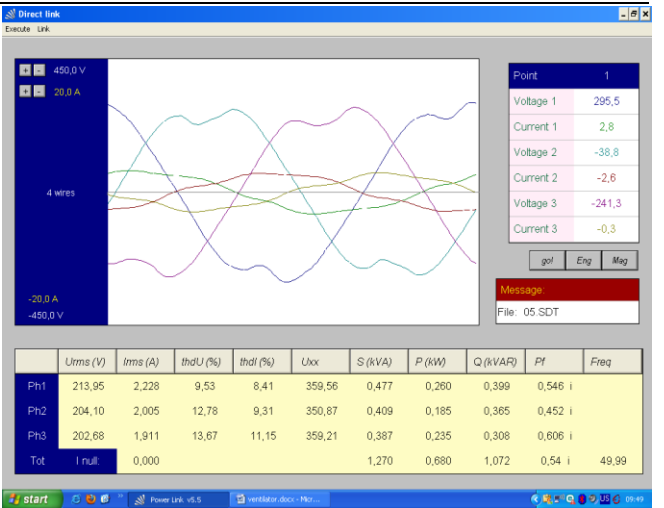


Fig. 8 Characteristics at a supply voltage value of 360 V (90% from the rated voltage value) at 100% open throttle valve.

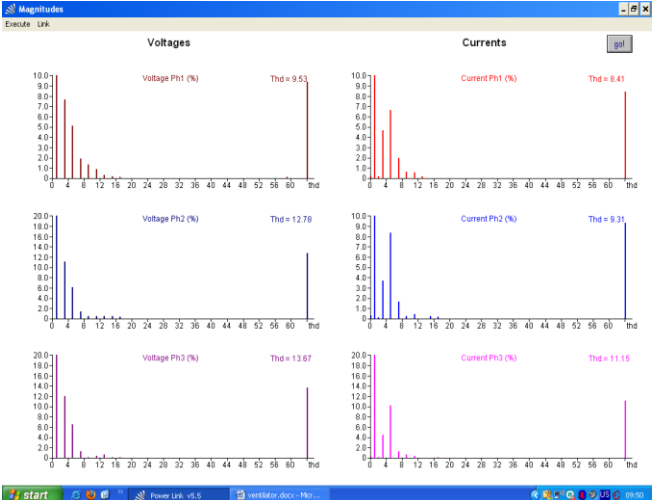


Fig. 9 Voltage and current harmonics at a supply voltage value of 360 V (90% from the rated voltage value) at 50% open throttle valve.

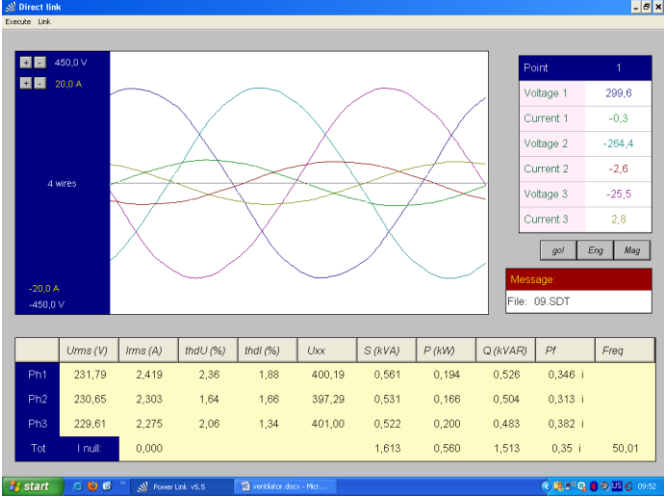


Fig. 10 Characteristics at a supply voltage value of 400 V (100% from the rated voltage value) at 25% open throttle valve.

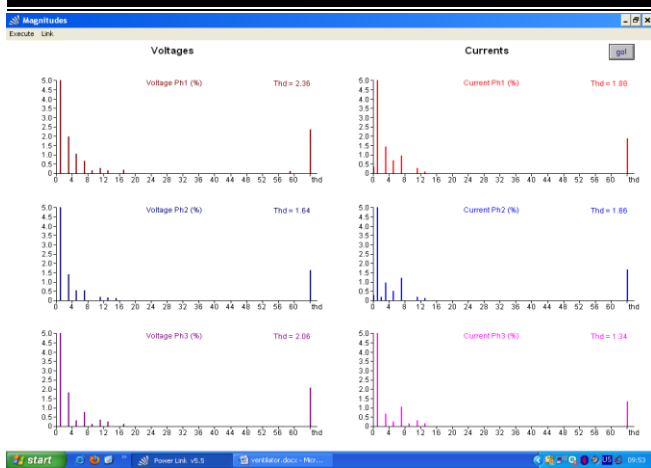


Fig. 11 Voltage and current harmonics at a supply voltage value of 400 V (100% from the rated voltage value) at 25% open throttle valve.

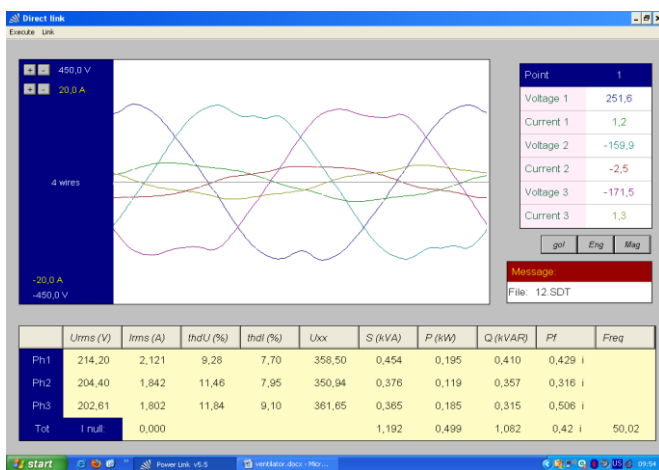


Fig. 12 Characteristics at a supply voltage value of 360 V (90% from the rated voltage value) at 25% open throttle valve.

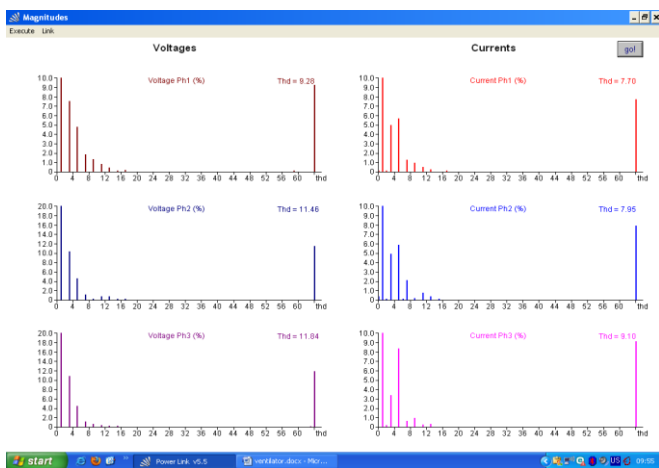


Fig. 13 Voltage and current harmonics at a supply voltage value of 360 V (90% from the rated voltage value) at 25% open throttle valve.

Table 1: Results obtained for maximum harmonic distortions.

Supply voltage	Throttle valve (opening)	Thd _U	Thd _I
100%U _N	100%	1.95	1.41
	50%	2.56	1.96
	25%	2.36	1.88
103%U _N	100%	1.49	1.62
	50%	1.49	1.76
	25%	1.48	1.95
95%U _N	100%	9.18	6.82
	50%	7.90	6.36
	25%	8.12	6.67
90%U _N	100%	15.85	10.39
	50%	13.67	11.15
	25%	11.84	9.10

The second part of the measurements concerned the operation of a centrifugal fan in conjunction with a frequency control. After carrying out a market survey, an Omron Corporation frequency controller Q2V-AB010-AAA was selected [9]. In Bulgaria this product is offered by sole trader GEMAMEX MOTION CO. Ltd. [10] and Sitel Ltd. [11].

Table 2: Frequency converter OMRON Q2V-AB010-AAA specifications.

Control mode	Open loop vector
Supply voltage	230 V single phase
Max. motor output at constant torque (HD - Heavy Duty)	1.5 kW
Max. motor output at variable torque (ND - Normal Duty – pumps and fans)	2.2 kW
Rated output current	HD 8 A / ND 9.6 A
Operating temperature	-10°C - +50°C
Degree of protection (IP)	IP20
Compatible motor type	Induction motor, Permanent magnet motor, Synchronous reluctance motor
Built-in communication	MODBUS Slave, Serial RS-485, USB

Voltage and current values have been measured using METREL MI 2292. The measurements have been carried out at different frequencies of the supply voltage – 10, 20, 30, 40 and 50 Hz.

Below are the results of the tests carried out – Figures 14~18 and Table 3.

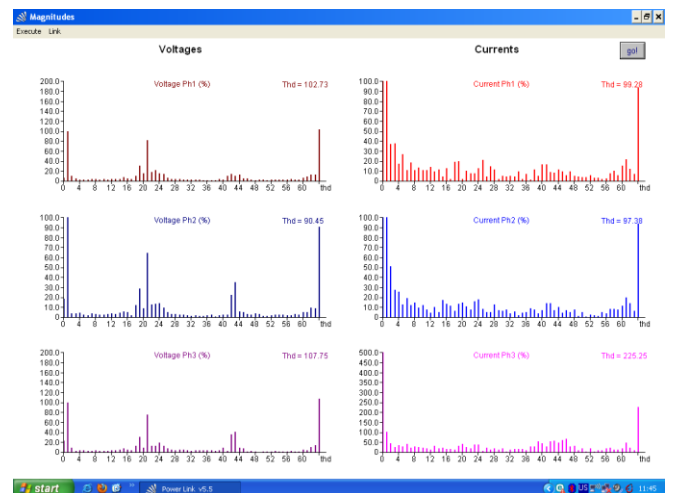


Fig. 14 Voltage and current harmonics at a supply voltage frequency of 10 Hz.

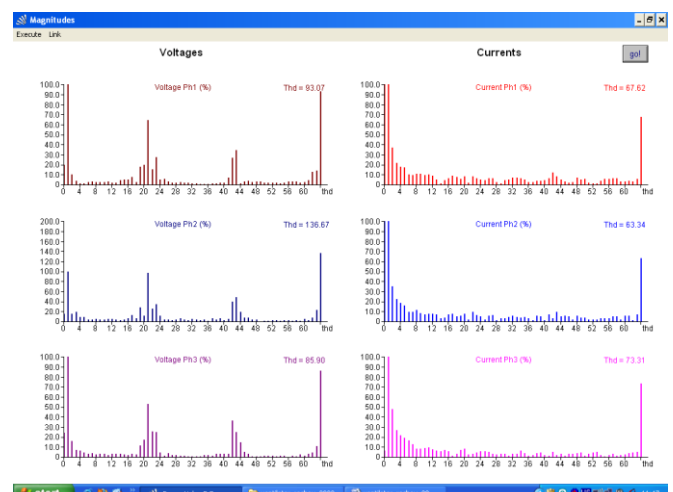


Fig. 15 Voltage and current harmonics at a supply voltage frequency of 20 Hz.

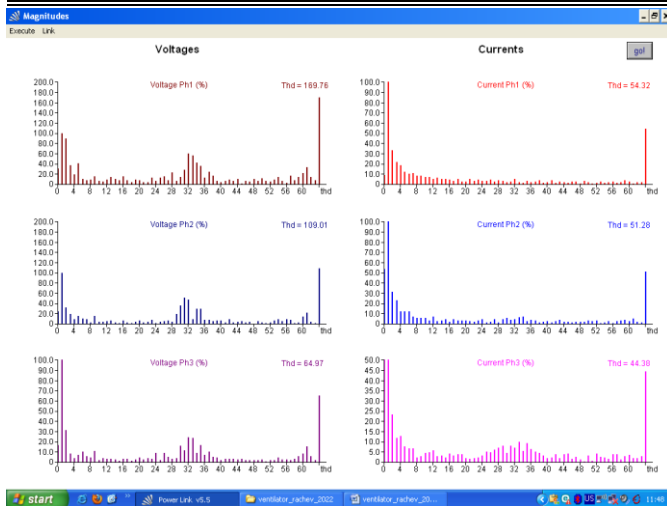


Fig. 16 Voltage and current harmonics at a supply voltage frequency of 30 Hz.

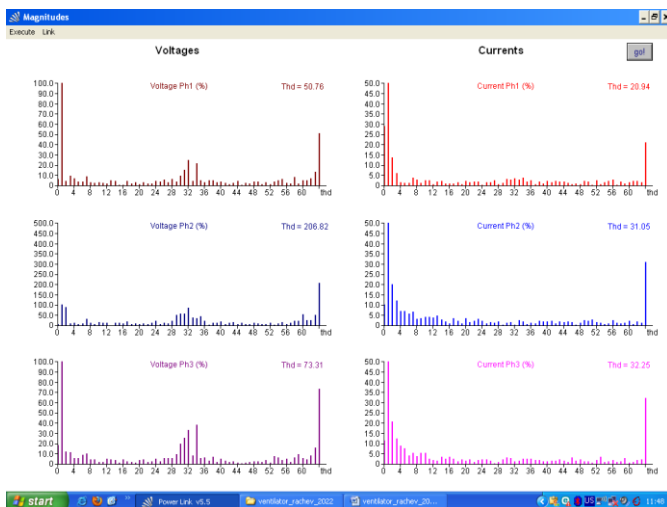


Fig. 17 Voltage and current harmonics at a supply voltage frequency of 40 Hz.

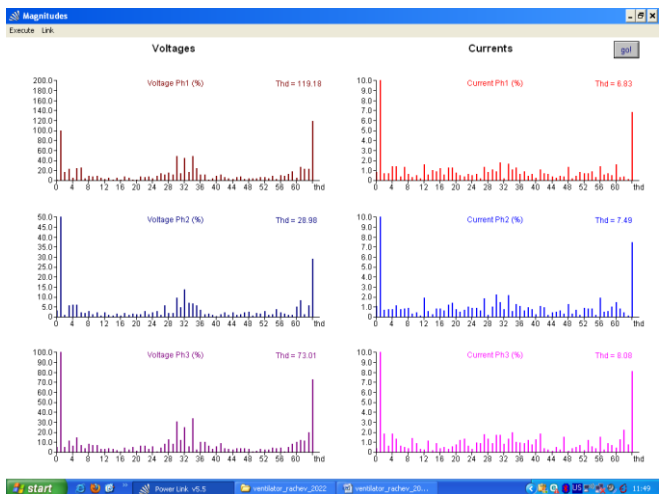


Fig. 18 Voltage and current harmonics at a supply voltage frequency of 50 Hz.

Other measurements are also possible, but those carried out so far show certain trends.

Table 3: Results obtained for maximum harmonic distortion in current at different supply voltage frequencies.

Frequency, Hz	Phase	Maximum harmonic distortion in current, Thd _i , %
50	1	6.83
	2	7.49
	3	8.08
40	1	20.94
	2	31.05
	3	32.25
30	1	54.32
	2	51.28
	3	44.38
20	1	67.62
	2	63.34
	3	73.31
10	1	99.28
	2	97.38
	3	25.25

4. Conclusion

Based on the work done, the following concluding remarks can be noted.

The topic discussed is interesting, as the results of some developments in this area have not yet been put into practice. Electric drives of fan mechanisms directly affect productivity and create opportunities for the rational flow of technological processes.

Regardless of the specific case – whether it is a new fan or an existing one – it would be a good idea to take into account the possible savings in electricity. They directly affect the monthly and annual electricity costs.

A specific centrifugal fan has been tested. Considering that the EM is a load with an active-inductive nature, the results obtained justify the preliminary expectations and attitudes. For example, when supplying with reduced voltage, the arising harmonic distortions in voltage and current of some of the phases increase significantly - this means that undervoltage protection should be provided in the power circuit of the EM. Generally speaking, in terms of voltage, there is a clear presence of 3rd and 5th harmonics, and in terms of current – mainly the 5th harmonic. The reported values for active power of the electric motor and root mean square current at 100% open throttle valve and supply voltage 400 V (100%) are 1339 W and 2.968 A respectively, differing somewhat from those declared by the manufacturer – 1250 W and 2.5 A, accordingly.

The issue of frequency control of an IM by VSD is also considered. From the experiments and the data obtained, it is clear that the tested motor - frequency control set gives good results and has great practical application not only in industry, but is also convenient for research, training and use in laboratory conditions, since the possibilities it provides can be practically seen.

The expansion and complication of the functions performed by the ED, the application of new control tools require a high level of training of specialists involved in its design, installation, adjustment and operation. They must be well aware of the purpose and element base of the individual components of the ED, its properties and characteristics, be able to analyze the control schemes of the ED, determine its economic indicators and select the appropriate elements for it.

With the help of the studied frequency drive, students and engineers from practice will be able to feel the need and effectiveness of such control of EMs, as part of EDs, and will be able to gain some practical skills.

5. Acknowledgments

The implementation of this paper is thanks to the support from Regional Development Fund under the Operational Program ‘Scientific Research, Innovation and Digitalization for Smart Transformation 2021-2027’, Project CoC ‘Smart Mechatronics, Eco- and Energy Saving Systems and Technologies’, BG16RFPR002-1.014-0005.

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Effect of thermal insulation on comfort and energy savings in buildings

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Abstract: Albania's construction sector has seen rapid growth with the introduction of diverse materials and advanced building techniques. However, the key challenge remains in effectively applying these innovations to maximize indoor comfort and energy efficiency at the lowest cost. Comfort plays a crucial role in occupant well-being and productivity, yet it is often overshadowed by concerns over upfront construction costs, overlooking long-term benefits such as improved health and reduced operational expenses.

Measurements across different seasons have shown that thermal insulation significantly enhances indoor thermal comfort. Data from the Electricity Distribution Operator also confirm that insulation can reduce electricity consumption by 15–28%, especially during peak usage periods. Supporting insulation in new buildings and encouraging retrofits in existing structures through coordinated local policies and utility programs could lead to substantial energy savings and improved living conditions nationwide.

KEY WORDS: THERMAL INSULATION OF BUILDINGS, THERMAL COMFORT, REDUCTION OF ELECTRICITY CONSUMPTION.

Introduction

Albania is a developing country, and traces of the former communist regime are still present in many aspects of life, including the field of construction. This sector has evolved significantly in implementing contemporary materials and techniques, but there is still much work, mainly in the mentality and way of designing and building with foresight. According to many studies, the higher the comfort level in buildings, the healthier, more satisfied, and more efficient the residents are. (The Health and Environment Alliance (HEAL), 2018) So, increasing the comfort level in apartments is the main challenge of designers and builders today.

Moreover, the realization of this challenge should be aimed at the most optimal and efficient cost. On this basis, but also as a need to meet the criteria, in the framework of the aspiration of EU membership, the Parliament of Albania approved in November 2015 Law 124, on 05.11.2015 "On energy efficiency", later regulated by Law no. 28/2021, for some changes and additions to Law no. 124/2015 "On energy efficiency" amended. According to the data, one of the essential elements of comfort is the thermal one, which is realized mainly through electricity. According to Balkan Green Energy News (2018), for 65% of households in Albania, most of the electricity consumption goes to heating their homes, while for approximately 60%, most of it is spent on cooling (Figure 1). According to the Directive 2010/31 / EC on Energy Performance in Buildings (DPNE), 25% of the total annual energy consumption goes for heating, and 20% goes for cooling.

Thermal insulation is the most efficient solution for storing the obtained thermal energy and prevents its transfer from the residential area to the outside environment. The quality of thermal comfort in apartments is mainly conditioned by the quality of masonry, which increases significantly through its thermal insulation. Many people still do not understand the great benefits of thermal insulation due to the lack of accurate and sufficient information. On the other hand, these benefits are neglected by many builders because of the momentary gains, without thinking about saving electricity, as a limited resource, or the increased costs of households that will live in these buildings.

The initiative of thermal insulation should be, in the first place, the responsibility of the Local Authorities, whose contribution makes the process faster and essentially affordable.

The intervention of the Local Authorities should be done in two plans:

1. First plan should be dedicated to new buildings, which is easier to implement, both in terms of technical and legislative sides. With a detailed study based on existing legislation, these authorities can undertake different policies to stimulate builders who apply thermal insulation in their constructions.
2. The second plan should be dedicated to the stock of existing buildings, where the process is a little more complicated but not impossible. In this contingent of housing, the initiative can

be taken by the Local Authorities themselves, through the funds at their disposal, but also by individuals who share the same building, if supported by incentive policy, or repayable financial assistance, based on a continuous awareness, on the medium-term benefits of the process.

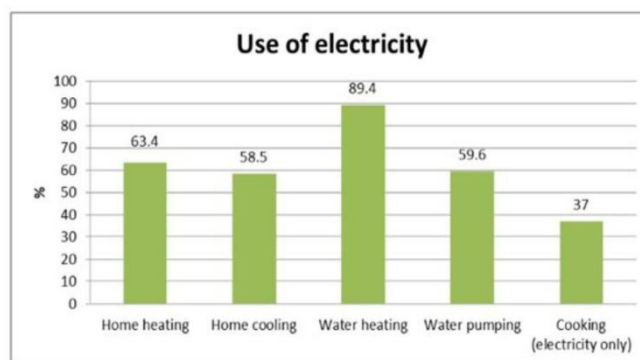


Figure 1: Use of electricity by households

Objectives

This research aims to identify the social and economic benefits of thermal insulation in residential buildings, based on the one hand on the actual perception of residents and the other hand in the analysis of technical measurements of electricity consumption. The ultimate objective is to analyze the improvement of the thermal performance of the indoor environment in a residential building, closely related to the need for comfort and reducing the cost of living.

Research Question

This research focuses on measuring well-being and improving the quality of life because of the thermal insulation of buildings and is based on the following questions:

- How can we measure the impact of thermal insulation on daily life?
- What is the impact of thermal insulation in reducing the cost of living?

Methodology

This research was conducted based on a process extended in several directions. It is based on a good knowledge of the legal framework, daily, continuous, and advanced work towards recognizing contemporary studies related to the requirements for comfort and its impact on daily activity, and a series of field analyses and surveys. Good knowledge of legislation and literature makes it possible for us to understand the directions we need to look for and the spaces where we can move. Analyzing the situation in a global context indeed begins with more straightforward analyses in the local context.

On this basis, the research is composed of a combination of qualitative and quantitative methods to answer optimally the questions that arise during the process.

The qualitative method consists mainly of an active search of statistical data concerning surveys and observations on thermal insulation and the impacts of its application on buildings. The quantitative method involves a survey conducted by interviewing residents in a thermally insulated residential building and extracting data to reach a convincing conclusion.

Limitations

Despite all the efforts to be as accurate as possible in determining the reduction of the amount of electricity due to thermal insulation, we find it difficult to be precise because we cannot fully identify the use of alternative sources of heat in certain moments.

Moreover, other minor issues came to the surface as we could not calculate the electricity consumption from newly purchased household appliances during the study period or the savings from replacing an old appliance with a new one with better technical properties. However, relying on professional judgment, these

restrictions are not to the extent that they have a significant impact.

Impact of thermal insulation on the improvement of everyday life quality

A focus group of 6 families was chosen after ensuring they lived in the same building before and after the thermal insulation. A formal survey was conducted and distributed to the families. Families count as a single subject of the survey, making a total amount of 6 subjects. The survey asked the subjects to describe their well-being in everyday life and inside their homes before and after the thermal insulation. They were asked to rate different aspects of their life such as physical well-being (having an excessive feeling of coldness/ warmth during winter/summer), emotional well-being (feeling comfortable and happy inside of home), psychological well-being (possible state of optimism related to the comfort when entering a home or while staying at home). Ratings for each category and a composed rating of all dimensions before and after the insulation are presented below. (Table 1)

Table 1: Presentation of the results from the survey

	Physical improvement	Emotional improvement	Psychological improvement	Average of general improvement/subject
Subject 1	4	4	3	3,67
Subject 2	5	3	3	3,67
Subject 3	5	5	4	4,67
Subject 4	3	4	2	3
Subject 5	4	3	2	3
Subject 6	4	4	3	3,67
Average group improvement/ aspect	4,17	3,83	2,83	

Legend

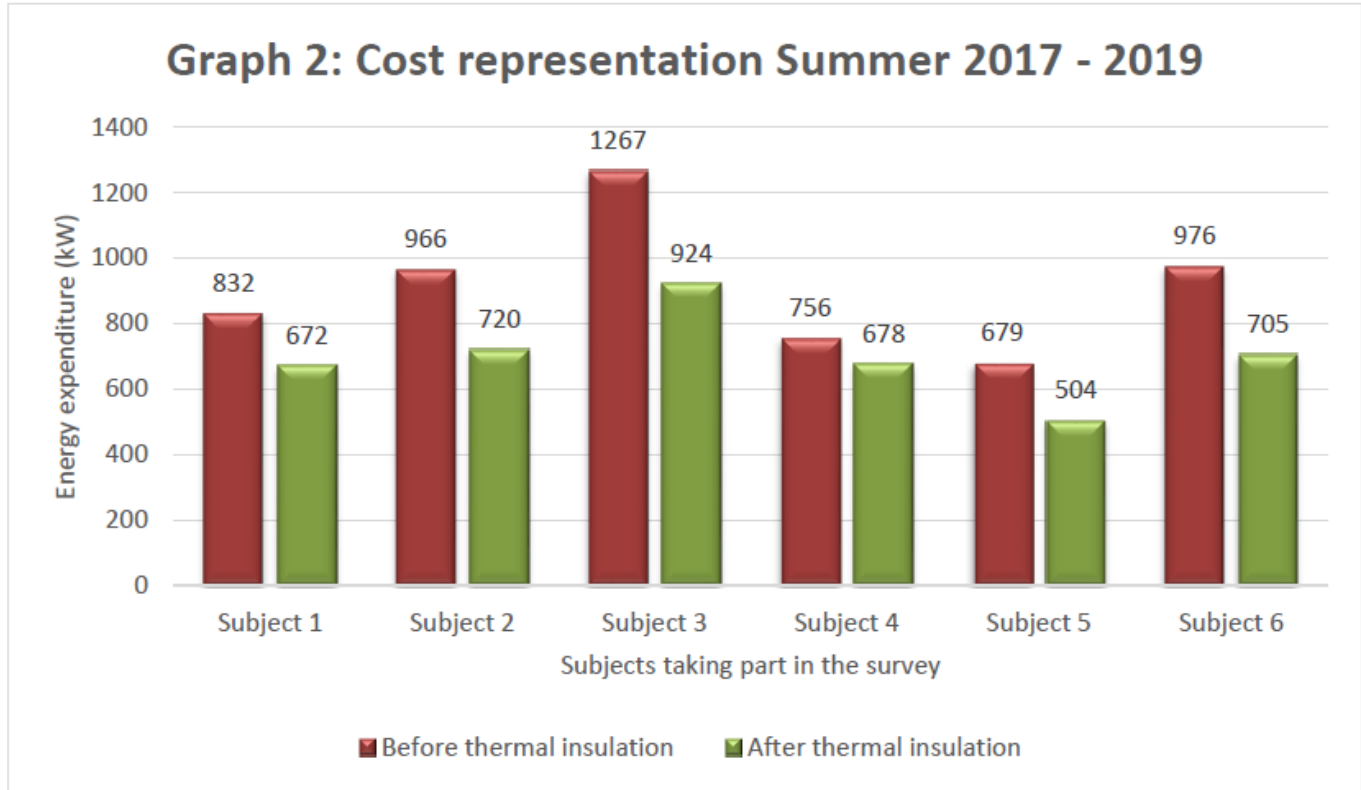
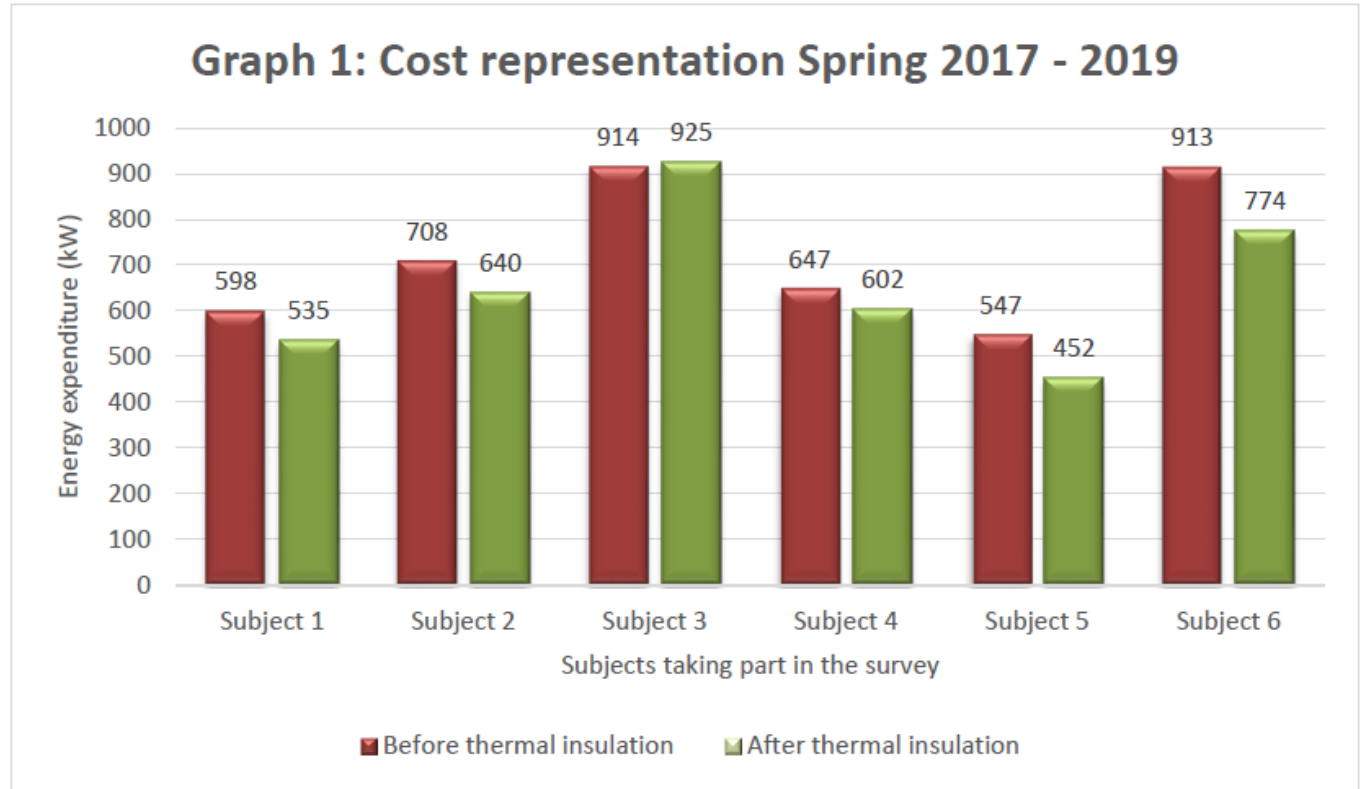
Improvement aspect
Subject
Subject evaluation
Evaluation span: 1-5
1-2: little or no improvement
2-4: notable improvement
4-5: great positive change

The general conclusion from the survey was satisfactory, and the subjective impression was overall positive. Most of the subjects had noted improvements in every aspect. As a result, they considered their life to be improved. Different aspects of well-being were also separately improved as the average ranking by each aspect lay between 2 and 4. It was expected for the subjects not to reach the maximum life

improvement level as more factors contributing to the improvement were not studied in this research.

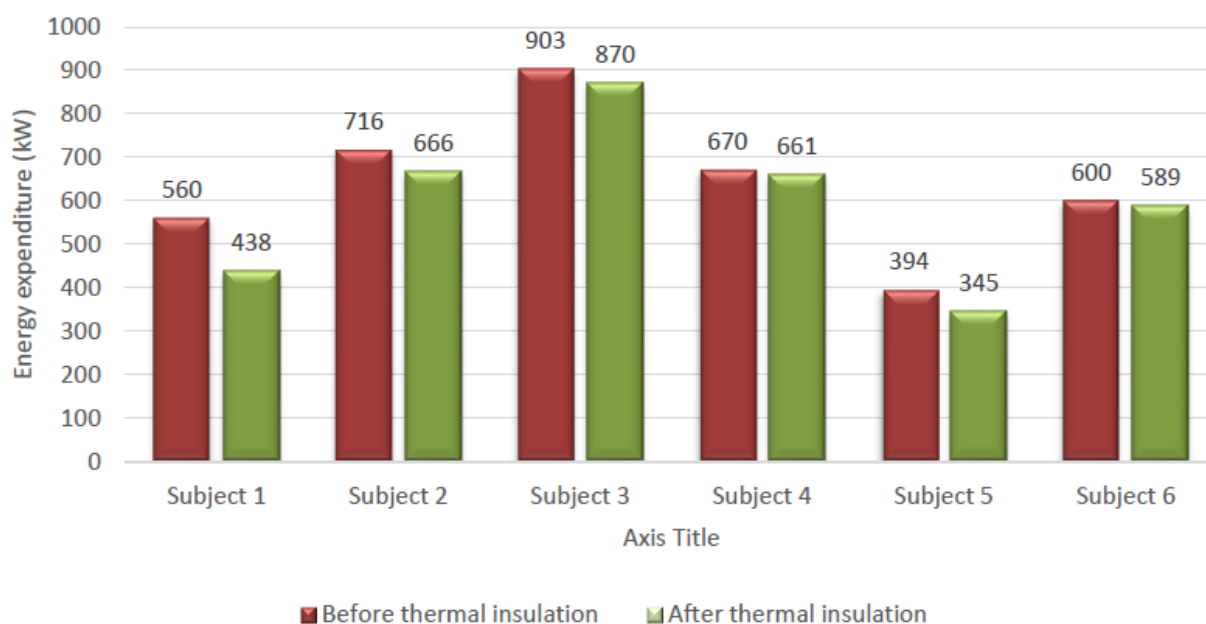
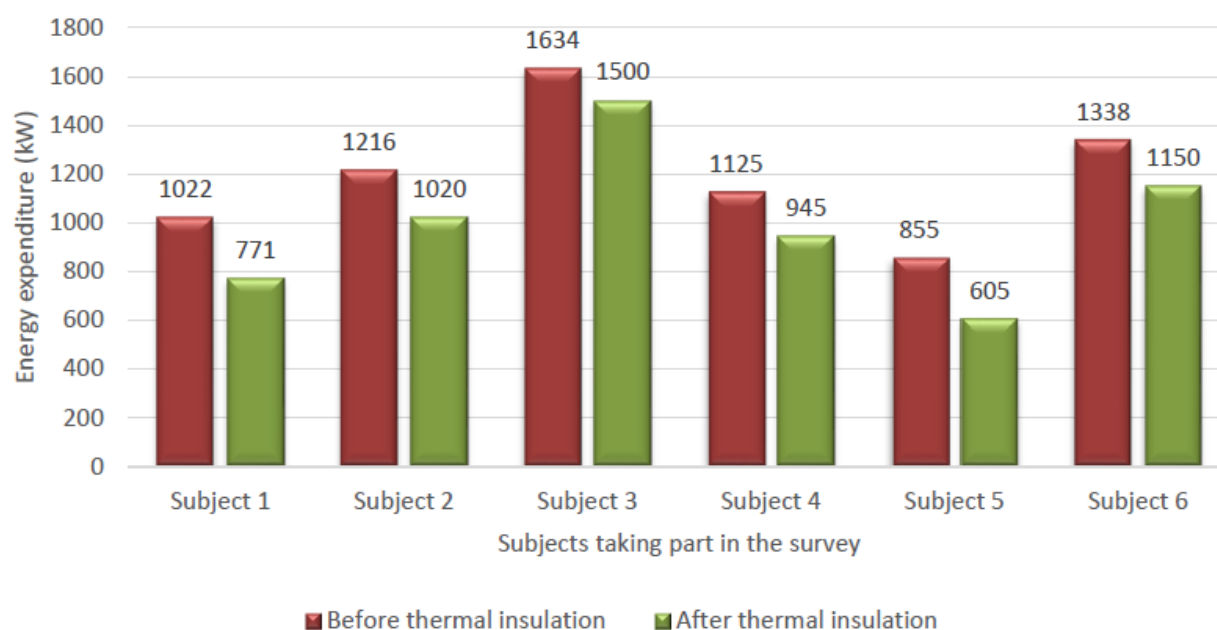
Impact of thermal insulation on electrical energy-related costs

The economic aspect is also crucial in the life of every average household as it heavily impacts the quality of all their daily activities. This paper interprets official data retained from OSHE for the same subjects that collaborated above. The data represent the yearly expenditure on electrical energy, and this research focuses on two critical years, the year before the thermal insulation and the year after. This selection was made to prove the difference in expenditure and, as a result, in cost during this timeframe. Data was compiled and formatted graphically. (See Graph 1-4)



The data in each of the four graphs correspond to each subject's average expenditures for each season. There is a difference between the respective values before and after the thermal insulation works. From the graphs, it is clear that in spring and autumn, when the need for heating - cooling is very low, the difference between these two values is not very large, although it is present.

When the need for heating - cooling is at the highest levels in the winter and summer periods, the difference between these two values is much more significant. We also see that the opinions obtained during the interview are in sync with the statistical data presented in the graph.

Graph 3: Cost representation Autumn 2017 - 2019**Graph 4: Cost representation Winter 2017 - 2019**

Conclusion

Through this research, certain conclusions were put on evidence. The research subjects felt the impact of thermal insulation in their everyday lives. They were physically feeling an increase in energy and health as having a comfortable interior and avoiding excessive temperatures in both directions, warm and cold, reduced their chances of getting sick and suffering from the seasonal flu and cold. The constant state of health also affected their psychological and emotional state as they were feeling more motivated to stay active during the day and even increased the amount of time they spent at home instead of avoiding it. From the obtained data, it is evident that the economic impact of thermal insulation has a positive impact on the household's savings in energy-related costs. Furthermore, the investment becomes profitable in a 4–5-year period if the investment was undertaken privately by the inhabitants

of the building.

Literature Review

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Подобрена конструкция на опори за изпитване на ударно огъване по метода на „Чук на Шарпи“

Improved support design for Charpy impact bending testing

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Резюме: Разработени са специални съставни сменяеми (подобрени опори) за изпитване на ударно огъване по метода на чук на Шарпи. Опорите са изработени, монтирани на махален чук на Шарпи и са изпитани с помощта на стандартни тестови образци с V-надрез. Изследвана е съвместимостта между стандартните и разработените от колектива опори.

Ключови Думи: Съставни Опори, Чук На Шарпи, Ударно Огъване

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Abstract: Special composite interchangeable (improved) supports for Charpy impact bending testing were developed. The supports were fabricated, mounted on a Charpy pendulum hammer and tested using standard V-notch test specimens. The compatibility between the standard and the supports developed by the team was investigated.

KEYWORDS: COMPOSITE SUPPORTS, CHARPY HAMMER, IMPACT BENDING

1 Въведение:

При увеличаване скоростта на натоварване обикновено се увеличава и чувствителността на материалите, към надрези, вътрешни дефекти, структурна нееднородност и др., като проявяват склонност към крехко разрушаване. Това налага определяне на техните динамични механични характеристики. Тези характеристики се определят чрез динамични методи на изпитване на пробни тела. При тези методи нарастването на натоварването и самото разрушаване на пробните тела протичат с голяма скорост (чрез удар). Високата скорост на разрушаване варира от няколко метра до няколко стотин метра за секунда и се постига по различни методи – удар чрез падане (механичен чук), ротационно движение, взрив и др.

От динамичните изпитвания най-разпространената характеристика която се определя е ударната жилавост на материалите. С определянето на ударната жилавост на материалите се разкрива влиянието на структурата (неправилната термообработка, едрината на зърната, наличието на флокени) и разположението на образаца (детайла) спрямо посоката на пластичната деформация и други фактори, върху съпротивлението срещу крехко разрушаване. Възприето е ударна жилавост да се бележи с K_C и се изразява чрез специфичната работа (E), изразходвана за разрушаване на образаца с първоначално напречно сечение (S) в мястото на умишлено създаден прорез (концентратор на напрежения) прореза [3], чрез огъване при ударно натоварване. В почти всички случаи елементите на това изпитване са стандартизирани. Определянето на ударната жилавост на материалите се извършва най-често с помощта на махалния чук на Шарпи. Макар че, принципа на действие остава един и същ, този тип машини и техните елементи непрекъснато се усъвършенстват. Обект на настоящата работа е усъвършенстване на опорите на махалния чук на Шарпи

2. Конструктивна разработка:

За изпитване на ударно огъване по метода „Чук на Шарпи“ са конструирани специални съставни опори, показана на (фиг.1), състояща се от:

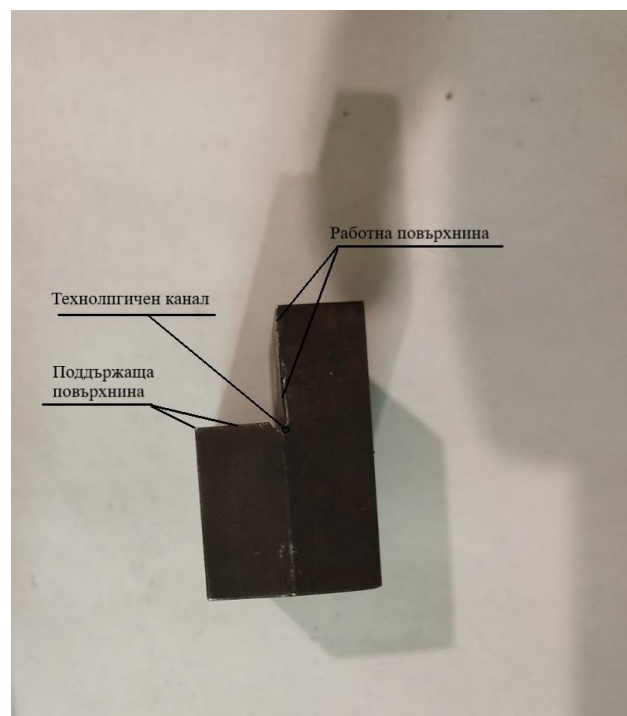
- опори със специална геометрия и профил на върха отговаряща на стандарта [1]
- специални поддържащи елементи
- крепежни елементи



Фиг.1 - Подобрени опори.

При изработването на опорите са спазени всички изисквания, указани в стандарта [1], геометрична форма на работните повърхности, материал, технология на закаляване, твърдост след закаляване и последваща обработка, клас на гравитация гарантиращ максимален акустичен контакт с корпуса на изпитателната установка и други.

Изработването на опори от две части позволява контакт на пробното тяло по цялото му сечение с работните повърхнини на опорите, който не е възможен при стандартните опори поради наличието на технологичен канал. Стандартната опора е показана на фиг. 2



Фиг. 2 - Стандартна опора за „Чук на Шарпи“

Подобрените опори се състоят от две части (Основа и Поддържаща пластина), закрепени помежду си посредством два специални болта. За гарантиране на прецизна сглобка преди закаляване и шлайфане към точни размери двете части са базирани и щифтовани. В основата са изработени преди закаляване два елипсовидни канала, чрез които се осъществява прецизна настройка на сглобеният възел при монтажа към изпитателната установка. Поглед отпред е показан на фиг. 3



Фиг.3 - Подобрена опора – поглед отпред

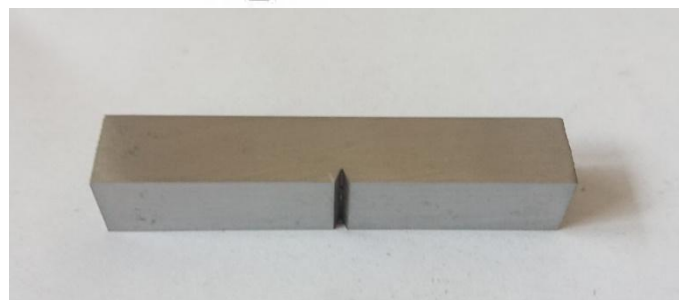
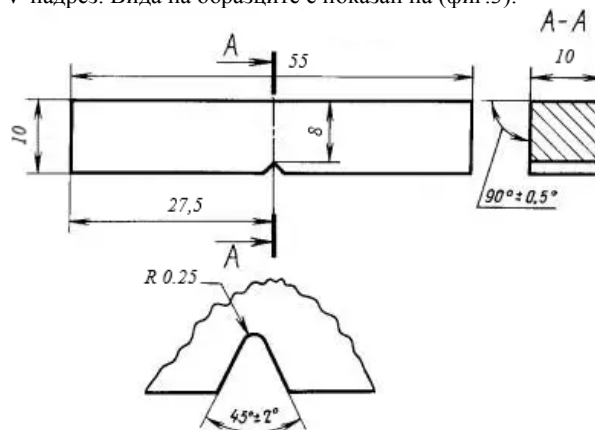
Подобрените опори са монтирани на стандартен Чук на Шарпи с цел да се проведе сравнителен тест между калибриран стандартен такъв и аналог с подобрените опори. На фиг. 4 са показани монтираните опори.



Фиг. 4 - Подобвени опори монтирани на експериментален Чук на Шарпи

3. Експериментална част:

Чука е настроен на 300J потенциална енергия при скорост на удара 5.6 m/s. За експериментална проверка на работоспособност са използвани 6 бр. стандартни образци [1] с V-надрез. Вида на образците е показан на (фиг.3).



Фиг. 5 – Стандартен образец с V – надрез

Образците са изрязани еднопосочно от лист ламарина с цел максимално уеднаквяване на механичните им характеристики. Първоначалните им размери са дадени в таблица 1

абл. 1

Номер	Дължина, L[mm]	Височина, H[mm]	Ширина, B[mm]	Дълбочина на надреза, D [mm]
1	55.10	10.05	9.95	1.95
2	55.05	9.95	10.00	2.00
3	55.00	10.10	10.05	2.05
4	54.95	10.00	10.05	2.00
5	55.10	9.95	9.90	1.90
6	55.05	10.05	9.95	1.95

Проведен е сравнителен анализ между получените резултати от проверен чук на Шарпи и изработения експериментален модел. Температура на изпитване 20°C.

Ударната жилавост K_C се изчислява по формулата [3]:

$$K_C = \frac{E}{B(H - D)} * 100, \quad [3]$$

където:

K_C - Ударна жилавост, [J/cm²]

E – Енергия за разрушаване, [J]

B – Ширина на пробното тяло, [mm]

H – Височина на пробното тяло, [mm]

D – Дълбочина на надреза, [mm]

Табл. 2

Чук 1 (Експериментален модел 300J)			Чук 2 (Проверен чук на Шарпи 30 kgm)		
Номер	Енергия E, [J]	Ударна жилавост K_C , [J/cm ²]	Номер	Енергия E, [J]	Ударна жилавост K_C , [J/cm ²]
1	76.80	96.02	4	77.50	96.27
2	76.20	96.48	5	77.00	96.73
3	77.00	95.79	6	76.75	95.46

Сравнението на резултатите от изпитването на образците показва разлика по – малка от 2%

Заклучение:

Конструирани са специални съставни опори за изпитване на ударно огъване по метода „Чук на Шарпи“.

Конструкцията е изработена и проверена съгласно изискванията на стандартите [1],[2].

Изпитани са 6 тестови образци с V-надрез при стайна температура (20°C) и е проведен сравнителен тест на работоспособността на създадената установка.

Резултатите показват, че установката е напълно работоспособна.

Подобрените опори позволяват ремонт след продължителна експлоатация.

Изработването на опори от две части позволява контакт на пробното тяло по цялото му сечение с работните повърхнини на опорите.

Подобреният контакт води до равномерно симетрично натоварване на опития образец.

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A Deterministic Method for Controlling Out-Of-Plane Distortions by High Power Arc Welding

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Abstract: The Cyber-Physical System (CPS) is one of the main concepts associated to the Industry 4.0 framework. The paper aims at analyzing the futures and architecture and technologies of CPS, retracting it in form its general conceptualization, to the interpretation in high relevant problem of welding manufacturing in context of Industry 4.0. The most recent approaches are based on empirical models or AI and rely on experimental data collection. On the other hand, the actuator shell control a certain parameter or parameter set. Under close consideration of the state of the knowledge to the problem of out-of-plane welding distortions, the aspects related to data sensing and actuating process parameters are analysed. However, due to the intensive development of the welding techniques and machines as well as the increasing focus on lightweight design pose a challenge that enters an unstudied parameter domain. To address this problem, a study was carried out using a combination of experimental and numerical methods. Based on the obtained results, the existing analytical expressions are supplemented and put into discussion. Essential findings, as well as the correlations between the occurring out-of-plane distortions and the welding process conditions and parameters are emphasized. Thus, the level of knowledge and the range of application of the existing analytical models are extended. On this basis, the development of highly effective deterministic-driven CPS in the context of Industry 4.0 is advanced.

KEYWORDS: INDUSTRY 4.0, CYBER-PHYSICAL SYSTEM, WELDING MANUFACTURING, OUT-OF-PLANE WELDING DISTORTIONS, ANALYTICAL MODEL, COMPUTATIONAL WELDING MECHANIC

1. Introduction

In the manufacture of large structures, e.g. constructions, ships, wagons, casks etc., welding plays a key role. One of the main problems in welding is welding distortions in general and in particular out-of-plane distortions. These may lead to dimensional instability and hence require strict control. In case of single or small series production, i.e. when the existing experience by the manufacturer is very limited, the problem of distortions control becomes even more acute.

The occurrence of welding distortions and in particular out-of-plane distortions is a consequence of complex thermomechanical processes, i.e. complex interactions between multiple influencing factors. Furthermore, the mutual relations are characterised by a high degree of non-linearity. It is important to note that, within the context of varying parameter sets, specific influencing factors or interactions may exert a substantial or even negligible effect, see Fig.1. Consequently, the process of control becomes increasingly challenging.

The Cyber-Physical Systems (CPS) have been proposed in context of Industry 4.0 as smart embedded and interconnected systems within production systems [1,2]. They operate at virtual and physical levels interacting with and controlling physical devices, sensing and actuating on the real world [3]. Originally based on the Internet of Things (IoT) [4], the CPS proposes to embed sensors and actuators, i.e. "things", connectivity, in order to allow the collection and exchange of data in order to control the manufacturing processes [5], i.e. to monitor geometric deformation on the physical twin [6] and to actuate and improve the process [7]. However, the crucial question is what data need to be collected and how the actuators shell respond.

The instability of thin-walled structures refers to the change in sign of the bending and angular distortion in flexible welded structures, such as butt joints with low wall thickness. A large number of studies have already been carried out in the literature, taking into account the influencing factors in varying degrees of complexity [8-10]. However, very fast-moving heat sources with high power and structures with very thin wall thicknesses are increasingly being used today in the context of lightweight design, which is penetrating more and more branches of industry. Primarily, the combination of both goes far beyond the range previously covered. Accordingly, negative angular distortion in conjunction with positive deflection is not addressed in the existing works, Fig.1.

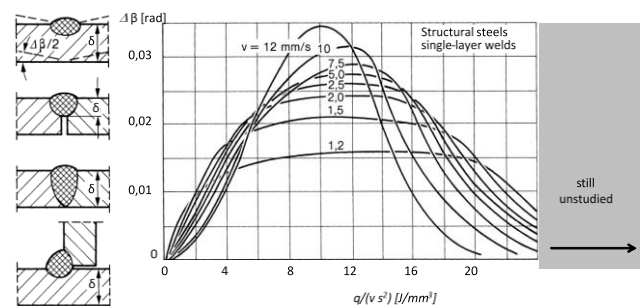


Fig. 1 Dependence of the angular distortion ($\Delta\beta$) on heat input (power q to welding speed v) and the square of the load-bearing thickness (δ) [after 10].

However, the idea of creating a CPS based on stochastic methods, AI and BigData, as proposed in [11], for example, comes up against the complexity of the physical problem and the question of rationality. On the other hand, the extension of the existing state of knowledge is clearly advanced. Therefore, the presented work aims to investigate an out-of-plane distortion problem using experimental-numerical methods and to complement the already existing analytical model. This includes the critical evaluation of the influencing factors and their interactions and the elaboration of a clear relationship in the form of an analytical expression, which can finally help to establish highly effective CPS.

As part of the experimental and numerical investigation of this phenomenon, the dependencies of the qualitative change in bending and angular distortion are to be analyzed. Furthermore, a possibility is sought to capture the instability in an analytical model. For this purpose, the numerically calculated plastic strains in the longitudinal and transverse direction of the seam are evaluated in different positions in the direction of the joint thickness. The primary objective is to investigate the extent to which the known correlations retain their validity for unambiguous quantification of the phenomena occurring.

2. Experimental study

Out-of-plane - bending and angular distortions that qualitatively deviates from the empirical values are already detected in a previous project on a butt joint of dimensions 250/100/1 L/B/H [mm] [12]. The experimental results are confirmed by thermomechanical finite element simulations. The investigations are intensified and the phenomenon of butt joints of double thickness is

analyzed. The line energy per unit length and the welding speed, as well as the thermal boundary conditions are varied according to the previously established dependencies. In addition, two different steels are used.

The geometrical symmetry axes along and across the weld seam in butt welding are also considered as symmetry axes for bending and angular distortion in a good approximation. It is therefore sufficient to document the distortions in the plate thickness direction of a quarter, cf. Figure 2: The deflections can be used to determine the time depending bending and angular distortion in the joining partners for each weld, Figure 3.

In order to determine the bending and angular distortion, the probe attached to the robot is used and the data thus determined compared with each other, Figure 4. The qualitative change in angular distortion is not achieved by increasing energy per unit length. However, all samples welded on the metallic substrate showed a negative bending; always associated with a negative angular distortion.

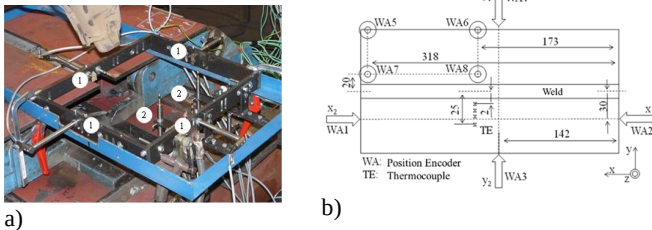


Fig. 2 Experimental set up (a) and positions of the measurements (b)

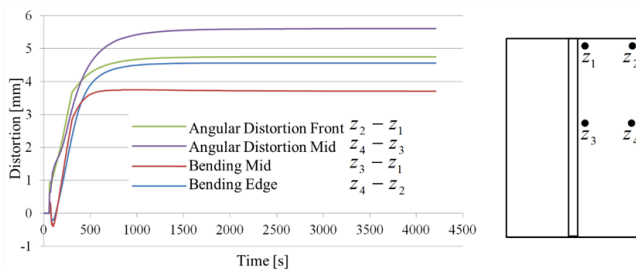


Fig. 3 Time dependant bending and angular distortion at the relevant positions transversal and longitudinal to the weld (exemplary for $q_s = 220 \text{ J/mm}$ and $v = 10 \text{ mm/s}$)

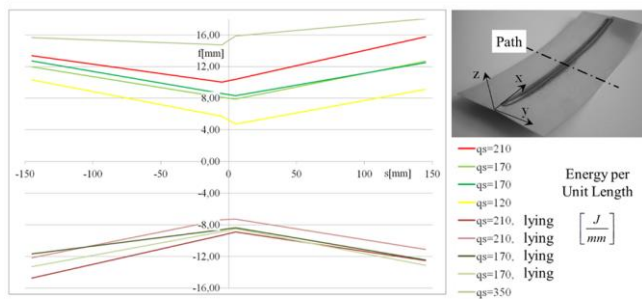


Fig. 4 Bending and angular distortion of 2 mm thick I-joints in dependency on the energy per unit length

Finally, the angular distortions of all experimental studies is compared with the correlations given in the literature, Figure 5. The in plane dimensions of the I-joints were always the same: 150/350 L/B [mm]. However, thickness, welding process and material varied. The 5 mm thick samples of the material S355J2G3 were single-layer plasma beam MAG hybrid welded. Since the two heat sources were very close in time and space, the heat source power is added for the calculation of the cross-section related energy per unit length. The 4 mm thick samples of material X5CrNi18-10 are

provided with a root layer before joining. The resulting deformations have not been documented. Since there was a complete cooling between the root and cover layer, only the heat output of the MAG-welded cover layer are used to calculate the related energy per unit length.

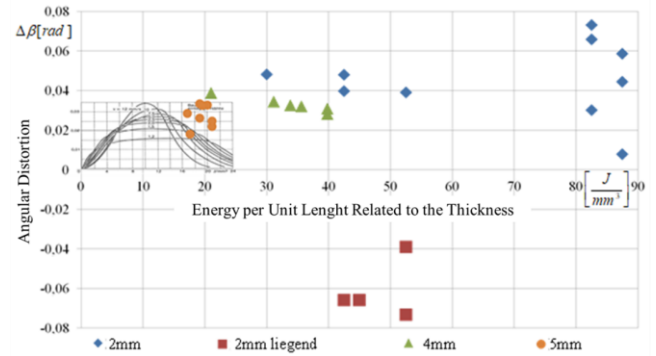


Fig. 5 Results of the measured angular distortions

3. Numerical study

The instability of thin-walled structures is investigated by means of continuous thermomechanical simulations. All relevant thermophysical and thermomechanical material characteristics, as well as the heat exchange with the environment were taken into account temperature depending. In order to calibrate the temperature field, measurements are also made during welding and cooling at different positions across the weld seam and on the top and bottom of the plate. Since the exact causes for the qualitative change of bending and angular distortion are still unclear, the experiments should be mapped as accurately as possible. Accordingly, a close-equalization is also performed by means of cut images, which is normally not taken into account for welding distortion calculations.

For the numerical simulations of the 2 mm thick butt joints, very fine discretized 3D models are created. For each set of parameters, the corresponding seam was modelled, Figure 6. Both the time-dependent temperature curve at different distances in transversal direction to the weld and the maximum temperatures to be derived from it were calibrated using the appropriate experiments, Figure 7-a to Figure 7-c.

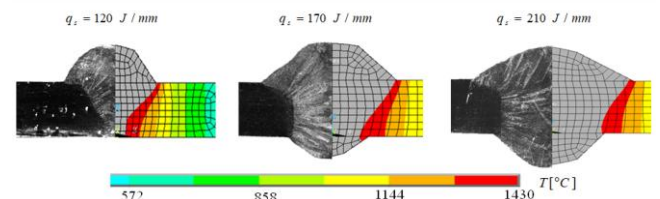


Fig. 6 Comparison of the molten area of the weld with the numerical calculated temperature field

For the calibration of the subsequent mechanical deformation calculation, the thermal expansion coefficient, the yield strength and the modulus of elasticity were varied within a 20% stray band. The in plane deformation as well as the bending and angular distortion measured within the experiments could be calculated quantitatively, Figure 8. However, the out of plane deformations qualitatively incorrect and corresponded in any case to those of the lying plate with forced cooling. Further investigation is needed to clarify the cause.

On butt joints of a thickness of 1 mm, however, the instability has already been demonstrated experimentally and could also be confirmed by means of thermomechanical numerical simulations, Figure 9-b. In this project, the energy per unit length was varied by means of variation of the heat source power and the qualitative

change of the out of plane deformations were also calculated numerically, Figure 9-a.

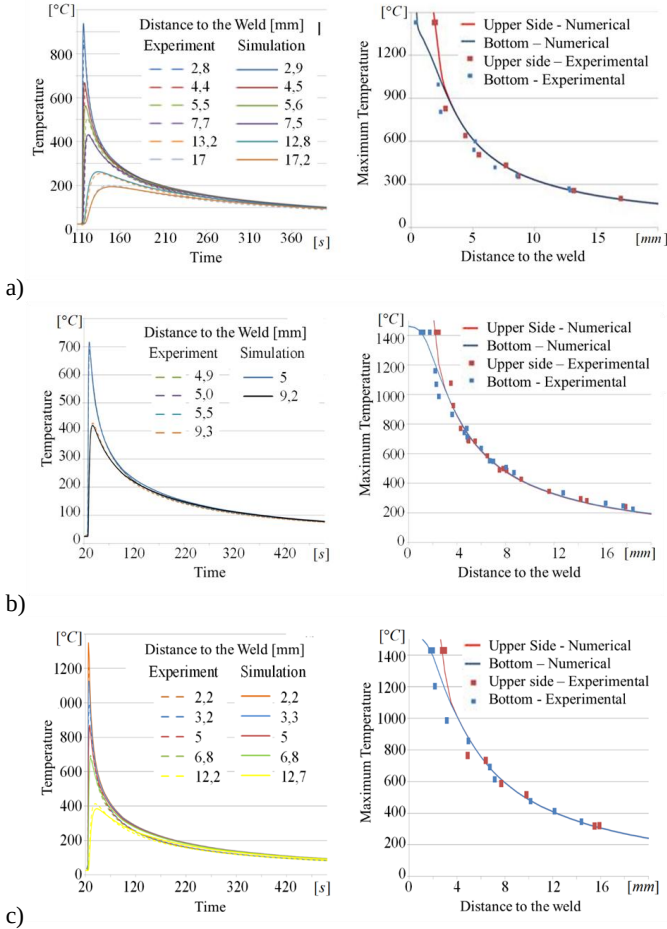


Fig. 7 Time dependent temperature curve in different distances to the weld (left) and maximum temperature distribution at the upper side and the bottom of the plate (right); experiment and numerical calculation; energies per unit length: a) $q_s = 120$ J/mm, b) $q_s = 120$ J/mm and c) $q_s = 210$ J/mm

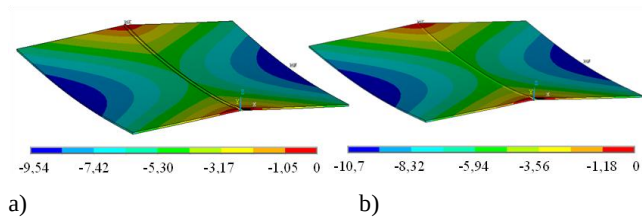


Fig. 8 Numerical calculated out-of-plane distortions, $q_s = 120$ J/mm (a) and $q_s = 170$ J/mm (b)

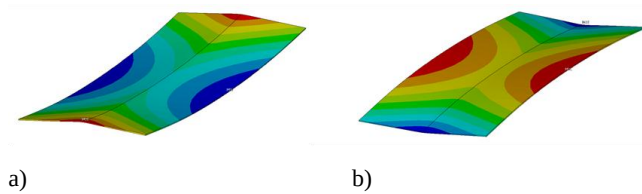


Fig. 9 Numerical calculated out-of-plane distortions: $q_s = 62.5$ J/mm (a) and $q_s = 54.7$ J/mm (b)

According to [10], cf. Figure 1, the angular deflection in MAG welding of structural steels increases with increasing energy per unit length, reaches a maximum and then decreases again. In order to investigate the behaviour in thin-walled structures under these conditions, the energy per unit length was successively increased, starting with a very low but realistic heat input, and the resulting

angular distortion in the center of the plate was evaluated, Figure 10. With higher energies per unit length, the bending and angular distortion increased. As shown in [10], there should be a maximum. However, a subsequent decrease of the out of plane deformations by simultaneously increase of the energy per unit length could not be observed. Bending and angular distortion remain quantitatively the same, but suddenly change their sign.

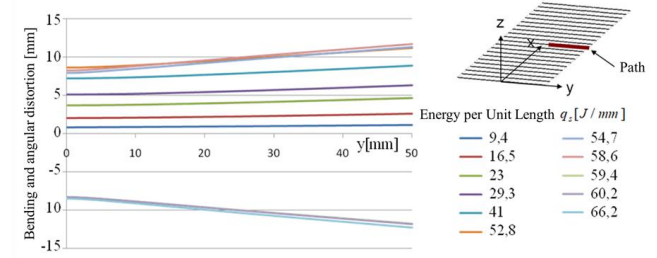


Fig. 10 Bending and angular distortion of thin-walled weld structure in dependency of energy per unit length

The analytical shrinkage force model calculates the plastic strains integrated over the width of the plastic zone and the corresponding points of action in longitudinal and transverse direction of the weld. The evaluation of the numerically calculated strains, Figure 11 to 13, also allows the calculation of the corresponding quantities that the shrinkage force model provides, Table 1. The points of action in both directions are calculated as follows:

$$A_p = \frac{\int_b^{\delta} \varepsilon_o \left(y, z = \frac{\delta}{2} \right) dy - \int_b^{\delta} \varepsilon_U \left(y, z = -\frac{\delta}{2} \right) dy}{\int_b^{\delta} \varepsilon_o \left(y, z = \frac{\delta}{2} \right) dy + \int_b^{\delta} \varepsilon_U \left(y, z = -\frac{\delta}{2} \right) dy} \delta$$

The sum of the plastic strains ε_{pl} is obtained from the mean of the summed plastic strains in the plane of each integration point alongside the thickness:

$$\varepsilon_{pl} = \frac{\int_b^{\delta} \varepsilon \left(y, z = \frac{\delta}{2} \right) dy + \int_b^{\delta} \varepsilon(y, z = 0) dy + \int_b^{\delta} \varepsilon \left(y, z = -\frac{\delta}{2} \right) dy}{3}$$

With increasing energy per unit length, the maximum temperatures and the width of the zone in which plastic deformations occur are increasing too. As a result, the plastic strains increase in longitudinal direction. The calculated points of action in longitudinal direction are very close to the centerline of the cross section. The maximum temperatures can be described with the approach of the line source in a thin plate. The points of actions of the strains in transverse direction are many times larger than those in longitudinal direction and have always an opposite sign compared to the longitudinal strains.

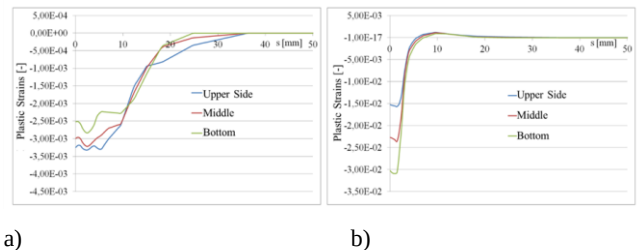


Fig. 11 Plastic strains at upper side, middle and bottom of the plate in longitudinal (a) and transversal direction (b) at energy per unit length $q_s = 47$ J/mm

The evaluation of the plastic strains and their points of action gives first indications about the characteristics of the detection function for thin-walled structures in the analytical shrinkage force model. The origin of the sudden sign change of bending and angular

distortion is not covered. In order to study this phenomenon more closely, the thermomechanical simulations were evaluated at each time step and the temperature field was compared with the out of plane deformations, Figure 14. There is a local bulging behind the heat source, which is also discussed in [9] (Contrary to the results of the numerical calculations presented in this paper, the bulging was detected bevor the heat source). The local bulging occurs at an early point of the welding. With increasing of the energy per unit length the start of the bulging happens earlier. The local bulging of the structure initiates an angular distortion, which is maintained until the complete cooling of the welded joint, see. Figure 10.

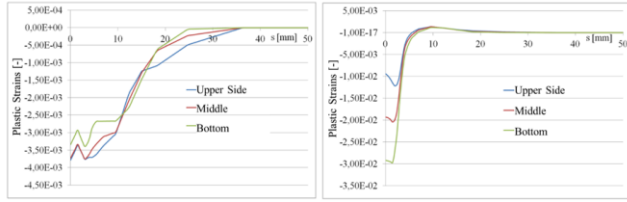


Fig. 12 Plastic strains at upper side, middle and bottom of the plate in longitudinal (a) and transversal direction (b) at energy per unit length $q_s = 55 \text{ J/mm}$

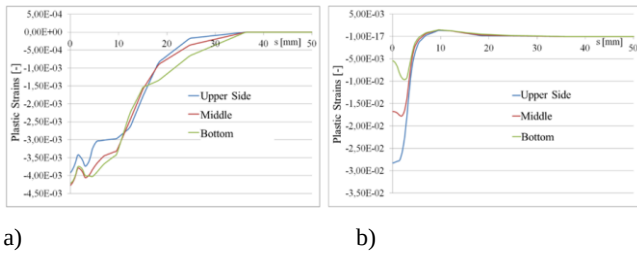


Fig. 13 Plastic strains at upper side, middle and bottom of the plate in longitudinal (a) and transversal direction (b) at energy per unit length $q_s = 62 \text{ J/mm}$

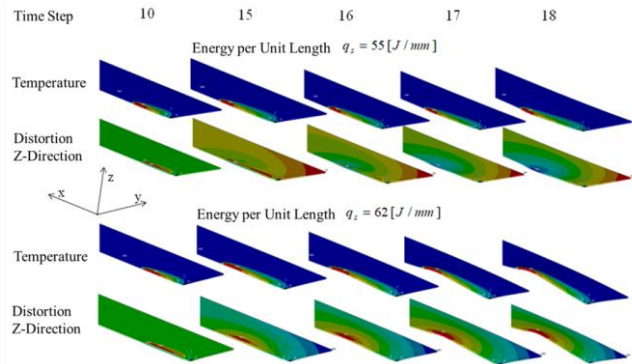


Fig. 14 Local buckling of the butt joint in different directions depending on the energy per unit length

4. Mathematical capturing of the unstable behavior of thin-walled structures in the analytical model

From the extensive thermomechanical simulations, the center of gravity of the plastic strains in longitudinal and transverse direction can be determined, Figure 15. The center of gravity in longitudinal and transversal direction at a specific energy per unit length have always opposite signs. The sums of the strains on the plate top and bottom side in transverse direction have a much higher difference and thus the distance of the center of gravity to the center of the crosssection is much larger than the distance regarding the longitudinal direction. The center of gravity of the plastic

longitudinal strains is, according to the line source in a thin plate, almost zero.

The points of action of the plastic strains in the longitudinal direction obtained by means of the simulations correspond to the known correlations in a very good approximation, Figure 16. Negative center of gravities are the result of the deformations shape of the butt joint. In the stability study of the coupled hybrid model it was found that a sign change at such marginal eccentricities has no influence on bending and angular distortion. The existing correlations are also maintained for thin-walled structures, with the center of gravity z_c for $A_2 \cdot K_{as} \geq 8$, see [10] or [12], that is, for very large energies per unit length related to the cross section, the center of the cross section of the butt weld.

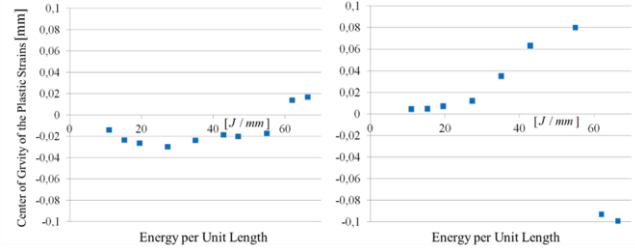


Fig. 15 Center of gravity of the plastic strains in longitudinal (a) and transversal (b) direction; welding of a butt joint of 1 mm thickness

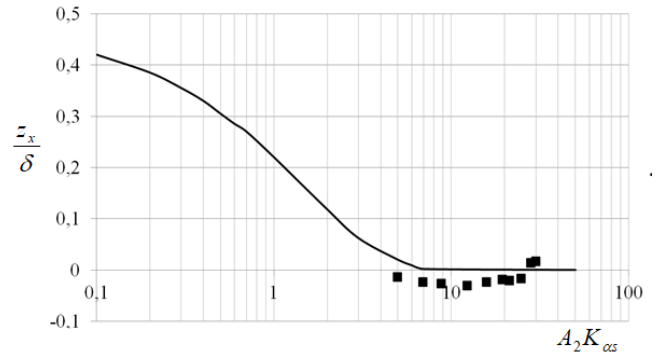


Fig. 16 Local buckling of the butt joint in different directions depending on the energy per unit length

The argument determining the influence of the welding conditions and parameters is given as follows:

$$A_2 = \frac{\alpha}{c \rho \delta} \frac{q_s K_0}{\sum \delta \varepsilon_s}$$

where α is the heat expansion coefficient, c and ρ are the heat capacity and the density respectively, q_s is the heat input (power per unit length), δ is the plate thickness, ε_s is the yield strain and K_{as} is a function of heat transfer conditions and thickness of the welding members, and depends also from A_2 [9].

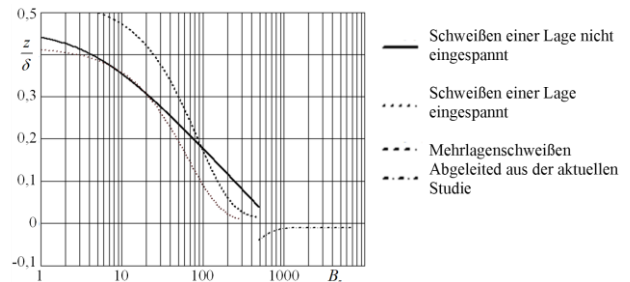


Fig. 17 Point of application of the transverse shrinkage, extended by thin-walled structures as function of B_z parameter

Hereby the parameter B_z consider the mutual influence of the is the heat expansion coefficient α , the heat capacity c and the density

ρ , the heat input q_s , the plate thickness δ , the yield strain ε_F and the functions characterizing the heat dissipation during welding, [9] and is given by the expression:

$$B_z = \frac{100\alpha}{c\rho\varepsilon_F} \psi_0 \eta_0 \frac{q_s}{\delta_{i-1}^2} \left[\frac{\text{kal}}{\text{cm}^3} \right]$$

The distribution of the transverse strains in the plate thickness direction is considerably more inhomogeneous than that of the longitudinal strains. With increasing line energy, it is to be expected that the eccentricity resulting from this inhomogeneity will decrease, cf. 1. However, when investigating the instability of thin-walled structures using calibrated thermomechanical FE simulations, there is an increase in eccentricity, followed by a change of sign, cf. figure 15-a. A continuous transition was not observed.

An inverse procedure by deriving the point of application of the transverse plastic strain from the numerically calculated distortions is possible, Figure 17. However, the numerical investigations of the phenomenon cannot be considered complete. Further investigations are necessary to fully clarify any dependencies on the geometric dimensions of the welded joint, the cooling behavior or other boundary conditions and the exact definition of "thin-walled". Consequently, the user of the coupled analytical model is advised that for $B_z > 500$, i.e. a very high energy input in relation to the sheet thickness, the eccentricity of the transverse strains can have either a positive or negative sign.

5. Conclusions

The instabilities that occur during welding are investigated in order to do meet the increasing use on lightweight construction and the associated growing use of thin-walled constructions. The following dependencies are recorded as part of the comprehensive investigations carried out:

- Angular distortion is a function of the related line energy;
- Angular distortion is dependent on the cooling conditions;
- Positive angular distortion corresponds to negative deflection;
- The sign of the angular distortion is decided at an earlier stage of the weld;
- The change in direction of the angular distortion changes the center of gravity of the plastic strains.

The limits of the analytical model should not be regarded as absolute. By means of further experimental and numerical investigations, any limitation with regard to the application of the model can be remedied.

The knowledge gained provides clear information about the required master data and its connection with the removal of out-of-plane distortions. On this basis, they make it possible to form a digital twin in the form of analytical outputs and to implement it in the context of Industry 4.0 in a practice-relevant CPS for welding process control. This advances the idea of implementing deterministic models in welding production control systems.

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A new type of nail for wooden structures with increased resilience

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Abstract: In the following work, we present the results from a research of a type of nail with a new form of section, in comparison to the round section that currently used nails have. This new form is similar to an equilateral triangle, the sides of which are curves [Reuleaux Triangle]. The body section of this new type of nail has three curves and three edges; his surface SR is with 5.56% larger than the surface SC of a round nail with the same section area. From the experimental research that has been made so far, it was established: (i) because of the larger compaction of the wooden material in the ends of the edges, and of the larger surface, you get a bigger friction force, resulting in a pulling-out force $F_{to,R}$ that is on average twice as bigger as the pulling-out force $F_{to,C}$; (ii) because that the new form of nail has edges, this leads to bigger resistance during the rotating of the joined wooden elements one against another – the moment M_r is on average 60% bigger than the one with elements, joined with a normal nail. These advantages, as well as the use of the existing technology and machines for the production of nails without having to effect any major changes, create the conditions for the application of the new type of nail in construction, furniture production and in the everyday life, for an output of products with larger resistance to external forces. This effect will be especially useful for increasing the residential buildings' resilience during earthquakes, hurricanes and other natural disasters.

KEYWORDS: NAILS, REULEAUX TRIANGLE, WOODEN STRUCTURES

1. Introduction

The production of nails worldwide is one of greatest in fabricated metal products: reinforcing bars – 400 million tons, sheet metal – 240 million tons, pipes – 60 million tons nails, and screws – 32 million tons in 2014 [1]. Nails are used for connecting elements of wooden constructions; the largest quantities are used for wooden-frame houses. The average wooden-frame house uses require between 20,000 and 30,000 nails of various types and sizes [2]. Earthquakes or hurricanes are considered as extreme conditions for those structures. A variety of nails is available for wooden structures, which are to be under heavy loading conditions – Fig. 1 [3], [4], [5].

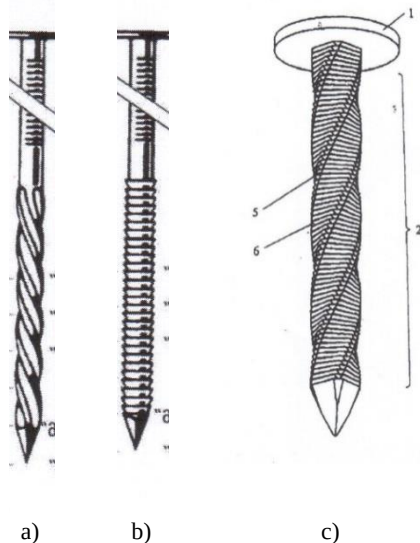


Fig.1. Design of nails for heavy loading wooden structures: a - with rolled rings; b - with rolled screw channels; c - with screw canals and rings: 1- nail head, 2 - nail body, 3 - screw cylindrical surface, 4 - linear rings

Most of these nails have a number of advantages, compared to conventional nails, but they are difficult to be manufactured in the existing automatic machines for nails and have a higher price.

The new type of nail [10] has a section, known as the Reuleaux Triangle. This geometrical figure has a shape, formed from the intersection of three circles, each having its center at the vertex of a triangle

– Fig. 2. The radius R is equal to the length of the triangle's side. In Fig. 2 we see that the Reuleaux Triangle includes three curves and three edges. The Reuleaux Triangle can be seen as a closed convex curve of constant width. This is a type of curves which, when rotated in a square, make contact with all four sides [6]. The

other definition is that of “curves of constant width that have the same “width” regardless of their orientation between the parallel lines” [7]. The surface – that is the curve with the largest area – also belongs to this type, while the Reuleaux Triangle is the closed curve with the smallest area, but with the same perimeter.

The more important qualities of the Triangle are:

- Its radius $R = 2,112r$, where r is the radius of a circle with the same area.
- With the same area, the perimeter of the Reuleaux Triangle PR is 5.56% larger than the perimeter PC of the given circle.

The second moment of area I and the elastic section modulus S , when you have a circular section, are the same as regard to a coordinate system, passing through the center of gravity in the circle, therefore with a circle $I_{x,c} = I_{y,c}$, $S_{x,c} = S_{y,c}$. With the Reuleaux Triangle $I_{x,R} = I_{y,R}$, $S_{x,R} \neq S_{y,R}$ as regards to a coordinate system, passing through the section's center of gravity. In agreement with the definition for S [8], [9] from Fig. 2b we can see that with the Triangle there are two elastic section modulus $S_{R,y1}$ ($S_{R,y1}$, $S_{R,y2}$) and one elastic section modulus $S_{R,x}$:

$$S_{R,y1} = I_{y1}/b; \quad S_{R,y2} = I_{y2}/a; \quad S_{R,x} = I_{x}/0.5R \quad (1)$$

By looking at the geometric proportions in an equilateral triangle it can be determined that $a = 0.577R$, $b = 0.423R$ and (1) becomes:

$$S_{R,y1} = I_{y1}/0.423R; \quad S_{R,y2} = I_{y2}/0.577R; \quad S_{R,x} = I_{x}/0.5R \quad (2)$$

where [6]

$$I_{x,y} = I_{y,x} = 1/48(10\pi - 17\sqrt{3})R^4 \quad (3)$$

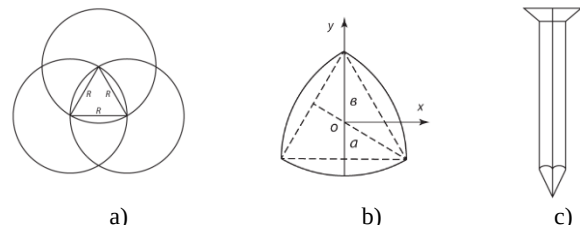


Fig. 2. a – a Reuleaux Triangle; b – a scheme for determining the elastic section modulus S ; c – a nail with a Reuleaux Triangle section

Here we present the results from our comparative experimental research for determining the maximal forces and moments, which impact wooden structures, the elements of which are to be joined with a nail with a round section, or a section of the Reuleaux Triangle type.

2. Methodics

A round section nail with the following characteristics: radius $RC = 3.5$ mm, length $LC = 190$ mm, area of the counter-section $A = 38.46$ mm², perimeter $PC = 21.98$ mm, was used in the experiments. The nail with the Reuleaux Triangle section, was with the same area A , radius $RR = 7.392$ mm, length of the section portion $LR = 85$ mm (the length of the entire round section nail is 145 mm), perimeter $PR = 23.2$ mm – Fig. 3; his edges were rounded with radius $R = 0.5$ mm. There have been made 10 such nails, with the Reuleaux Triangle section portion been made on a filament erosion machine.

In Table 1. are given the values of the second moment of area I and the elastic section modulus S for the two types of nails.

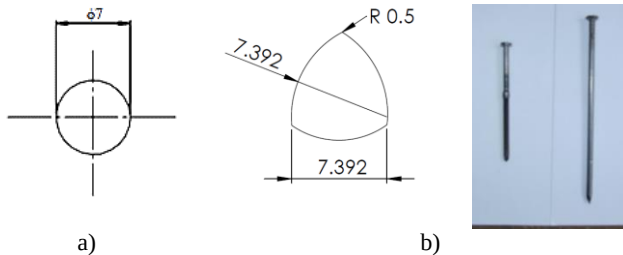


Fig. 3. Comparison of the ordinary and the new nails: a – comparison of the cross-section dimensions; b – view of the used nails with the new shape and $\phi 7$

Table 1. Value of I and S for ordinary and new nails

Section	I_x, mm^4	I_y, mm^4	$S_{y,1}, \text{mm}^3$	$S_{y,2}, \text{mm}^3$	S_x, mm^3
Circle	117.8	117.8	33.65	-	33.65
Relo	122.54	122.54	39.19	28.73	33.15

There were two types of experiments.

2.1 Experiments for determination of the take-out force P_{10}

In that case wooden elements (beams) made out of dry coniferous wood with sizes (length x height x width): 150 mm x 60 mm x 48 mm. We drive in them nails of the two types so that the top of the nail comes out of the other side of the wooden element. After that the nail is taken-out. A mechanical testing machine Instron1195 was used, allowing to mark-down the diagram moving – force when we drive and take-out the nails. From these diagrams we calculate the maximum force of the driving in and the removal. We drilled, in advance, holes with 3 mm diameter in the wooden elements, to assure the driving was to be done easily, and without unnecessary force that would possibly lead to the deformation of the nails. There were 10 experiments held with each of the two types of nails.

2.2 Experiments for determination of the torque M_r

In this case, wooden slats with dimensions (thickness x length x width) 30 mm x 200 mm x 65 mm from dry coniferous wood were used. Two slats are connected to each other with a nail at a 90° angle. The resulting wooden structure was tested in rotation under two types of load: when an external force acts simultaneously on the two slats - Fig. 4.; when an external force acts on only one slat - Fig. 5. The maximum moment at which the structure becomes inefficient (the slats are rotated relative to each other) is denoted with M_r and respectively. Using the calculation schemes for these moments shown in Fig. 3c and Fig. 4c is obtained:

$$M_r^{two} = 2 \times 0.2 \times 0.3543F, \text{ Nm} \quad (4)$$

$$M_r^{one} = 0.155F, \text{ Nm}$$

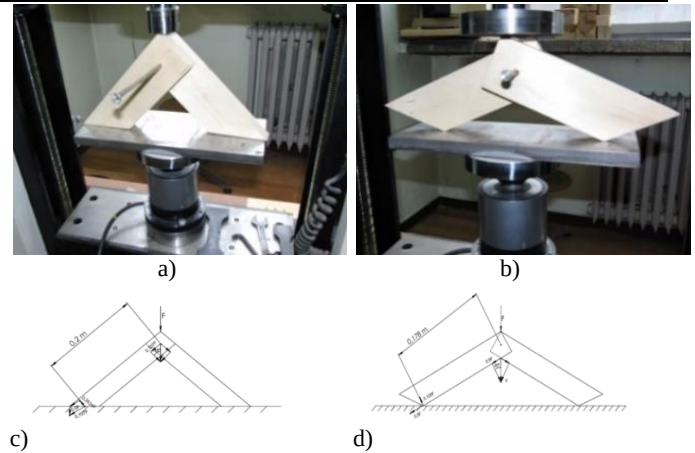


Fig.4. Pictures of tested wooden structure when force acts simultaneously on the two slats: a – in the beginning; b – during the experiment; c, d – scheme to determine the moment

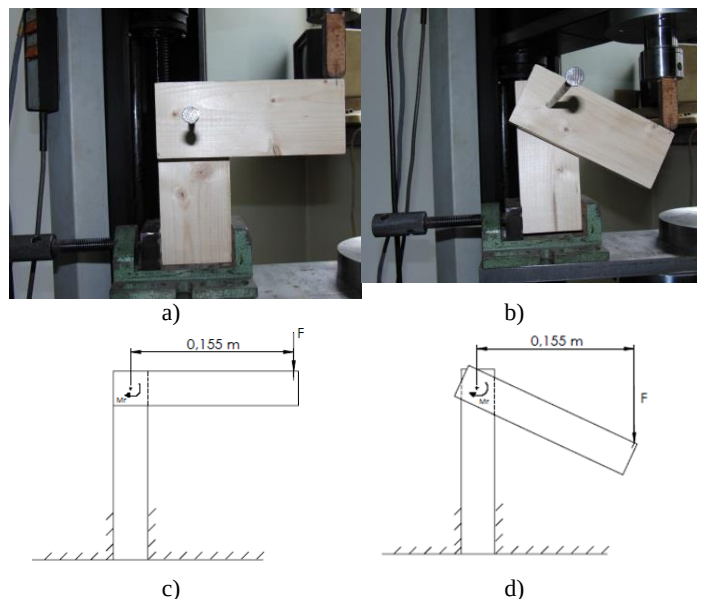


Fig.5. Pictures of tested wooden structure when force acts on one slat: a – in the beginning; b – during the experiment; c, d – scheme for determine of torque

3. Results

3.1 Determination of the driven and take-out forces

The driving of the nails is at a speed of 10 mm / min, and the removal of them is at a speed of 20 mm / min. The obtained values of the forces of driving F_d and take-out F_{10} are given in Table 2.

Table 2. Driven in and take-out forces

Type	Driven force F_d , N	Take out force F_{10} , N
Circle cross-section	3728	2453
	3267	2158
	3482	1864
	3709	2394
	2943	2551
	3434	2048
	3744	2366
	3160	2370
	3460	2483
	3420	2644
Average	3435	2333
Rele Triangle	4513	5494
	4218	4513
	4120	5297

cross-section	4120	5240
	4120	4905
	4218	5248
	4194	4463
	4124	4562
	4158	4470
	4262	5274
Average	4205	4947

3.2. Determination of the moment M_r

When connecting the wooden slats, the nails were driven in at a speed of 10 mm / min. The speed of movement of the contact element in the torque test M_r was 5 mm / min. The results are shown in Table 3. Due to the small differences in the values of the moments in the individual experiments, in Table 3 only their average values are given.

Table 3. Average values of M_r^{two} and M_r^{one}

Crosssection	M_r^{two} , Nm	M_r^{one} , Nm
Circle	20.83	7.6
Releaux Triangle	34.72	15.2

4. Conclusions

From Table 1 it can be seen that the resistance against elastic bending of a nail with a section of the Reuleaux Triangle depends on the application point of the external force. Fig. 6 shows the forces F_1 , F_2 and F_3 , which are used to determine the elastic section modulus S . The difference in the magnitude of these forces gives us grounds for the following conclusion:

- When it is necessary to achieve maximum resistance against elastic bending of a nail with a Reuleaux Triangle section, when driving the nail it must be oriented so that the external force acts in the direction of the force F_1 from Fig. 6. This means that, when using the new nail, an oriented driving can be performed according to the location of the edges on its stem. Oriented driving is a unique quality of the new nails, which will lead to drastic changes in the integration of wooden structures.

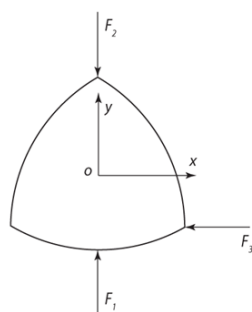


Fig. 6. A scheme of the forces, acting upon a section of a Reuleaux Triangle nail, when determining the elastic section modulus S : $F_1 > F_3 > F_2$

From Table 2. we can calculate the difference between the average forces of driving and removing a nail with a round section and with the Reuleaux Triangle one:

When driving a nail with a section of Rele's Triangle, the force $F_{d,R} = 1.24F_{d,C}$.

When removing a nail with a section of the Rele Triangle, the force $F_{to,R} = 2.12F_{to,C}$.

This means that wooden structures, whose elements are joined with nails with a Reuleaux Triangle section, will have twice as much resistance to destruction as those, joined with ordinary nails, when the wooden structures are subjected to superior destructive forces. This result can be explained by the following effects, which occur when driving and taking-out a nail with a Reuleaux Triangle section: (i) in the ends of the edges of the nail you get a compaction of the wooden material, which increases the coefficient of friction and the friction force in these areas along the length of the nail; (ii)

the larger perimeter determines a larger area of the surrounding surface of the nail body and hence a greater friction force on this surface than the friction force arising on the surrounding surface of a nail with circular section.

From Table 3. it can be determined:

When an external force acts simultaneously on two elements of a wooden structure, the maximum moment at which the elements will not rotate relative to each other is $M_{(r,R)}^{two} = 1.66 M_{(r,C)}^{two}$.

When an external force acts on an element of a wooden structure, the maximum moment at which the elements will not rotate relative to each other is $M_{(r,R)}^{one} = 2M_{(r,C)}^{one}$. This means that wooden structures, whose elements are connected with a nail with a Reuleaux Triangle section will have between 1.66 and 2 times more resistance to destruction than those, connected with ordinary nails, when forces, which strive to rotate the wooden elements relative to each other, act on them. This result is due to the presence of three longitudinal edges on the body of the nail with a Reuleaux Triangle section.

The presented results were obtained by using one nail of each type to connect the wooden elements. When using N number of nails, the effects of applying a nail with a section of the Rele Triangle will increase in proportion to N , when building wooden structures. In this way, greater resistance of wooden structures can be achieved, both in conditions of static external forces (furniture) and in dynamic forces (hurricanes, earthquakes, floods).

An important feature that can help the wide application of the new type of nails is that for its production the same materials, machines and technologies are used, which are used for the production of nails with round section.

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Current trends in HRM in the era of Industry 4.0: challenges and opportunities of using artificial intelligence

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Abstract: The article provides an insight into the analysis of trends in contemporary HR in the era of Industry 4.0, with an emphasis on the role of artificial intelligence (AI) in managers' decision-making processes. The study addresses the opportunities and threats associated with the implementation of AI within HR and its impact on organizational effectiveness and human resource management. Using secondary data analysis and literature synthesis, we offer a deeper insight into modern HR management approaches and discuss the potential risks associated with digital transformation. The aim of the study is to provide practical recommendations for managers on how to deal with the challenges of the current Industry 4.0 era.

Keywords: INDUSTRY 4.0, ARTIFICIAL INTELLIGENCE, TRENDS IN MANAGEMENT, DIGITAL TRANSFORMATION, MANAGERIAL DECISION-MAKING, HUMAN RESOURCE MANAGEMENT

1. Introduction

In this study, we address the opportunities and threats associated with the implementation of artificial intelligence within HR and its impact on organizational effectiveness and human resource management. Using secondary data analysis and literature synthesis, we offer a deeper insight into modern HR management approaches and discuss the potential risks associated with digital transformation. The aim of the study is to provide practical recommendations for managers on how to deal with the challenges of the current Industry 4.0 era.

Today's world is changing under the impact of the technological transformation known as the Fourth Industrial Revolution. This brings technologies such as industrial robotics, Artificial Intelligence (AI), Internet of Things (IoT) Cloud Computing or Big Data Analytics (BDA). The technologies of the fourth revolution are universal and disruptive. They have the potential to transform industrial organisation, innovation and value creation. This is why they tend to change the regional economic environment [19, 13]. Industry 4.0 is defined as the introduction of new technologies into production processes and supply chains as part of the fourth industrial revolution. New technologies are introduced into the process that collectively change current production processes and offer customers and organisations products and services with greater added value [6]. Industry 4.0 was already established in 2011 as a project within the German government's high-tech strategy. According to Xun Xu (2021), it is: "intelligent networking of machines and processes for the industry based on CPS – a technology that achieves intelligent control using embedded networked systems" [24].

Industry 4.0 is an era that integrates modern technology and innovation. Artificial intelligence is an essential part of this transformation. It enables intelligent machines to perform autonomous tasks such as self-monitoring, diagnostics or analysis. AI therefore integrates technologies that enable software, systems and machines to perceive, understand, evolve and learn based on their own experience or augment human activity. Everyday advances in this technology are progressing along with Industry 4.0 [2]. Human resources and corporate management plays a vital role in filling the gap between technology and human capital. Although technology has the capability to take over most human tasks, there is a constant need for flexible human capital functions to address the challenges of managing people [15].

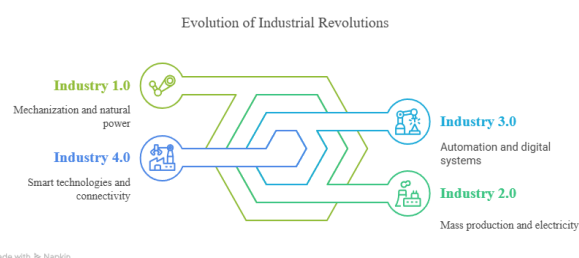


Figure 1 Four Industrial revolutions

2. Methods

The article follows the five-step process for developing a systematic literature review adopted by Senyo et al. (2019): (1) defining criteria for inclusion and exclusion of literature, (2) reviewing the literature, (3) refining the literature, (4) analyzing the selected literature, and (5) presenting the findings [20, 23]. The process allowed us to extract key information from the available scientific literature and identify similarities and differences between it. Based on the literature review, we formulated the research question: "How is artificial intelligence changing current HR management approaches and what are the main challenges and opportunities"? We complemented the systematic literature review with statistical data related to the issue through relevant sources such as Statista, Eurostat, WHO reports or OECD data.

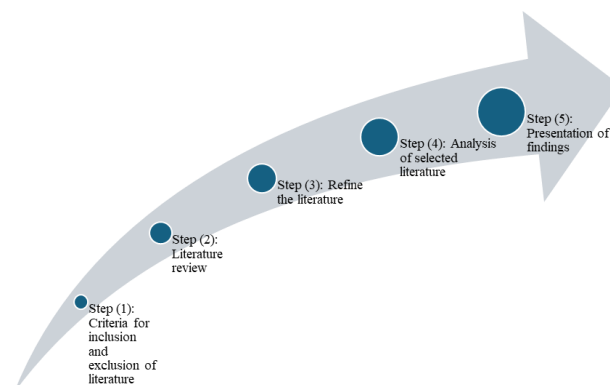


Figure 2 Five-step process for creating a systematic literature review

Source: own elaboration, according to Senyo et al. (2019), Doi: <https://doi.org/10.1016/j.ijinfomgt.2019.01.002>

A systematic literature review was conducted by reviewing scientific databases such as WoS or Scopus. In particular, the criteria for selecting the literature was the publication date between 2019 and 2025 to ensure the timeliness of the available data. We

focused on studies thematically related to the impact of AI on the field of management and human resource management, especially systematic reviews, meta-analyses and empirical studies.

To complement the literature, we analyzed statistical secondary data from reputable databases. The data we focused on reflected the level of automation, the adoption of AI in HR, the impact of AI on jobs and digital maturity.

As part of the thematic analysis, we identified several key research areas, which are illustrated in the figure below:



Figure 3 Research areas
Source: own elaboration

3. Research results

The following tables provide an overview of the sources and relevant literature related to two chosen areas of investigation (1) The role of artificial intelligence in HR management, (2) Trends in contemporary management in the era of Industry 4.0, and (3) Opportunities and threats to the adoption of AI in the field of human resources. The tables are divided separately and respond separately to the issues under investigation. From the key information for each area, we have created a discussion and output of our paper.

Table 1 Review of the research results first study area

Author, author's collective	The role of artificial intelligence in HR management
Keshavi, V.C., 2024	Task automation, data-driven decision making in recruitment - CV analysis, profiles, historical data
Aini, Q. et al., 2024	Improving quality in recruitment, increasing efficiency in performance appraisal and staff development
Bharadwaj, V., 2024	Changing traditional HR processes - recruiting, onboarding, performance reviews, training, automation, improved decision making, supporting diversity and inclusion, workforce planning, predictive analytics
Kaur, R., 2024	Automation of routine and administrative tasks (recruitment, onboarding, document management), recruitment improvement (chatbots, ATS, video analysis,...), personalisation, real-time performance evaluation, change of HR role from administrative to strategic
Ali, A. & Rafi, N., 2024	Process automation, machine learning, predictive analytics, predicting talent needs, improving areas such as employee retention, engagement and performance management, diversity and inclusion

Source: own elaboration

Artificial intelligence is having a significant impact on the way companies manage human resources (HRM). In particular, AI technologies increase efficiency in the recruitment process, performance appraisal as well as in the actual work activities [9, 5]. Through AI, greater efficiency is achieved in administrative tasks, data-driven decision making, and likewise provides data-driven knowledge support for optimizing human capital management [3, 21]. On the other hand, the integration of AI into HRM brings challenges such as ethical issues, data security and potential algorithmic biases [3, 9]. To eliminate these challenges, companies need to implement elevated policies, maintain human oversight, and ensure transparent AI-driven processes [5].

In the following figure, we can observe the percentage of companies using AI in EU member countries:

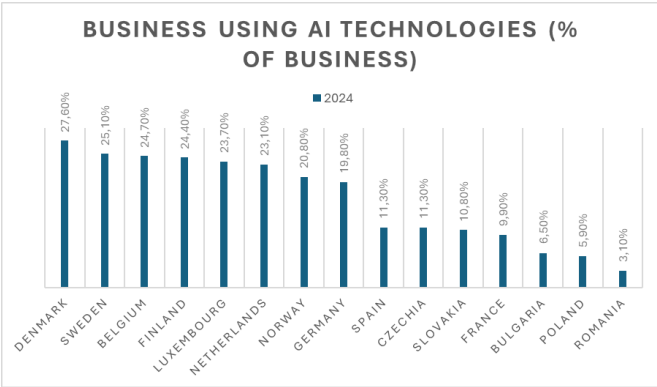


Figure 4 Business using AI technologies
Source: own elaboration, According to Eurostat (2024), Available at: [Digitalisation dashboard](#)

The highest proportion of companies implementing AI in their processes was recorded in Denmark (27.6%), where the largest number of companies use these technologies. On the other side of the ranking is Romania (3.1%), which recorded the lowest number of companies using AI in their processes. From the data, we can conclude that there are significant regional differences in the adoption of AI, with Northern European countries being significantly ahead in this respect compared to some Eastern EU countries.

Table 2 Review of the research results second study area

Author, author's collective	Trends in contemporary management in the era of Industry 4.0
Panicker, R.K., & Anusha, M.N., 2024	Digitalization and automation, IoT, smart factories, Artificial Intelligence (prediction, computer vision, machine learning), Big Data, simulations, autonomous robots
Hall, S. & Elshennawy, A., 2024	Collaborative and team-oriented leadership, technology and digital leaders, autonomy, digital literacy, IoT, Big Data, AI
Vraňaková, N. & Babel'ová, Z.G., 2024	Changing requirements for employee skills (specialised, flexible), complex employer-employee relationship, training as a priority and motivation
Dahinwal, J. et al., 2023	Robotics, Big Data analysis (analysis of large data sets), IoT, Cloud Computing, from traditional HRM to strategic HRM, new leadership, upskilling/reskilling, new job roles (AI, machine learning,...)
Adel, R. 2024	Digitalisation, real-time monitoring, intelligent decision-making, intelligent management systems, collaborative and sustainable ecosystems, intelligent organisations

Source: own elaboration

Nowadays, companies are increasingly implementing AI into their processes, making it possible to make intelligent decisions and use real-time tracking systems [17, 1]. Moving towards data-driven management enables improved performance metrics and better response to dynamic changes in the market [18]. Collaborative and sustainable company ecosystems support the implementation of these innovations and the adaptability of teams [1]. Digital skills of employees play an important role in this, with Eurostat (2023) reporting that the largest share of the population aged 16-74 in the Netherlands (82.7%) has at least basic digital skills, while the lowest share was recorded in Romania (27.7%), as shown in the figure below.

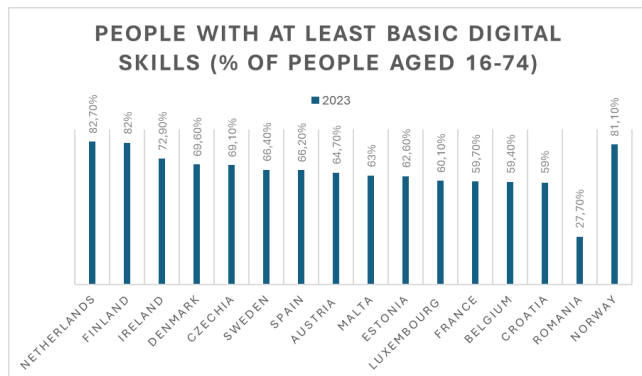


Figure 5 People with at least basic digital skills

Source: own elaboration, According to Eurostat (2023), Available at: [Digitalisation dashboard](#)

These visible differences can affect the speed and success of AI implementation in organisations, in EU countries.

Leaders need to adapt to the new era as well. They need to be collaborative and team-oriented. They are required to have a combination of technological prowess and HRM skills [8]. There is a shift from the traditional understanding of roles to self-managing employees, which requires the need for new competencies and the ability to adapt to technological innovations [22].

Table 3 Review of the research results third study area

Author, author's collective	Opportunities and threats of implementing AI in HR
Zawada, M., 2024	Automation, predictive analytics, increased productivity, supplementing human work, not replacing it Ethical issues and bias, loss of jobs, reduction of the human element
Konovalova, V. et al., 2022	Increase efficiency, productivity and objectivity, personalize HR processes, improve communication, promote inclusion Dehumanization of HR processes, ethical and legislative problems, algorithmic bias, low readiness of HR departments, privacy threats
Madancian, M. & Taherdoost, H., 2024	Streamlining HRM processes (recruitment, onboarding, performance evaluation,...), better decision making, increased work productivity Ethical challenges, threats to the human element in HR, bias, privacy
Yuling & Shan, L., 2025	Streamlining recruitment, improving employee training and development, performance data collection and analysis, competitive advantage (strategic HR planning) Changing work processes from

	traditional HR, ethical and legislative challenges, skills gap, data protection
Naidu Mandala, G. et al., 2025	Automation of HR processes, predictive analytics (turnover, performance,...), increased employee engagement (chatbots, feedback), personalized learning, increased diversity and inclusion Ethical issues, data dependency, privacy, technology readiness, professional readiness

Source: own elaboration

AI in HRM brings many opportunities. It improves recruitment through data analytics and better matching of candidates [26, 25]. It also enables the provision of personalized employee development by creating customized training [12]. Last but not least, it enables predictive analytics for workforce planning [14, 25].

However, the integration of AI into HRM also brings challenges such as ethical issues, data security, and potential algorithmic biases [3, 9]. Ethical issues in recruitment in terms of recruitment bias and performance appraisal issues [26, 14]. Similarly, the overuse of AI technologies can cause dehumanization of HR processes [12, 14].

According to a 2024 survey by Paychex, Inc. titled "Balancing Tech and Touch in Human Resources," based on responses from 325 HR professionals from organizations with 20 or more employees, employees using AI at work save up to one full workday (7.5 hours) per week. The survey also revealed that more than half of respondents (56%) consider AI to be a tool that speeds up recruiting and employee screening, as shown in the chart below.

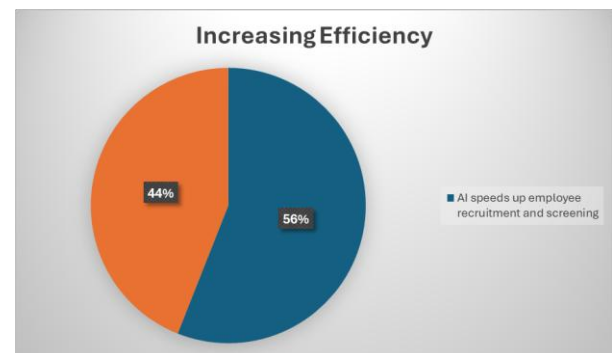


Figure 6 Increasing Efficiency

Source: own elaboration, According to Paychex, Inc. (2024), Available at: [39% of Employees Believe Current Level of AI Involvement in HR Processes is Appropriate; 20% Prefer More](#)

4. Discussion

AI is having a profound impact on human resource management. Keshavi (2024) emphasizes task automation and data-driven decision making [11]. Aini et al, (2024) appeal that AI implementation can improve the quality of the recruitment process and increase the effectiveness of employee performance appraisals [3]. Bharadwaj, (2024) and Kaur, (2024) argue that traditional HRM processes such as recruitment, onboarding, performance appraisal, and training are currently undergoing a change through automation and AI implementation, emphasizing improved decision making based on data analytics [5, 10]. Ali & Rafi (2024) add that AI improves areas such as employee retention, engagement and commitment [4].

On the other hand, integrating AI into the HRM process brings challenges in the form of ethical issues, data security and potential algorithmic biases, which are issues that need to be covered [3, 9]. In the context of Industry 4.0, Panicker & Anusha (2024) and Adel (2023) particularly highlight the application of digitization and automation within organizations, enabling intelligent decision making based on big data analytics and real-time tracking [17, 1].

However, there is also a need for increasing the level of technology skills for employees, as well as for HRM leaders, for the successful introduction and adoption of new technologies [8].

With the advent of new technologies and AI, Zawada (2024) and Konovalova et al. (2022) discuss the potential opportunities and threats of their adoption in HRM [26, 12]. Through data analytics, AI improves recruitment and enables personalised development of employees, according to individual needs, but on the other hand, ethical issues, data protection and potential dehumanisation of HR processes emerge.

5. Conclusion

AI is transforming HRM by improving the efficiency of some HR functions, particularly in the areas of recruitment, performance appraisals, administrative tasks, and employee screening. AI technologies support diversity, inclusion and data-driven decision making. On the other hand, they bring challenges such as ethical issues or data security. Regional differences in the adoption of AI suggest that Northern European countries are well ahead in this respect. Overall, AI contributes to better HRM but requires the implementation of policies and human oversight.

6. Acknowledgement

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Critical assessment of some applications of artificial intelligence

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Abstract: Artificial intelligence applications are rapidly entering many aspects of business, state administration and education with the aim of increasing productivity and efficiency. The report examines the possibilities for implementing artificial intelligence in their activities and the related ethical and legal aspects, as well as the risks. A review and analysis of some applications of AI is made.

Keywords: ARTIFICIAL INTELLIGENCE APPLICATIONS, BUSINESS, STATE ADMINISTRATION, EDUCATION

1. Introduction

Mathematical problem solving is a crucial aspect of contemporary society, and artificial intelligence (AI)-driven mathematical reasoning has become integral to data analysis. The recent literature review examines the many datasets used to enhance the ability of AI models to address mathematical word problems. These datasets offered a variety of problem sets and functioned as benchmarks for assessing the performance of several deep learning models, including recurrent neural networks (RNNs) and graph-based models. Datasets like GSM8K presented problems that even the most advanced transformer models found difficult to surmount, establishing a new benchmark for the examination of AI systems in mathematical problem-solving, [1].

In January 2025, TechTarget published an article “25 of the best large language models in 2025“, [2]. In his blog Anthony Cardillo, [3], discusses 44 Large Language Models (LLM). Both authors cover ChatGPT, Perplexity, Gemini, and DeepSeek as some of the best Generative Pre-trained Transformers AI language models. Our experience shows that these LLMs are, maybe, the most popular among students and researchers in Bulgaria. INSAIT claims their LLM product BgGPT is unique and based on the Bulgarian language.

ChatGPT by OpenAI is known for its versatility in generating human-like text, engaging in conversations, and assisting with tasks like writing, coding, and brainstorming. It generally has a user-friendly interface. However, its knowledge is based on its last training data cutoff, so it may not always have the most current information without integrated web Browse features (which are available in some versions). Accuracy can vary, and it sometimes generates plausible-sounding but incorrect or nonsensical information.

Perplexity AI is designed with a focus on providing accurate, up-to-date information by citing sources from the web. This makes it strong for research and fact-checking. Its interface is often described as a hybrid of a search engine and a chatbot. While it excels at information retrieval and providing sourced answers, it might be less geared towards creative writing or extended, open-ended conversations compared to models like ChatGPT.

Gemini 2.0+ (often referred to as Gemini) by Google is a multimodal AI model, meaning it can understand and process information from various formats like text, code, images, and sometimes audio/video. It aims for strong reasoning capabilities and creative content generation. As a Google product, it often integrates well with other Google services. User experience can vary depending on the specific application or interface being used (e.g., a standalone app, integrated into a search).

BgGPT is a Bulgarian-first large language model developed by INSAIT. It is based on Google's Gemma models and has been specifically fine-tuned for the Bulgarian language, demonstrating strong performance in Bulgarian while retaining competitive English capabilities. Its primary audience is Bulgarian-speaking users and developers. The user interface is a chat platform, and it aims to understand Bulgarian cultural nuances.

DeepSeek is an open-source model, often highlighted for its strong performance in coding and technical tasks, as well as its cost-

effectiveness (being free and open-source). It supports a high context length and performs well in both English and Chinese. Users find it efficient for tasks requiring logical reasoning and structured problem-solving. However, it might be less optimized for creative content generation or general conversation compared to some other models, and some reviews have noted potential concerns regarding data privacy given its origin.

Finding direct comparative scientific articles for all five specific free versions from a user-experience viewpoint is challenging, as academic research often focuses on benchmark performance of base models, specific capabilities (like reasoning or bias), or the underlying technology. User experience is also more commonly discussed in tech reviews and user forums.

To solve this problem Gemini 2.5 Pro was prompted:

“Can you provide a comparison of five free Generative Pre-trained Transformers AI language models ChatGPT, Perplexity, Gemini 2.0+, BgGPT (<https://bggpt.ai>), and DeepSeek from a user's viewpoint? Please summarize the results in a table. Please provide scientific articles as references.”

Gemini 2.5 Pro was selected for the task due to its capabilities to use Google Search and Google Scholar in particular. The answer is summarized as follows:

ChatGPT (Free Version) [4]

- (1) Primary Strength: Versatile conversation & content generation
- (2) Ease of Use: Very high; intuitive chat interface
- (3) Accuracy: Variable; can "hallucinate"
- (4) Creativity: High
- (5) Coding Ability: Good
- (6) Up-to-date Information: Limited to training data (unless browses)
- (7) Multimodality: Primarily text (some versions may have image input)
- (8) Speed: Generally fast
- (9) Customization/Control: Limited in free version
- (10) Key User Focus: General assistance, writing, brainstorming
- (11) Potential Limitations: Can be verbose, potential for inaccuracies, knowledge cutoff

Perplexity AI (Free Version) [5]

- (1) Primary Strength: Accurate, sourced information retrieval
- (2) Ease of Use: High: search-like interface
- (3) Accuracy: Generally high: cites sources
- (4) Creativity: Moderate
- (5) Coding Ability: Limited (focus is on information)
- (6) Up-to-date Information: Yes, actively searches the web
- (7) Multimodality: Primarily text: can analyze uploaded files
- (8) Speed: Fast, includes search time
- (9) Customization/ Control: Some control over search focus
- (10) Key User Focus: Research, fact-checking, learning

(11) Potential Limitations: Less conversational, creative output may be limited

Gemini 2.0+ (Free Version) [6]

- (1) Primary Strength: Multimodal understanding & reasoning
- (2) Ease of Use: High; varies by Google interface
- (3) Accuracy: Generally high, especially in reasoning
- (4) Creativity: High
- (5) Coding Ability: Good
- (6) Up-to-date Information: Often, through Google Search integration
- (7) Multimodality: Strong (text, images, sometimes audio/video)
- (8) Speed: Generally fast
- (9) Customization/ Control: Some, depending on the interface
- (10) Key User Focus: Creative tasks, complex queries, multi-format input
- (11) Potential Limitations: Can sometimes be overly cautious or "Google-centric"

BgGPT [7]

- (1) Primary Strength: Bulgarian language & cultural nuance
- (2) Ease of Use: High; chat interface
- (3) Accuracy: High for Bulgarian; good for English
- (4) Creativity: Moderate
- (5) Coding Ability: Not a primary focus
- (6) Up-to-date Information: Limited to training data
- (7) Multimodality: Primarily text
- (8) Speed: Good
- (9) Customization / Control: Standard chat interaction
- (10) Key User Focus: Bulgarian language interaction & information
- (11) Potential Limitations: Primarily for Bulgarian/English, newer model

DeepSeek (Open Source) [8]

- (1) Primary Strength: Coding, technical tasks, open-source
- (2) Ease of Use: Moderate to High; intuitive interface
- (3) Accuracy: High in technical domains; can be biased
- (4) Creativity: Moderate
- (5) Coding Ability: Very Strong
- (6) Up-to-date Information: Limited to training data
- (7) Multimodality: Primarily text
- (8) Speed: Fast, efficient
- (9) Customization / Control: High (as open-source)
- (10) Key User Focus: Developers, technical users, data analysis
- (11) Potential Limitations: May have data privacy concerns for some, less conversational finesse

2. Experiment: solve reasoning problems

Students and academics are tempted to use Generative Pre-trained Transformers AI language models as tools in their study and research. A simple experiment was conducted to explore the problem-solving capabilities of the abovementioned LLMs. Regarding the set of five popular free Generative Pre-trained Transformers AI language models, a simple logical problem was presented. The surprise was that only one of them was able to return the right answer. After three months, the test was repeated. The experiment is designed to test the functionality of the AI language models in solving reasoning problems from a user's viewpoint and does not cover the structure of the models and program code.

The problem:

"Maria has 2 sisters and a brother, John. How many sisters does John have?"

Test results in a three-month interval for 5 five popular GPT AI language models are summarized as follows in Table 1

Table 1. Test results in a three-month interval for 5 five popular GPT AI language models. Answers were cited.

Application	February 2025	May 2025
ChatGPT [4]	John has 2 sisters .	John has 3 sisters .
Perplexity [5]	If Maria has two sisters and one brother named John, then John has the same two sisters: Maria and her other sister. This means John has two sisters .	If Maria has two sisters and one brother named John, then John has the same two sisters: Maria and her other sister. This means John has two sisters .
Google Gemini [6]	Maria's brother has two sisters .	
Google Gemini (2.5 Flash) [6]		John has 2 sisters . Maria and her other sister are John's sisters.
Google Gemini (2.5 Pro) [6]		Here's how to solve this: Maria has 2 sisters. Maria herself is also a sister to John. So, John has Maria + Maria's 2 sisters = 3 sisters .
BgGPT [7] <i>The conversation is in Bulgarian</i>	Mary's brother also has two sisters, since they are siblings in common. So, Mary's brother has two sisters . Мария има две сестри и един брат Иван. Колко сестри има Иван? Братът на Мария също има две сестри, тъй като те са общи братя и сестри. Така че братът на Мария има две сестри.	Ivan has one sister, who is common to him and Maria. Since Maria has two sisters and one brother (who is Ivan), this means there are three children in the family: Maria, Ivan, and another sister. Therefore, Ivan has only one sister . Иван има една сестра, която е обща за него и Мария. Тъй като Мария има две сестри и един брат (който е Иван), това означава, че те са три деца в семейството: Мария, Иван и още една сестра. Следователно, Иван има само една сестра.
DeepSeek [8]	John has 3 sisters . (8 pages of reasoning, verification with an example, and conclusion)	John has 3 sisters . (8 pages of reasoning, verification with an example, and conclusion)

The only application that answered correctly in February 2025 was DeepSeek. It means mathematical logic is implemented in the AI language model. All other AI language models provided wrong answers.

The same test was conducted 3 months later. During that time, Google launched few more free versions of Gemini, and they were included in the experiment. Google Gemini (2.5 Flash) application delivered the same result. Google Gemini (2.5 Pro) application returned the right answer. Perplexity and the original Gemini 2.0. Unfortunately, the product of INSAT BgGPT deteriorated. It was expected that the logical capabilities of the AI language models would improve, but the reality is different. Some companies improved their AI language models, most probably adding mathematical logic. Others left these improvements at a later stage. Unfortunately, the attempt of INSAIT to add mathematical logic to BgGPT, if any, was a failure. DeepSeek returned the same right answer. It is interesting to note that DeepSeek claims that "Think before responding to solve reasoning problems". The results from this simple experiment prove the claim.

3. Conclusion

Most of the free Generative Pre-trained Transformers AI language models were not trained to solve reasoning problems at the beginning of 2025. With time, the leading vendors improved their language models, adding additional versions with capabilities to solve reasoning problems. Most probably, the paid versions provide such capabilities. Users need to be aware that not all Generative Pre-trained Transformers (GPT) AI language models are trained to solve reasoning problems, and they must carefully select what model to use for a specific task.

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Верификация на процедура за разузнаване на киберзаплахи посредством използване на инструментариума на системи за симулиране, наблюдение и мениджмънт на мрежовата инфраструктура на организация

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Verification of a Cyber Threat Intelligence Procedure Using the Toolkit of Systems for Simulation, Monitoring and Management of an Organization's Network Infrastructure

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Abstract: In this report, based on a previously developed procedure for cyber threats intelligence to an organization's information infrastructure, a scenario for its verification is proposed by using the capabilities of a management, monitoring and simulation environment.
Keywords: VERIFICATION, PROCEDURE, SIMULATION, MONITORING AND MANAGEMENT SYSTEMS, CYBER THREATS

1. Въведение

Инструментите за мониторинг на текущото състояние на мрежата са в основата на изграждането на всяка система за управление на комуникационните и информационните ресурси и представляват средство за наблюдение и управление на всички структурни елементи на мрежата (комуникационни канали, мрежови устройства и др.).

Средствата за наблюдение и управление на мрежата включват комплекс от програми, предназначени за автоматизиране процеса на управление на мрежата, обединени в обща платформа. С помощта на тази платформа се осигурява контрол на всички аспекти от функционирането на мрежата – от работата на устройствата и състоянието на кабелите до различни делови процедури.

Платформата предоставя на администратора на мрежата възможност за изработване на определена стратегия за управление и да изпълнява голям брой функции, свързани с управлението на мрежата. Тя прилага обектно ориентирана архитектура и технология с използване на бази данни.

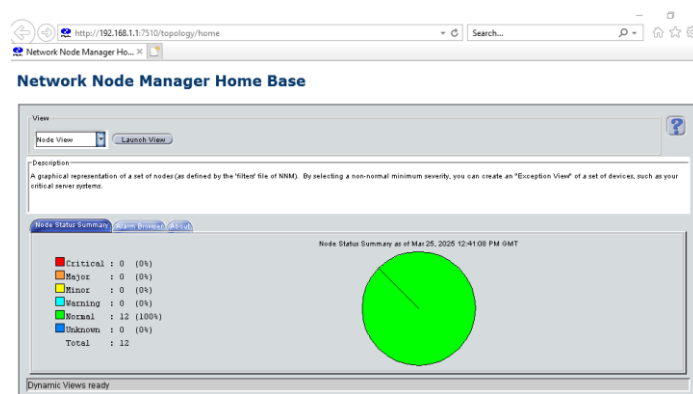
Администраторът на мрежа трябва да има точна представа за нейния състав, структура и конфигурация. Това се представя с логическата топология на мрежата и с описание на активите на мрежата.

Логическата топология изобразява устройствата в мрежата, портовете с които те са свързани към мрежата и IP (Internet Protocol) адресите на тези портове.

2. Наблюдение на структурата на мрежата

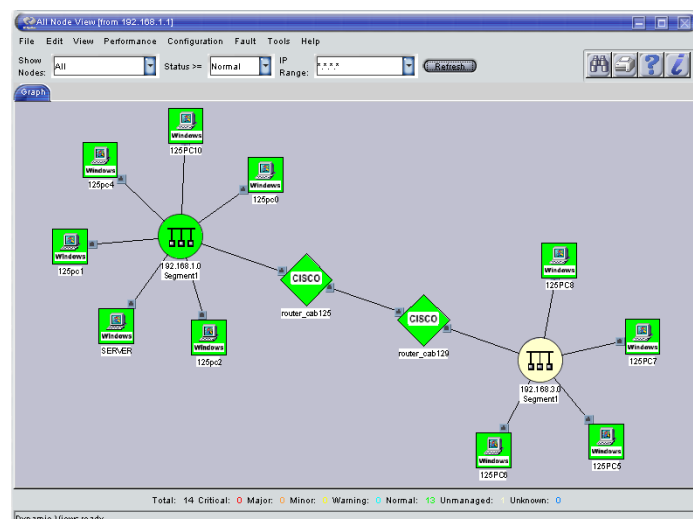
Основната идея при наблюдението и управлението на защитата на една мрежа е да се следи за устройство, което по принцип не е в описанията на активите на мрежата на организацията. Наличие на такова е признак за пробив. Друг признак за атака е наличието на ненормална мрежова активност (трафик) [1,2].

Използването на HP Open View за наблюдение на структурата на мрежата предоставя като резултат различни изгледи с активните и неактивни устройства/възли. Изборът на изгледа с възлите на мрежата е показан на Фиг. 1 [3,4].



Фиг. 1: Начален екран на HP Open View

Схемата на мрежата открита с този продукт е показана на Фиг. 2.

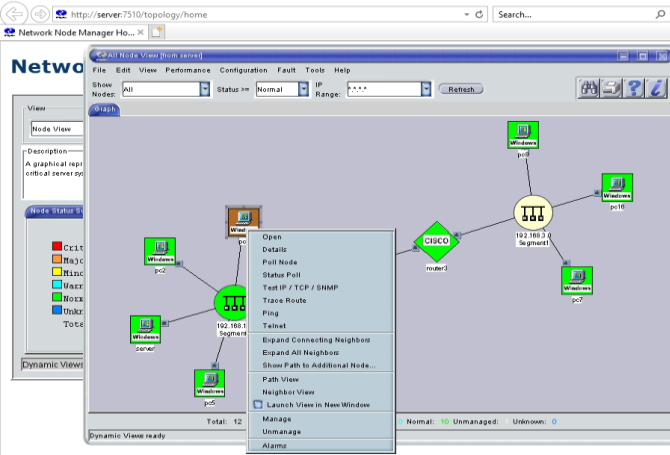


Фиг. 2. Карта на мрежата с показани основните ѝ възли

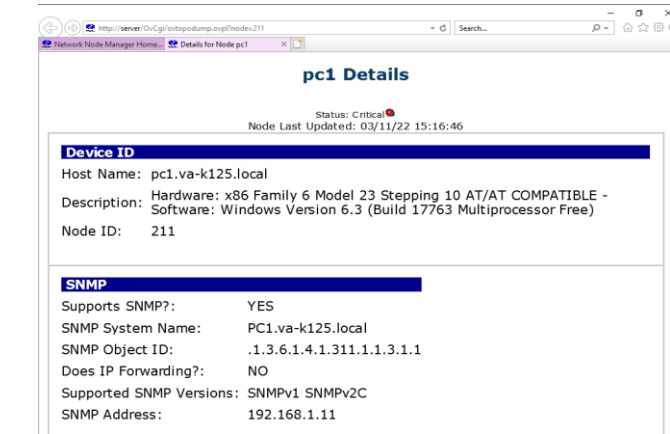
Анализ на резултатите: При наличие на опис на активите на мрежата опитен администратор може да открие появата на нов възел или отсъствие на възел, който би трябвало да е наличен в мрежовата архитектура.

3. Наблюдение на профилиите на мрежовите елементи

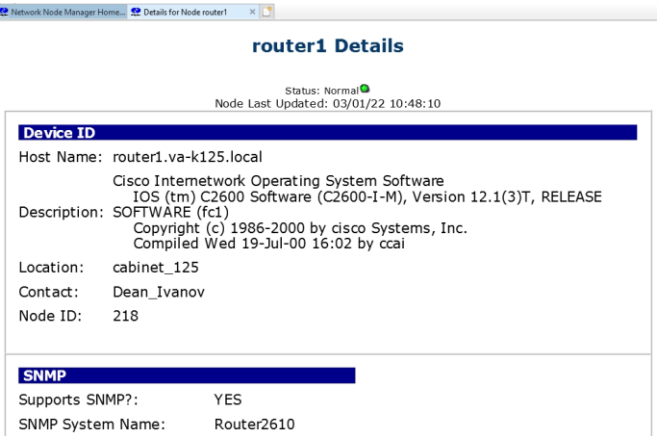
За определяне на логическата (IP) и физическата (MAC) адресация, след като е наличен изгледът Node view/All, може да се избира поотделно всеки един възел от картата на мрежата. С десен бутон на мишката да се отваря контекстно (падащо) меню (Фиг. 3).



Фиг. 3. Избор на устройство и извикване на контекстно меню с десен бутон на мишката
От него се избира “Details” (фигури Фиг. 4 и фиг.5).



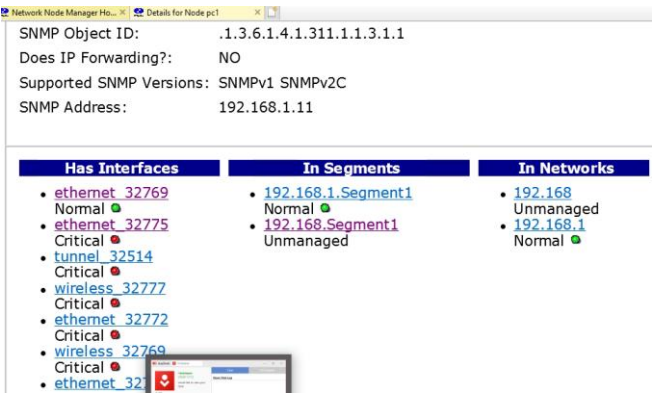
Фиг. 4. Разглеждане на детайлите на устройство (работна станция – персонален компютър PC1)



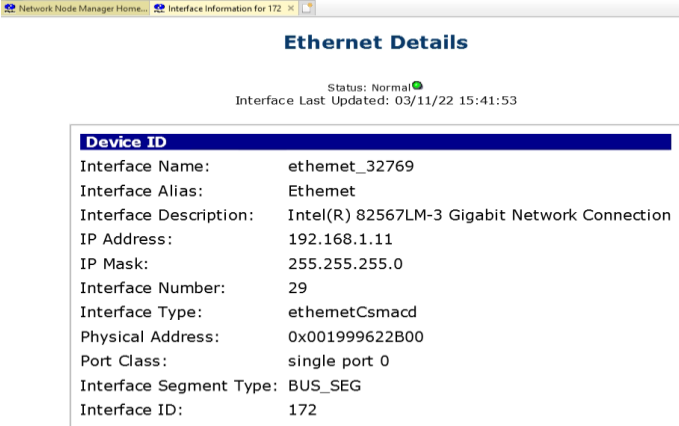
Фиг. 5. Разглеждане на детайлите на устройство рутер (router)

От фигури 4 и 5 може да се извлече информация за хардуера и софтуера на устройството, неговия IP адрес, името и домейна, с което е обявено в DNS сървъра. Посочени са и поддържаните версии на SNMP (Simple Network Management Protocol).

За да се види MAC адресът, трябва да се кликне върху мрежовата платка, например Ethernet 32769 (фиг. 6) и след това да се види физическия адрес (в случая – 0x001999622B00) (фиг. 7).



Фиг. 6. Избор на мрежовата платка



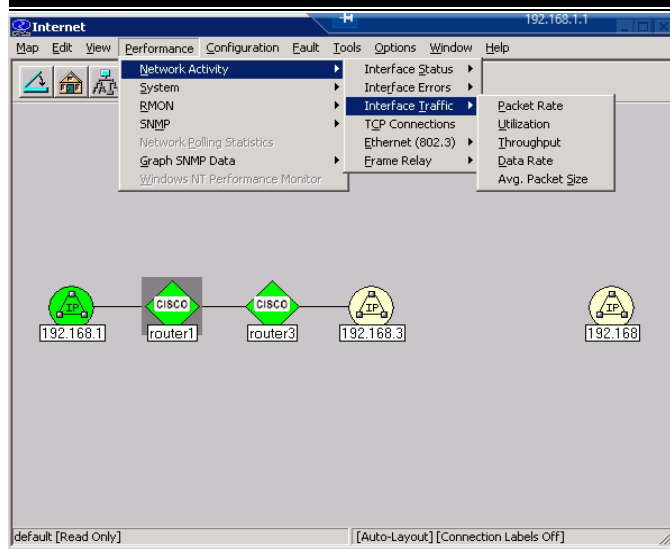
Фиг. 7. Определяне на физическия адрес

Анализ на резултатите: При наличие на опис на активите на мрежата опитен администратор може да открие появата на нов неизвестен възел, с IP, MAC адрес, софтуер и хардуер, различен от описаните.

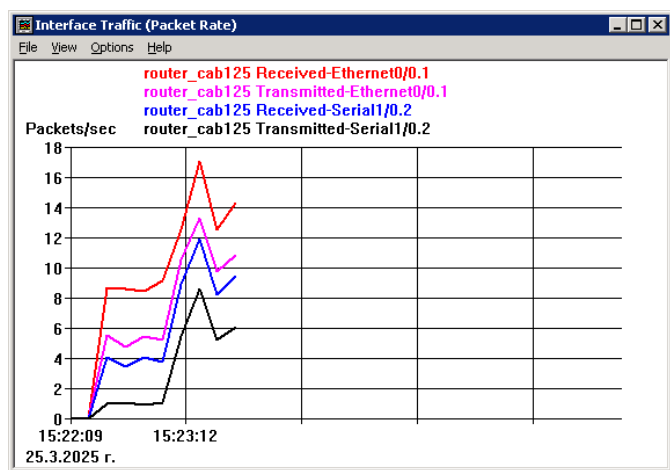
4. Наблюдение на трафика в мрежовата инфраструктура

HP Open View позволява при осъществен достъп през Remote Desktop да се покаже трафика на пакети (Packet Rate), полезният трафик (Throughput), трафик на данните (Data Rate) и SNMP трафик за избрано устройство. Началното меню за разглеждане на трафика е дадено на Фиг.8.

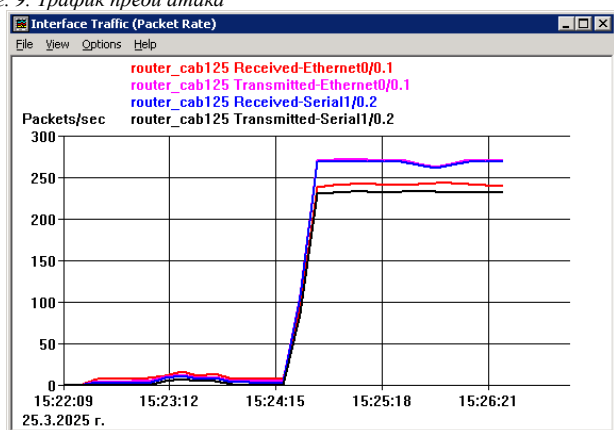
Например, ако е избран рутер 1, трафикът на пакети (Interface Traffic), преди и след атака към мрежата е показан на Фиг. 9 и Фиг. 10.



Фиг. 8. Начално меню за разглеждане на трафика



Фиг. 9. Трафик преди атака



Фиг. 10. Трафик след атака

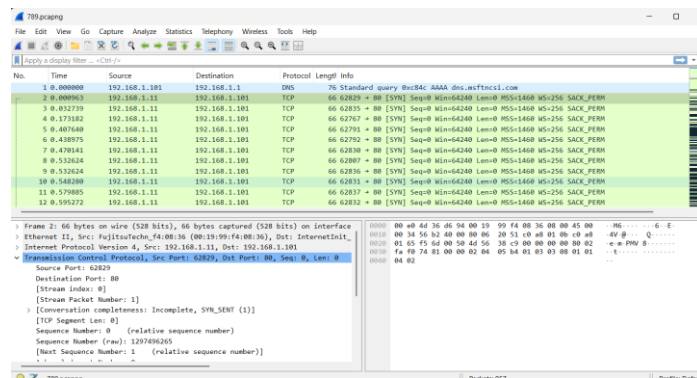
Анализ на резултатите: Преди атаката трафикът на пакети в мрежата е около под 18 пакета/сек. Многократно завишаване на трафика с повече от 200 пакета/сек. говори за извършването на атака от тип DDoS.

5. Прилагане на средства за прихващане и анализ на пакети

След като е открита атака, следваща стъпка на Анализатора по киберсигурност е да открие източника на атака. Това може

да осъществи, като се използват възможностите на софтуерния продукт Wireshark, който функционира като програма протоколен анализатор на пакети (sniffer). Резултат от работата на Wireshark е показан на Фиг.11. Избран е втория пакет и е разгънато съдържанието на TCP сегмента.

Анализ на резултатите: Както се вижда на фиг.11, атаката е от източник с IP адрес 192.168.1.11 и е насочена към възел с IP адрес 192.168.1.101. Тя е DoS атака от тип SYN Flood т.е. източника непрекъснато иска да установи логическа връзка с втория компютър (3-way handshaking procedure), без да завърши докрай процедурата. Втория компютър не може да предоставя услугите, за които е предназначен, понеже се стреми да завърши установяване на логическата връзка.



Фиг. 11. Резултат от работата на Wireshark

6. Заключение

Представянето на сценария за разузнаване на киберзаплахите като процедура позволява систематичното описание и прилагане на редица подтехники и средства и очакваните резултати от тях.

Разгледаните средства и инструменти успешно верифицират описаната процедура на техниката за разузнаване на кибер заплахите.

Анализът на процедурата налага извода, че е необходимо изграждане на компетенции у потребителите, за да се идентифицира и определи кога и кой инструмент е целесъобразно да бъде използван.

Предположеният емпиричен метод и подход за верификация има интердисциплинарен характер, тъй като може успешно да бъде приложен за други области, тъй като верификацията на други техники и процедури може да бъде представена по аналогичен начин.

Благодарности.

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Киберсигурността от гледна точка на модела за разширяваща се вселена

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Резюме: Статията третира предизвикателствата пред киберсигурността на мета ниво. Приложена е аналогия с модела за разширяваща се вселена. Разкриват се и се систематизират неизследвани области, които са свързани с тежки последствия за сигурността на киберфизичния свят.

Ключови думи: киберсигурност, кибер, сигурност, разширяваща, вселена, аналогия

Увод

Предизвикателствата на кибер сигурността излязоха от зоната на технологиите и засегнах цялото общество във всички негови аспекти. Представяме един модел на динамиката на проблемите в областта на кибер сигурността. Той е базиран на аналогия с модела за разширяващата се вселена и служи за анализ и задълбочаване на разбирането за процесите, които водят до усложняване и трудности при противодействието срещу злонамерените актьори. Въпреки несъвършенството на представената аналогия с модела за разширяващата се вселена считаме, че представеният анализ показва дълбочината на проблема и нови неизследвани страни на противоборството при защитата на киберфизичния домейн. Осветява тенденции, които се виждат ясно благодарение на аналогията. Такава неординарна картина на кибер сигурността пояснява предизвикателствата пред изследователите и цялата индустрия за програмни и апаратни средства за сигурност на ИКТ (Информационни и комуникационни технологии).

Същност на проблема

След появата на всяка авангардна технология започва процес на инкорпорирането ѝ в киберфизичния свят. Така съществуващия технологичен парк се променя и усложнява непрекъснато. Същевременно се увеличава технологичното разнообразие. Налага се възникващите технологии да функционират и взаимодействат със съществуващите. Тук изниква въпроса какви проблеми поражда интегрирането на новите технологии?

В действащия технологичен парк от ИКТ всяка платформа има свой жизнения цикъл. Този парк обхваща всички отделни инсталации на операционни системи, приложения, устройства, например принтер, маршрутизатор, фитнес тракер, интелигентен телевизор, медицински устройства в клиниките, банкомати, таблети, телефони, индустриални контролни системи, около 130 компютърни платформи в произволен съвременен автомобил и всички компютризиращи системи по кораби, самолети, сгради, улици, в домове, обществени сгради, под земята, под водата и във въздуха, радио ретранслатори, сателитни системи и други устройства, поддържащи телекомуникационни среди.

От една страна всички тези платформи остаряват, а от друга непрекъснато се роят нови технологии и производители на нови продукти, всеки с нова версия, всяка с множество инсталации. Стартъпи предлагат авангардни машини за бази данни, операционни системи, фърмуер, облачни услуги (SOA, SaaS и т. н.), онлайн продукти за графика, за работа с бази данни и др. Продуктите на стартиращите компании узряват, жизненият им цикъл напредва, преминава и те остаряват. През цялото време тези продукти участват в реално действащия дигитален технологичен парк. Бъдещето продължава непрекъснато да приижда с овеществени нови модели платформи, предлагащи нови услуги за потребителите.

Методология

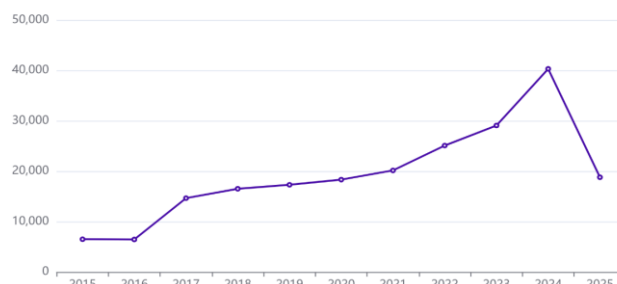
Киберфизичният домейн включва цифровите платформи, които осигуряват телекомуникационната инфраструктура, инсталираните системи за автоматизация, инстанциите на услугите в интернет и огромно множество локални инсталации. Глобалната повърхност за атаки включва всички регистрирани

и неизвестни уязвимости и слабости в защитата на конфигурациите на тези цифровите платформи.

Предложеният модел базиран на аналогия, без да е напълно релевантен и с ясни очертания и ограничения, представя неординарна картина на кибер сигурността. Предизвикателствата пред киберсигурността засягат националната сигурност. Непрекъснато се появяват нови непознати проблеми пред изследователите, индустрията за програмни и апаратни средства за сигурност на ИКТ, критичната инфраструктура и организациите. Анализите на отделните компоненти от аналогията с разширяващата се вселена са направени на базата на визията ни за взаимодействието на остарелите, актуалните и авангардните технологии, които присъстват едновременно в цифровия свят. Съдържанието на тези анализи осветлява сложни връзки.

Подобно на модела за разширяващата се вселена в астрономията, вселената от уязвимости, които се съдържат в реално действащия дигитален парк се увеличава по отношение на броя на уязвимостите. Вижда се и на Фиг. 1.

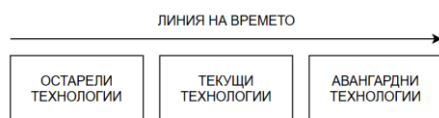
Vulnerabilities by type & year



Фиг. 1. Нарастване на броя на уязвимостите [20].

Тази на пръв поглед странна междудисциплинарна аналогия, познат методологически подход, прилагаме за описване на модел, който да позволи поглед към уязвимостите в нова светлина. За да се направят изводи за неизвестни страни на процесите, свързани с тях. Освен, че уязвимостите са събрани в регистри и списъци, описани са тежестта и въздействието им върху сигурността на платформите, те пораждаят и процеси, които се предмет на настоящото изследване. За целта въвеждаме работен модел с линия на времето, на която условно обозначаваме миналото и бъдещето. Така се вижда, че общия брой уязвимости расте в две посоки – веднъж през жизнения цикъл на платформата (хардуерна, софтуерна или само обикновено приложение), което отбелязваме по оста в посоката на миналото и втори път с новите продукти и версии, които пристигат от бъдещето. Тази гледна точка може да ни помогне за по-дълбоко изясняване на нови страни на проблема със сигурността в системите от ИКТ. Защо от ИКТ, а не само от ИТ (Информационни технологии)? Защото инфраструктурните мрежови услуги, известни със слабостите си, например DNS, NTP, DHCP, както и SS7 и други протоколи от телекомуникациите се използват и досега в инсталирани инстанции от най-различни производители. Вярно, някои от тях имат нови версии, но те навлизат бавно и предстои разкриването и осветляването и на техните уязвимости...

Върху линията на времето от Фиг 2. постоянно се появяват нови дигитални технологии. Примерите са облачни изчисления, IoT, контейнери, DLT (Distributed Ledger Technology), BYOD (Bring Your Own Device), AI и други, които не достигат популярността на изброените.



Фиг 2. Жизнен цикъл на ИКТ

Вследствие на множество фактори слабостите в изброените технологии са налице, а общият брой на уязвимостите непрекъснато се увеличава. Моделът на разширяващата се вселена се отнася до пространството на космоса и разстоянията в него. Предложената аналогия е фокусирана към увеличаването на континуума на пространството на уязвимостите. В света на ИКТ авангардните технологии може да се оприличат на свръхнови звезди, а остаряващите платформи на червени джуджета. И в двата случая от гледна точка на киберсигурността се вижда, че тези обекти са атрактори за интересите на зловерните актьори. При авангардните технологии са налични множество неизвестни уязвимости, а при остарелите слабостите са известни и лесни за ютилизирание. Дейта центровете с хиляди сървъри и телекомуникационни връзки може да се оприличат на галактики, в които се развиват споменатите процеси. Същевременно “вакуумът” в цялото това пространство генерира елементарни частици, тоест слабости и уязвимости.

Литературен преглед

Блокчейн и цялата гама DLT се появили на сцената преди двадесет години с твърденията, че тази технология по природа е защитена и успешно може да се използва и за кибер защита [1], [2]. Интернет на нещата (IoT), следвани от умния град (Smart City), умния автомобил (Smart Car), носими устройства (Wearables) и още умни парадигми навлязоха и донесоха всички слабости по сигурността, които са пропуснати в бързането поредната иновация да излезе на пазара [3], [4]. Актуалният Изкуствен Интелект показва сложен комплекс от нови непознати слабости в сигурността, които предоставят на злонамерените актьори възможности за неординарни атаки например генериране на незащитен програман код [5], [6], генериране на вредоносен програман код [7], [8], отравяне (poisoning) на масиви с данни за обучение, използване на остарели библиотеки и криптографски алгоритми [9], [10], [11].

Континуумът на уязвимостите

В продължение на представената аналогия представяме факти с аналогии за поведението на континуума на уязвимостите по линията на времето от Фиг 2.

В края на 2009 г. е установено, че 52% от всички уязвимости са били „изоставени“, тоест за тях вече не е наличен производител, който да се погрижи за актуализации за тях [Грешка! Източникът на препратката не е намерен.]. Изоставени софтуерни проекти с отворен код, изоставени сайтове са коментирани в [12].

Тъмна материя. Идеята с аналогия за тъмната материя във вселената и артефактите в системите от ИКТ се появява през 2012 г. в работата [13]. Тази категория се отнася до всички технологични компоненти, които присъстват в комплексите от информационни и комуникационни системи, но не се контролират от екипите за съпровод и поддръжка и не са известни на екипите по сигурността. Те са друг естествен атрактор за зловерните актьори. Към категорията тъмни данни [14] се отнасят забравени, недостъпни или оставени без вниманието на ИТ екипите масиви с данни, директории с документи, мултимедия и др. Изтичането на тези данни може да доведе до осветляване

на чувствителна информация за институциите и бизнеса. В допълнение изследователите въвежда категорията сенчест ИТ. Тя включва всички неконтролирани платформи в една организация. Сенчестият ИИ е сяпо петно. Служителите внедряват неконтролирано ИИ преди официалната политика без да осъзнават рисковете за излагането на данни или ефективната реакция при инциденти. Тези внедрявания на „сенчест ИИ“ заобикалят традиционните прегледи, създавайки невидими повърхности за атака и нови непознати рискове.

Малко организации са картографирали къде се използва ИИ. Без тази видимост е почти невъзможно да се управлява излагането на данни или да се реагира ефективно на инциденти.

Цифровото замърсяване оприличаваме на космическия боклук. 1. По веригата за доставки производителите пускат на пазара милиони нови устройства с уязвимости [15] или без защита, с отворени портове за достъп. 2. Замърсяване със стар програман код, което е експониран в интернет. Той съдържа остарели компоненти, които са известни със слабостите си, но се прилага от разработчиците [32]. Нивото на тази тренд ангажира държавните институции, които са отговорни за националната сигурност [16].

Изследователите непрекъснато откриват неподозирани варианти за атаки. Например подават от отдалечено разстояние команди към интелигентните устройства за гласова комуникация с потребителя използвайки лазер, който е насочен към микрофона [16] при Alexa, Siri и Google Smart Speakers [17].

Как се увеличава броят на уязвимостите?

1. Поради обратно действие „назад във времето“ следва от количеството действащи платформи и инстанции на приложения от зоната на миналото. То непрекъснато се увеличава поради приключване на жизнения им цикъл. Тези платформи и приложения имат различен жизнен цикъл. Например индустриалните контролни системи (ICS и SCADA) са замислени за жизнен цикъл над 15-20 години и голяма част от производителите им засега не са възприели все още процеса производство на ъпдейти, в бранша им липсва опит и експертиза по темата сигурност. Същевременно тече процес на свързване на тези платформи с външни мрежи и информационни системи, най-вече през интернет.

Познатите от ИТ платформи се ъпдейтват редовно, но паркът е огромен и операционните системи и приложенията остаряват. Устройствата в телекомуникационните среди често не се ъпдейтват, защото са недостъпни, отдалечени и трудно се рестартират.

Вече са неизброими платформите с мобилни устройства, интелигентните битови уреди, носимите върху тялото дигитални принадлежности, всички артефакти, които станали причина за въвеждане на термина Internet of Everything [18], [19].

Към миналото постоянно, в непрекъснат поток се отправят милиарди устройства, експониращи уязвимости, част от които ще бъдат известни и регистрирани. От тях също част ще бъдат осигурени с актуализации или друга защита (закърпени), но ще има и неизвестни останали без ъпдейти, които ще бъдат експлоатирани от хакерите заедно с известните. Производителите изчезват по различни причини – от фалит до сливане или закупуване, а някои просто не са в състояние от определен момент нататък да произведат ъпдейти, в същото време злонамерените актьори усилено изследват остаряващите технологии и откриват уязвимости, които няма кой да закърпи.

2. При текущите технологии актуалните платформи са в състояние на редовна експлоатация и се съпровождат от техните производители. Последните издават ъпдейти и поддържат продуктите си в съответствие с регулаторните мерки и договорните си отношения с организациите потребители. На пазара се появяват нови производители и броят на тези платформи

непрекъснато расте. Основните проблеми при тези платформи са свързани с непрекъснатото увеличаване на броя на откритите уязвимости [20]. Това се дължи на липсата на изисквания за кибер сигурност при инженеринга и дефицита на експертиза.

3. Авангардните технологии се появяват в условия на конкуренция, благодарение на което при тях компонента киберсигурност е символичен и недостатъчен. В последните години на пазара излязоха последователно DLT (Distributed Ledger Technology), IoT и AI (Artificial Intelligence). Практиката потвърди ефекта от неглижирането на киберсигурността при инженеринга на тези технологии. Нещо повече. DLT се анонсират за защитени и се предлагат включително за инструменти за киберзащита [2], [21]. При недостига на кадри за киберсигурност е ясно, че в проектните производствени етапи за тези технологии изискванията за киберсигурност са пропуснати.

За да изясним нивото на сложността на проблема с киберсигурността в цифровия свят отчитаме съвместното съществуване и взаимодействие на така специфицираните три вида технологии. Този важен момент явно показва ефект на мултиплициране на слабостите и разкриването на неясно пространство с възможности за атаки от страна на зловредните актьори.

Върху всички платформи действат две сили, които са разположени в двете посоки на едномерното пространство на времето, съдържащо увеличаваща се по броя уязвимости вселена. Едната сила е бъдещето, което иска нови продукти и услуги, а другата е миналото, което се изразява в остаряване, съпроводено с откриване на нови уязвимости и незаинтересованост към съществуващите. Колкото повече остаряват инсталациите, толкова повече уязвимости се откриват в тях. Специалният момент е, че не се откриват една по една, в единични инстанции. Следните два случая го показват. Например микро уеб сървъри са инсталирани в хиляди модеми, комутатори, хладилници... Новооткрита уязвимост в ядрото, което всички производители са взели от случаен сайт с публично отворени сорсове и доработили за техни си нужди, води до компрометиране на всички устройства, в които е приложено това ядро. Случаи с големи количества, от порядъка стотици хиляди броя, произведени ADSL модеми, които са без елементарна защита и още си работят в интернет [22], [23]. Огромна част от пробивите в сигурността на ИКТ се извършват през уязвимости, които са известни от години. В устройствата с по-дълго минало има открити повече уязвимости и непрекъснато се откриват нови.

Експерти по сигурността са открили критична уязвимост в кода на стандарта ASN1, формална нотация за обмен на данни в телекомуникациите, в библиотеката, която се използва в телекомуникационни продукти и би могла да позволи на хакерите да се възползват и поемат контрола на дори ключови части на телекомуникационната инфраструктура в света. Грешката е в кода на библиотеката, която се използва в комуникационни продукти например радиостанции в клетъчни кули, маршрутизатори, комутатори, както и базова линия чипове в мобилните телефони. Регистърът [24] със посоченото сечение показва списък, който съдържа проблеми с тази уязвимост от 2002 г. до момента на създаването на настоящата статия през 2025 г.

Разследването на популярния проект с отворен код JsonWebToken, показва, че атакуващ може да използва уязвимост CVE-2022-23529 с CVSS 7.6 за да получи отдалечен достъп. Съществуват над 22 000 проекта с отворен код, използващи тази библиотеката и е била изтеглена над 36 милиона пъти само за един месец [25].

Изводи

Считаме, че бъдещето ще се характеризира с непрекъснато активиране на стартиращи предприятия, които се интересуват единствено от проникване на пазара. Тенденцията изискванията за сигурност да остават извън обхвата на проектите за информационни технологии ще продължи, тъй като ги оскъпява, натоварвайки бюджетите им. Независимо дали става въпрос за

автомобили и охрана на домове, животоподдържащи системи, фитнес тракери, неприкосновеност на личния живот или други технологии. Тези факти се комбинират с нарастващ дефицит от кадри за работните места, свързани с темата киберсигурност и близката до нея информационна сигурност. За всички тези твърдения съществуват достатъчно конкретни статии с описания на различни случаи: човекът имал в телефона си съобщение, че вратата и прозорците на дома му са затворени и заключени, но не било точно така, а автомобилите вече ги крадат не с „лапи“ и подобни „инструменти“, а с лаптопи, потребителите нямат никакви гаранции за данните, които се снемат от фитнес тракерите им и отиват в облака, където върви здрав бизнес с тях...

Представеният модел налага извода, че процесът на нарастване на уязвимостите, неминуемо пораждащ и злонамерени действия, е интендна характеристика, технологична парадигма на дигитализацията. Подходът към проблемите с тази характеристика е единствено по пътя на законотворчеството и на налагането на технологични нормали и процеси.

Възможен е все пак и вариант за решение, който е аналогичен на случая с телекомите в миналото. Тогава още през 30-те години на миналия век технологиите смениха хиляди служители, които се занимаваха с ръчно комутиране на телефонните линии.

Заключение

Наследените проблеми по киберсигурността са свързани с остарелия действащ парк. Актуалните проблеми са свързани с инстанциите, които имат съпровод, неизвестните са характерни за авангардните. Авангардните технологии са базирани върху инфраструктура, която е конструирана от актуални технологии. Съвместното съществуване на остарели, актуални и авангардни цифрови технологии непрекъснато мултиплицира във времето наследените, активните и неизвестните проблеми по киберсигурността. Този ефект отваря широк оперативен простор за зловредните актьори. Пример за усложняване на проблематиката при концепцията за интелигентен град е представен в [26].

Емпиричните ни наблюдения показват следните трендове. Софистичността на хакерите се повишава. Зловреден модул (dropper) е разпространяван пре кеширащата интернет трафик технология CDN. Модулът е прикрит в ълдейт на антивирусна програма, докато последния престоява в кеширащия буфер [29]. Увеличаване на обхвата на инцидентите по киберсигурността и трудностите при ликвидиране на последствията от тях [30]. Непрекъснато усложняване на технологиите за разследване на киберинциденти [31].

Основните причини за увеличаване на континуума на уязвимостите са организационните проблеми, които се отнасят до изоставянето на регулаторните мерки и корпоративната култура по темата киберсигурност от развитието на технологиите. Това води до несинхронизирано взаимодействие между производителите и потребителите на ИКТ.

Представените предизвикателства поставят задачата за адекватни регулаторни мерки, както се вижда и от [27], [28].

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Digital twins in security

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Abstract: Digital twins combine real-time data from physical objects with advanced simulation techniques to enhance the security ecosystem. They enable predictive analytics, anomaly detection, and optimized decision-making in complex operational environments by integrating technologies such as IoT, artificial intelligence, and blockchain.

KEYWORDS: DIGITAL TWINS; IOT; BLOCKCHAIN; CYBERSECURITY; SIMULATION; PREDICTIVE ANALYTICS; INTELLIGENCE; RISK MANAGEMENT; DATA INTEGRATION; SECURITY 5.0

1. Introduction

Digital twins [1] are an innovative approach that combines physical reality with virtual simulations, enabled by technologies such as the Internet of Things (IoT), artificial intelligence (AI), cloud computing, and big data. This technology enables real-time monitoring, analysis, and management of physical objects and systems, thereby transforming the way we approach complex ecosystems, including those in the security sector. The main purpose of digital twins is to provide not only continuous updates and visualization of object behaviors and parameters, but also to offer predictive solutions and optimized action scenarios.

The paper explores the nature, structure, functions, and applications of digital twins in the security context. It highlights their role in intelligent data management, increasing operational efficiency, and minimizing risks through simulations and real-time analysis. At the same time, it also examines the main challenges that need to be overcome to realize their full potential as a key element in modern security strategies.

According to the Markets and Markets report [2], the global digital twins market is projected to grow at a compound annual growth rate (CAGR) of 61.3% from 2023 to 2028, from USD 10.1 billion in 2023 to USD 110.1 billion by 2028.

Digital twin technology builds virtual versions of real-world systems or assets using simulation, real-time data, and advanced analytics. Digital twins improve decision-making, maximize effective actions, and reveal deep insights. With the collaboration of tools like digital twin software, security systems can move from static, traditional approaches to data-driven, dynamic solutions. That's why the decision to implement digital twin technology is important in today's security sector.

2. Concept of digital twins in security

A virtual model that is created to exactly replicate a real system, element, or procedure is called a "digital twin." By using digital twin technology, security services can simulate a connection between the virtual and real worlds [3]. This technology allows for continuous tracking and simulation of real-world assets, allowing for the prediction of possible outcomes. Therefore, it facilitates analysis without the need for direct interaction with the physical object, which, given the subject matter of the services' activities, can be resource-intensive, life-threatening, and unmasking to the adversary. It essentially functions as a real-time virtual model of a physical object, optimizing its effectiveness and leading to management decisions using analytics and data.

3. Difference between digital twin and modeling [4]

In both cases, it is a type of modeling, but while in the digital twin the aim is for a copy that is as close to the original as possible, which changes and reacts absolutely adequately to it, in the modeling method an ideal model is created, containing only such elements that are essential for research, not having a dynamic and continuous connection with the object of modeling. In modeling, the information is ignored, which is the result of the available digital capabilities operating in the creation of the methodology, and in the digital twin, technologies and computing power allow maximum proximity to the original, which allows for greater reliability of the results obtained, while the digital twin is dynamically connected to the object, which allows for completely accurate and adequate online information to be obtained when studying and working with it. Historically, classical modeling resorted to abstraction from information that is insignificant for the subject of research, due to the impossibility of working with huge volumes of data. Digital twins are the result of the opposite concept. New technologies allow the collection and processing of large volumes of data, as well as the clarification of connections and interdependencies, seemingly insignificant - in relation to significant properties and actions of the object of monitoring, impact and management.

4. Key components of digital copying and security functioning

To realize its full potential, integration and coordination of several key elements is necessary:

❖ Data integration

The core of a digital twin [5] involves integrating data from multiple sources, such as operational, communication, and sensor data from physical assets. This data is continuously collected and fed into the digital twin to maintain the accuracy and relevance of the model. Data integration can also include an additional layer of blockchain technology to ensure its security and authenticity [6].

Data integration is widely used in high-risk and technological sectors with the possibility of damage and disasters as well as human casualties: in the military sphere – development of military operations, battles, testing of weapons systems – determination of the range of action, the area of defeat, effectiveness, possible counteraction, the volume of casualties, training of forces and means, in the security sphere – creation of scenarios for covert operations, sabotage and sabotage, in the aerospace sector, for example in digital twins of jet engines. During flight, these digital twins collect data from sensors, information about the atmosphere (such as humidity and air density) and operational information (such as temperature and pressure) directly from the aircraft engines.

❖ Simulation and modeling

Digital twins can use sophisticated tools to simulate the behavior of a physical asset under different conditions. These simulations are essential for testing scenarios in a safe environment so that optimization can be performed before any use in the real world. The scenarios can be enormous in number when preparing and planning a high-risk activity aimed at intelligence and counterintelligence operations, with the possibility of material and human casualties. Since the digital twin is an exact digital copy, its study in the conditions of its dynamic relationship with the real counterpart gives us accurate information for analysis, predictions and preparation of solution options in any conditions, without exposing the object to danger.

❖ Analytics and machine learning – using AI

By analyzing the collected data – results, projects, results and suggestions for improving risky processes and security actions are identified. As a result of the ability of machine learning algorithms to learn from data over time, digital twin technology becomes deeper and more effective in anticipating, forecasting and creating predictive assessments of future crises or streamlining security procedures.

For example, machine learning methods are used by digital twins of reconnaissance drones [7] and space observation satellites to examine data received from a large number of sensors that are part of the intelligence arsenal of the devices. Air temperature, wind speed and direction, air pollution, etc. are included in this data. This predictive ability ensures that drones and satellites operate as efficiently as possible, extending their lifespan and increasing the overall productivity of the technological intelligence-information network.

❖ Visualization

Security leaders tasked with making decisions under time pressure can more easily and quickly perceive and analyze complex data and simulations due to the advanced visualization capabilities that digital twins often offer. This can include everything from simple 2D schematics to complex 3D models and augmented reality (AR) applications.

For example, security managers, analysts, and planners can visually walk through a digital twin of a reconnaissance mission using AR overlays. This helps them see future spatial and structural changes or systems in the context of the real-world situation and expand and enhance the effectiveness of prepared probabilistic scenarios. This ability to visualize how modifications look and behave in the real world significantly improves analysis, forecasting, selection, and management decision-making.

❖ Integration with IoT

IoT and digital twins work together [8]. IoT is the transmission between the object and the digital twin. Real-time data is collected from the physical complex of intelligence technical devices through sensors and IoT devices, which then translate it to the digital analogue for immediate analysis. Moreover, the continuous flow of data ensures the dynamic correspondence of the digital copy to the original, so as to ensure adequate management.

Let's imagine a technology intelligence monitoring system using digital twins. IoT sensors, which are installed on various parts (or all in the case of IoE) of the equipment, collect information on operational parameters, including people, communication devices, movements, routes, biometric data, temperature, speed, vibration intensity and energy usage. This information is fed into the digital twin, an exact copy of the real intelligence system. Real-time data analysis is performed on the digital twin to detect any anomalies, changes, threats, signs of crisis or inefficiency. Monitoring the

digital twin can immediately alert the team of technologists and analysts if a given monitoring area goes outside the parameters of set scenarios, so as to create an opportunity for proactive intervention by crisis response teams and prevent a harmful outcome that violates the security of security services' activities and operations.

❖ Blockchain and digital twins

When it comes to data, its authenticity, non-manipulation and integrity, it is also necessary to pay attention to blockchain technology. The technological properties of the blockchain, which are guaranteed by an additional cryptographic protection layer, make it increasingly widespread. Even registers with hereditary data can be converted, digitized in a protected and secure way [9]. Another advantage is that data can be updated, supplemented or edited in real time, which is a prerequisite for timely and specific decisions, without affecting the original object.

Thanks to the two cryptographic keys, which are at the beginning and end of the information unit, the confidentiality of the data is maintained, making the technology most suitable for use in the Security sector.

On the other hand, blockchain is also the basis of smart contracts [10], which also find application in copying data and creating a digital twin placed in an augmented reality environment.

5. Resource-saving value of digital twins

Digital twins are not just a new technology in the Security 5.0 ecosystem, built and driven by data; they are a guarantee for the effective construction of a safe environment and successful intelligence and counterintelligence activities. Digital twins give the security system the tool to turn huge volumes of data into valuable intelligence, which is essential for security and safety structures to remain innovative and competitive at reasonable or even eliminated risk.

Let's look at the resource that digital twins provide to security systems.

❖ Predictive Operations Support

Digital twins can save significant resources - budget, materials, equipment, human labor and especially time, which is especially critical in security. Forecasting and predictive assessments of problems arising during operational combinations and covert operations allows for the elimination of obstacles and problematic elements, thus realizing operational resource savings. Compared to traditional approaches, which often lead to unplanned operational interruptions and increased costs for repetitive operations or elements thereof, this proactive approach to supporting activities, actions and operations that are already underway is significantly more effective.

Let us give an example of the implementation of a planned operational activity. The plan is divided into stages that are subordinate to a single operational plan, with current control being applied as standard – to monitor the enemy's reaction and one's own incorrect actions. While target control requires the entire operation to be carried out and the result to be compared with the set operational goal, current control allows for timely corrections that increase the effectiveness of the operation being carried out and reduce the number of management cycles required to achieve the goal. When current control is ensured by continuous and direct control of the digital twin, then making decisions on corrections is timely and instantaneous, since one works directly with the twin, which would not be possible or would be very complicated and dangerous when working directly with the original – problems with conspiratoriality, environmental resistance, enemy

counterintelligence activities, etc. With the digital twin, each operation has a virtual equivalent that dynamically accumulates data from each element of the operation – equipment or human resources. Sensors monitor every change, movement, and change in the environment.

The digital twins (Digital Twins are a powerful tool in the security ecosystem, especially with the development of Security 4.0 and 5.0 concepts that integrate technologies such as IoT (Internet of Things), machine learning, artificial intelligence and big data. They represent virtual replicas of real objects, processes or systems that synchronize in real time and offer monitoring, analysis, forecasting and simulation capabilities. In this context, they can play a key role for security services in the fight against espionage, organized crime, terrorism, drug trafficking and drug distribution.

6. Essence, structure and content of digital twins [11]

Digital twins combine physical reality with virtual simulation through the application of technologies such as IoT devices (for sensor data), cloud computing, big data, and AI. They are used to track and analyze physical objects or processes in real time.

- **Structure.** The main components include: Physical object or system – a real-world object that needs to be observed or analyzed; Virtual model – a digital representation of the object or system, built using modeling platforms; Data interface – collection and transfer of data from the physical object to the digital twin and vice versa.
- **Content:** This includes storage of data extracted in real time from the physical object, predictive algorithms, and simulation models for optimization of various actions.

7. Applications of digital twins in the security ecosystem

Intelligence and counterintelligence: Digital twins can simulate cyberattack scenarios to identify vulnerabilities in the security of information systems; Use to analyze the behavior of potential perpetrators, including predictions of areas in which espionage operations may be carried out.

Fighting organized crime: Tracking the movements of criminal networks through real-time sensor data; Optimization of detention strategies through simulation of potential actions of organized groups.

Counter-terrorism: Simulating attacks in sensitive areas such as airports, ports and urban areas to assess their vulnerability; Optimizing the actions of specialized services in the event of incidents.

Countering drug trafficking and drug distribution: Using IoT devices in collaboration with digital twins to track drug logistics routes; Predicting delivery or warehouse locations through data algorithms based on previous cases.

8. Features and challenges in using digital twins [12]

Dynamic data management: The ability to collect real-time data and process it allows for more accurate analysis and optimization of actions;

Adaptability: Digital twin models can change and adapt depending on the analysis of new data, making them suitable for dynamic scenarios.

Simulations: They provide an environment for safely testing strategies before implementing them in real-world settings.

Challenges: Data security: Risk of cyberattacks aimed at compromising the digital twin or accessing sensitive data; Complexity and cost - the development and integration of such technology requires serious investments; Insufficient standardization: The lack of global standards for the development and support of digital twins can hinder their universal use.

9. Positive and negative effects of use

Positive: Optimize operations: Increase efficiency in security-related operations through analysis and simulations; Predict and prevent threats: Create predictive models for potential attacks; Reduce risk - avoid real-world testing that can be risky or costly.

Negatives: Dependence on technology - over-reliance on digital systems increases vulnerability to technological failures; Ethical issues - possibility of data misuse or use of digital twins against innocent individuals; Risk of faulty simulations: If models or data are incorrectly specified, results can be misleading.

10. Digital twins in the Security 4.0 and 5.0 ecosystem

Security 4.0: Focus on integrating IoT devices that work together with digital twins to provide monitoring and automated security management.

Security 5.0: Here, the focus is on intelligent and humanized management through AI and real-time data analytics. Digital twins play a critical role in integrating human and technological efforts to achieve a balance between automation and ethical management.

Digital twins are the future of security on a global scale, and their potential continues to expand with the advancement of technologies such as AI and IoT. They provide security services not only with a tool for management and analysis, but also a means to predict and adapt in an environment of rapidly evolving threats.

11. Digital twins in intelligence and counterintelligence

In the field of intelligence and counterintelligence, digital twins are a revolutionary technology that combines the capabilities of simulation, automation and real-time analysis to improve decision-making efficiency, operational security and resource management. They provide new tools for predicting, testing and solving complex scenarios that involve dynamic information and rapidly changing threats.

The essence of digital twins in intelligence

Digital twins in intelligence are digital models of real-world objects, structures, networks, or processes, often associated with the collection, analysis, and interpretation of strategic and operational data. They are based on the integration of multiple technologies: IoT, artificial intelligence (AI), Big Data, machine learning, and blockchain. Their main goal is to provide: Simulation of threats and scenarios – through virtual role-playing of different situations; Integration of data from multiple sources – such as sensors, satellite surveillance, and online platforms; Proactive prediction of threats and adversary behavior.

Types of digital twins [13] in counterintelligence

- **Object-oriented digital twins** – create digital models of critical objects (such as infrastructure, facilities or even

transportation networks). They are used to: Identify vulnerabilities in strategically important objects; Plan defensive measures against attacks on the infrastructure.

- Network digital twins – present a simulation of communication networks and operating systems: Tracking information flows between objects and agents; Detecting anomalies in cyber flows that may indicate system breaches or espionage activity.
- Humanitarian-oriented digital twins - develop models of human behavior or groups in a specific social or political environment. Example: Predicting the reactions of a given target audience to political messages or propaganda. Simulations of behavior and activities of suspected individuals or groups.

12. Functions in intelligence and counterintelligence:

Operational Analysis and Planning - Scenario Payout: Digital twins allow for the payout of thousands of scenarios in a secure digital environment, for example, how an intelligence operation will proceed or how a cyber incident will spread. Strategy Optimization - identifying optimal tactics for intelligence or defense through virtual simulations.

Threat monitoring and prediction - Digital twins are used to create virtual models of real-world objects (such as critical facilities or urban infrastructure) to simulate: Terrorist attacks; Cyberattacks on networks or systems; Natural disasters and other emergencies.

Predictive analytics analytics – using AI and Big Data to identify enemy behavioral patterns.

Cybersecurity and espionage detection – cyber intelligence: Digital twins can be the basis for analyzing large volumes of network data in real time. They can identify anomalies or intrusions in communication networks; Example: Creating a digital model of a government information network to detect weaknesses susceptible to espionage.

Agent and operations management – digital twins can simulate and model field operations, such as agent routes and logistics in enemy territory. Example: Creating a digital replica of an enemy area to monitor and predict enemy movement.

Counter-disinformation and information warfare – using digital twins to simulate the spread of false information or to counter cyber campaigns aimed at disinformation. Predicting the reactions of target groups and developing strategies to neutralize campaigns.

13. Challenges in use [14]:

- Data security: Digital twins process huge volumes of sensitive information, making them potential targets for cyberattacks.
- Model complexity: Realistic modeling of systems with multiple variables requires powerful computational resources.
- Ethical and legal issues: Creating virtual models of individuals or social groups raises questions about the protection of personal data.
- Data integration: Combining data from different sources (sensors, intelligence operations, etc.) can lead to errors in analysis or simulation.

Effectiveness of digital twins in intelligence and counterintelligence:

- Faster reactions: Digital twins allow for immediate simulation of various incidents, which shortens decision-making time;
- Predictive power: They predict potential threats and weaknesses that can be addressed proactively;
- Cost-effectiveness: Allows testing of operations and strategies without risks to operational teams or resources;
- Strengthening countermeasures: Integrated use of real and simulated data increases threat prevention capabilities.

Features of application in intelligence and counterintelligence:

- Conspiracy: Digital twins allow for a high degree of secrecy in modeling and simulations;
- Interactive deception: Digital twins can be used to create fake targets or information to deceive the adversary;
- Rapid adaptation: They manage to adapt to ever-changing environments by constantly updating their models based on real data.

Digital twins provide a powerful tool for managing complex systems and operational scenarios in intelligence and counterintelligence. They combine the capabilities of high-tech data collection, analysis and simulation, while improving the speed, efficiency and accuracy of decision-making. Although there are challenges related to data security and model complexity, this technology is key to modern intelligence and countering threats, providing a strategic advantage on a global scale.

Conclusion

In the context of the security ecosystem, digital twins are emerging as one of the most promising solutions to address today's challenges and the complex dynamics of threat environments. They play a critical role in the development of the concepts of "Security 4.0" and "Security 5.0", allowing organizations to move from reactive management to proactive and predictive strategies. Through the integration of IoT devices, artificial intelligence and real-time analytics, these technologies enable a seamless synergy between human and machine interaction, optimizing processes and limiting risk.

Digital twins extend the capabilities of Security 4.0 by supporting automated monitoring through the integration of a large number of IoT devices. At the same time, in Security 5.0, they inspire a human center of control, where technology not only supports, but adapts operations to ethical and functional requirements. Such interaction provides not only automation, but also intelligent management of complex threats, such as hacker attacks, cross-border terrorism, organized crime and cybersecurity.

The main advantage of digital twins in the security ecosystem is their ability to create predictive models of potential incidents, optimize operational decisions, and minimize the cost of testing real-world scenarios. For example, through "advanced visualizations," security services can simulate situations involving changes in infrastructure or the dynamics of specific terrain, which helps create more adequate action plans. Current applications include intelligence, crisis management, and identifying security vulnerabilities, which integrates the work of all participants in the ecosystem.

However, the ecosystem is not without challenges. The main limitations are related to technology dependency, ethical issues regarding data privacy, and the risk of incorrect modeling, which can lead to misleading results and ineffective actions. To realize the full potential of digital twins, more attention needs to be paid to issues of standardization, cybersecurity, and transparency in data processing.

In conclusion, digital twins represent not only an innovation in security, but also a major catalyst for the transformation of the global security ecosystem. They offer a holistic and dynamic approach to managing complex situations by effectively combining technology, analytical algorithms and human interaction. By entering the security ecosystem, digital twins do not simply improve current processes, but shape the vision of the future – security that is integrated, sustainable, ethically driven and fully adaptable to ever-evolving threats.

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Екосистема на сигурност 5.0

Security Ecosystem 5.0

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Abstract: This article investigates the concept of Security 5.0 as a new paradigm in national and international security frameworks, emphasizing the central role of artificial intelligence (AI) within this ecosystem. The study traces the historical evolution of security paradigms, the structural components of the Security 5.0 ecosystem, its technological foundations (including AI, big data, IoT), and challenges in implementation. The analysis addresses both the benefits of AI integration —such as enhanced threat detection and adaptive security protocols—and critical ethical dilemmas, including risks of AI misuse for criminal or adversarial purposes. The paper systematically reviews the transformation of security services (e.g., cybersecurity, intelligence, and defense systems) and outlines future development prospects as the field transitions toward Security 6.0.

Keywords: SECURITY 5.0, ARTIFICIAL INTELLIGENCE (AI), SECURITY ECOSYSTEM, CYBERSECURITY, BIG DATA, INTERNET OF THINGS (IOT), SECURITY SERVICES, BLOCKCHAIN

1. Въведение

1.1. Определение и еволюция на концепцията за сигурност

Сигурност 5.0 представлява революционен подход към управлението на защитни системи, който интегрира изкуствения интелект като централен компонент, а не просто като спомагателен инструмент. Тази концепция е естествено продължение на еволюцията на сигурността, където всяко поколение добавя нов слой на комплексност: Сигурност 1.0 – Физическа охрана и механични системи; Сигурност 2.0 – Аналогови електронни системи; Сигурност 3.0 – Дигитализация и компютърни мрежи; Сигурност 4.0 – Свързаност, облачни технологии и интеграция; Сигурност 5.0 – Интелигентни, автономни и адаптивни екосистеми

Подобно на Индустрия 5.0, концепцията поставя човека в центъра на технологичната екосистема, използвайки високотехнологични решения за подобряване на безопасността и защитата на обществото.

1.2. Новата философия на сигурността

Сигурност 5.0 се характеризира със следните основни принципи:

- Човекоцентричен подход, поставящ хуманните ценности и нужди в центъра на технологичните решения
- Интеграция между физическа и киберсигурност за цялостна защита
- Превантивност и предсказуемост чрез възможностите на изкуствения интелект
- Синергия между частния и публичния сектор при разработването на иновативни технологии
- Създаване на устойчива, адаптивна и етична система, способна да реагира на непрекъснато променящите се заплахи

2. Структура на екосистемата на Сигурност 5.0

В центъра на екосистемата на Сигурност 5.0 стои интеграцията между: Изкуствения интелект и неговите приложения; Интернет на нещата (IoT) и свързаността; Блокчейн технологиите; Биотехнологиите; Квантовите изчисления; Иновативните материали и производствени процеси

Тази екосистема е проектирана като взаимосвързана мрежа от компоненти, където всеки елемент допринася за цялостното функциониране на системата. Основната цел е да се осигури всеобхватна защита срещу комплексните и бързо еволюиращи заплахи в съвременния свят, като същевременно се поддържа

баланс между ефективност, етика и зачитане на личната неприкосновеност.

3. Ключови технологии в екосистемата на Сигурност 5.0

3.1. Големите данни (Big Data)

Големите данни служат като фундамент на модерната сигурност, предоставяйки огромни масиви от информация, които могат да бъдат анализирани и използвани за превенция на заплахи.

Характеристики: Огромен обем – ежедневно се генерират петабайти данни от различни източници; Висока скорост – обработка в реално време на информационни потоци; Разнообразие – структурирани и неструктурирани данни от разнородни източници; Достоверност – основаваща се на методи за валидиране на информацията.

Приложения в сигурността:

- Мониторинг на социални мрежи за идентифициране на радикализация;
- Анализ на транзакционни данни за откриване на финансови престъпления;
- Проследяване на комуникационни модели за превенция на терористични атаки.

3.2. Изкуствен интелект и машинно обучение

Изкуственият интелект се утвърждава като централен компонент в екосистемата на Сигурност 5.0, осигурявайки: Автоматизирано разпознаване на заплахи и аномалии в поведението; Предиктивен анализ за прогнозиране на потенциални рискове; Обработка на естествен език за анализ на комуникации и документи; Компютърно зрение за идентификация и наблюдение; Автономно вземане на решения в критични ситуации.

3.3. Интернет на нещата (IoT)

IoT технологиите създават мост между физическия и дигиталния свят чрез интеграция на разнообразни устройства, сензори и аналитични системи. Те позволяват: Създаване на интелигентни периметри за сигурност; Непрекъснат мониторинг на критична инфраструктура; Проследяване на активи и персонал в реално време; Ранно предупреждение при потенциални заплахи; Интелигентна интеграция на системи за контрол на достъпа.

3.4. Блокчейн технологии

Блокчейн технологиите осигуряват: Защитено и неподправимо съхранение на чувствителна информация; Проследимост на действията в системата за сигурност; Сигурни комуникации между различните компоненти; Децентрализиран контрол, намаляващ риска от единична точка на отказ; Автоматизирано изпълнение на протоколи за сигурност чрез умни договори.

4. Водеща роля на изкуствения интелект в екосистемата на Сигурност 5.0

4.1. Приложения на ИИ в Сигурност 5.0

Изкуственият интелект се прилага в различни аспекти на сигурността: Разузнавателен анализ – обработка и интерпретация на огромни масиви от данни за извличане на ценна информация; Кибер защита - автоматично откриване и неутрализиране на заплахи в реално време; Физическа сигурност – интелигентно видеонаблюдение и биометрична идентификация; Управление на кризи – моделиране на сценарии и подпомагане вземането на решения; Противодействие на тероризма - анализ на комуникации и поведенчески модели.

4.2. Интегриране на ИИ в специалните разузнавателни и технологични средства

В контекста на специалните разузнавателни средства (СРС), интеграцията на ИИ позволява: Автоматизирано проследяване на подозрителни дейности; Разпознаване на шаблони и аномалии в комуникациите; Прогнозиране на терористични заплахи чрез предиктивен анализ; Обработка на многоезични източници на информация; Минимизиране на фалшиви сигнали и повишаване на прецизността.

5. Изкуствен интелект при подготовката на кадрови служители

5.1. Симулационни тренировъчни системи

ИИ революционизира обучението на специалисти по сигурността чрез: Създаване на реалистични виртуални среди за тренировка; Персонализирани обучителни програми, адаптирани към индивидуалните способности; Симулации на различни сценарии за управление на кризи; Автоматична оценка на представянето и обратна връзка; Виртуални инструктори, способни да адаптират обучението в реално време.

5.2. Приложения в различни разузнавателни сценарии

ИИ системите могат да подпомагат обучението в различни специализирани области:

Икономическо разузнаване: Big Data анализ на научни публикации и патенти; Персонализирани стратегии за вербуване, базирани на професионални амбиции; Контертероризъм - анализ на социални мрежи за откриване на радикализирани индивиди; AR интерфейс за незабележимо предаване на инструкции на внедрени агенти.

6. Престъпност и изкуствен интелект в екосистемата на Сигурност 5.0

6.1. Нови форми на престъпност, базирани на ИИ

Технологичният напредък създава и нови предизвикателства: Deepfake манипулации за измами, дезинформация и изнудване; Автоматизирани кибератаки с ИИ-базирани инструменти; „Умни“ злонамерени програми, способни да избягват детекция; Прецизно таргетиран фишинг кампании с използване на ИИ; Автономни оръжейни системи, контролирани от ИИ.

6.2. Предизвикателства пред правоприлагащите органи

Правоприлагащите органи се изправят пред следните предизвикателства: Необходимост от нови технически умения и познания; Трудност при събиране на дигитални доказателства; Трансгранична природа на престъпленията; Бързо еволюираща технологична среда; Правни и етични ограничения при използването на ИИ за противодействие.

7. Критични аспекти на Сигурност 5.0

7.1. Етични дилеми

Имплементацията на Сигурност 5.0 повдига важни етични въпроси: Защита на личните данни и баланс между сигурност и поверителност; Рискове от алгоритмична дискриминация и предубеденост; Автономност на системите и човешки контрол над критични решения; Прозрачност и обяснимост на алгоритмите за ИИ; Потенциал за злоупотреба с технологиите за масово наблюдение.

7.2. Правни предизвикателства

Регулаторната рамка следва да обезпечава: Законово признаване на дигитални доказателства; Отговорност при автономно вземане на решения от ИИ; Международно сътрудничество при трансгранична киберпрестъпност; Баланс между секретност на операциите и правен надзор; Адаптиране на съществуващото законодателство към новите технологии.

8. Перспективи за развитие и преход към Сигурност 6.0

Преходът от Сигурност 5.0 към Сигурност 6.0 се очертава като естествена еволюция, характеризираща се с: Още по-високо ниво на автономност и самообучение на системите; Подълбока интеграция между човешкия и изкуствения интелект; Квантови изчисления и комуникации за подобрена сигурност; Разширено използване на биотехнологии и невро-технологии; Глобални стандарти за етично използване на ИИ в сигурността.

9. Заключение

Сигурност 5.0 представлява фундаментална промяна в подхода към национална и обществена сигурност. Интеграцията на изкуствен интелект, големи данни, IoT устройства и автономни системи създава безпрецедентни възможности за предиктивно разузнаване и проактивна защита. Същевременно, новите технологии поставят и нови предизвикателства пред обществото - балансиране между сигурност и граждански свободи, защита на личните данни и етично използване на разузнавателните средства.

Успешната имплементация на Сигурност 5.0 изисква не само технологично обновление, но и нова правна рамка и обществен консенсус за границите на тяхното приложение. Изкуственият интелект несъмнено ще продължи да играе централна роля в тази трансформация, но истинската ефективност на системата ще зависи от способността ѝ да

интегрира технологичните иновации с хуманните ценности и етични принципи.

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