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PREFACE

Scientific society: employees of higher educational institutions and research institutes, including graduate students and students, as well as representatives of organizations and firms engaged in the field of knowledge-intensive business, welcome you to the 2nd International Scientific and Practical Conference "Development and Design of Modern Materials and Products", organized based on the Engineering and Generative Design Department Dnipro University of Technology.

We are organizing a conference in the context of the Russian-Ukrainian war, which changed everything not only in Ukraine, in Europe, but also in the whole world.

We hope that such a conference is another opportunity to gather scientists from different directions and countries of the world, with the aim of preserving global scientific unity in such difficult conditions.

We are sure that the results of our joint work will be interesting and useful for all participants of the conference and will serve to solve modern problems of the world scientific community.

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FEATURES OF THE STRUCTURE OF WEAR RESISTANT COATINGS OBTAINED BY MULTICHAMBER DETONATION SPRAYING

Abstract. This study explores multichamber detonation spraying (MCDS) as a method for applying advanced wear-resistant coatings. MCDS enables the deposition of coatings with exceptional strength, heat resistance, and corrosion resistance. The technology is effective for various materials, including metals, ceramics, and composites, and is particularly suited for thin-walled and complex-shaped parts.

Keywords: *Wear-resistant coatings, multichamber detonation spraying, plasma-detonation modification, nanostructures, microhardness, porosity reduction, industrial applications, aerospace coatings, advanced materials.*

The technology is intended for applying wear-resistant, heat-resistant, heat-shielding, corrosion-resistant and special coatings with increased strength characteristics, from powder materials based on: metals and alloys, ceramics, cermets and their mixtures. Coatings are formed on parts from materials: based on aluminum and magnesium alloys, titanium and nickel alloys, polymer and carbon-carbon composite materials. Including, on the surface of thin-walled products that have a complex shape and do not allow heating.

The process of cumulative detonation spraying of coatings (CDS) is implemented using a multi-chamber detonation device (MCDD). It implements an overcompressed (non-stationary) mode of detonation combustion of a gas mixture in specially shaped chambers and cumulation of energy from these chambers, which increases the pressure in the combustion products to 40 bar and ensures the formation of a high-speed jet in a cylindrical nozzle. The speed of the combustion products in the nozzle reaches 1.8 km/s, which makes it possible to effectively accelerate the powder material to speeds of 1.2-1.6 km/s with a pulse frequency of 30 Hz.

The purpose of the study is to study the features of structure formation and its influence on the strength and crack resistance properties of detonation coatings during pulsed plasma processing at all structural levels:

- microstructure study; microhardness; phase composition; volume fraction of structural-phase components and their parameters; presence of defects;
- morphology of dispersed phases; subgrain structure; character of dislocation density distribution;

- analytical evaluation of the properties of strength and crack resistance of the obtained coatings by structural parameters;
- study of the relationship between the structure and the level of hardening and local internal stresses formed in the structure of detonation coatings

Table 1

Technological modes and materials for detonation spraying.

Technological parameters		**The porosity of the obtained coatings, %**
Air consumption (Va, m3/h)	**Combustible gas to oxidizer ratio (β)**	
1,24…1,5	**4,85…4,96**	**0,7…1,3**

Powder Cr_3C_2 -NiCr brand Amperit 584.054 (75% Cr_3C_2 +25%NiCr) fractional composition d = 10…45 µm.

The coatings were sprayed at a detonation frequency of 20 Hz, a distance to the sample of 55 mm, a speed of 1500 mm/min, the number of passes was 4.

It is shown (table 2) that when spraying Cr_3C_2 -NiCr powder in the optimal mode (I) (reducing air consumption from 1.24...1.5 m3/h to 0.84...1.09 m3/h and, accordingly, increasing propane-butane consumption) due to higher heat input, the following occurs:

- change in the ratio of the emerging phase components - the amount of Cr_3C_2 increases (from 32% to 49%) with a decrease in the share of (Cr_3C_2 + Cr_2O_3) (from 40% to 26%);
- increases (on average by 18%) microhardness;
- the subgrain structure and particle size of phase precipitates are crushed (by 1.2 times);
- dislocation density gradients in the coating material are insignificant (from $\rho = (2…4)\times10^{10}$ cm^{-2} to $\rho = (5…6)\times10^{10}$ cm^{-2}).

Table 2

Changes in structural parameters in Cr3C2 -NiCr coatings

Structural parameters	Mode I	Mode III
Phase composition	Cr_3C_2~ 49% $(Cr_7C_3 + Cr_2O_3)$ ~ 26% Matrix (Ni-Cr): lamellas~ 22% Particles (not melt) ≤ 3%	Cr_3C_2~ 32% $(Cr_7C_3 + Cr_2O_3)$ ~ 40% Matrix (Ni-Cr): lamellas ~ 22…24% Particles (not melt) ≤ 1%
D_G, μm	1,5…3,5	1,0…2,0
d_S, μm	0,1…0,3	0,2…0,3
d_P, μm	1,0…10 (Cr_3C_2) 0,01…0,05 $(Cr_7C_3 + Cr_2O_3)$	1,0…10 (Cr_3C_2) 0,015…0,08 $(Cr_7C_3 + Cr_2O_3)$
λ, μm	1,0…10 (Cr_3C_2) 0,1…0,19 $(Cr_7C_3 + Cr_2O_3)$	1,0…10 (Cr_3C_2) 0,07…0,09 $(Cr_7C_3 + Cr_2O_3)$
ρ , cm^{-2} **(coating)**	2×10^{10} (lamella) 4×10^{10} (lamella/lamella) $(5…6)\times10^{10}$ (carbide/lamella)	$(8…9)\times10^{9}$ (lamella) 8×10^{10} (lamella/lamella) $(7…9)\times10^{11}$ (carbide/lamella)
ρ, cm^{-2} **(melting line)**	$4…5\times10^{10}$	$6…7\times10^{10}$
ρ, cm^{-2} **(substrate)**	$1…2\times10^{10}$	$1…2\times10^{10}$

Analytical evaluation of strength and crack resistance properties of coatings

1). Structural strengthening (ΣσT):

$$\Sigma\sigma_T = \Delta\sigma_0 + \Delta\sigma_{Т.Р.} + \Delta\sigma_З + \Delta\sigma_C + \Delta\sigma_Д + \Delta\sigma_{Д.У.}$$

where **Δσ0** is the lattice friction stress (resistance of the material lattice to the movement of free dislocations)(Peierls–Nabarro);

Δσт.р. is solid solution hardening with alloying elements and impurities (according to the Mott–Nabarro theory);

Δσ3 and **ΔσC** are grain and subgrain hardening (Hall–Petch);

ΔσД is dislocation strengthening due to interdislocation interaction (theories of J. Taylor, A. Zeger, N. Mott and G. Hirsch)

ΔσД.У. is dispersion strengthening due to dispersed particles (Orowan).

2). Local internal stresses taking into account the dislocation structure (dislocation density):

$$\tau Л/ВН = G \cdot b \cdot h \cdot \rho / [\pi(1 - \nu)].$$

where G – shear modulus;

b is the Burgers vector;

h is the foil thickness (2×10-5 cm);

ν is Poisson's ratio;

ρ is the density of dislocations.

Plasma-detonation (pulse-plasma) surface treatment (modification)

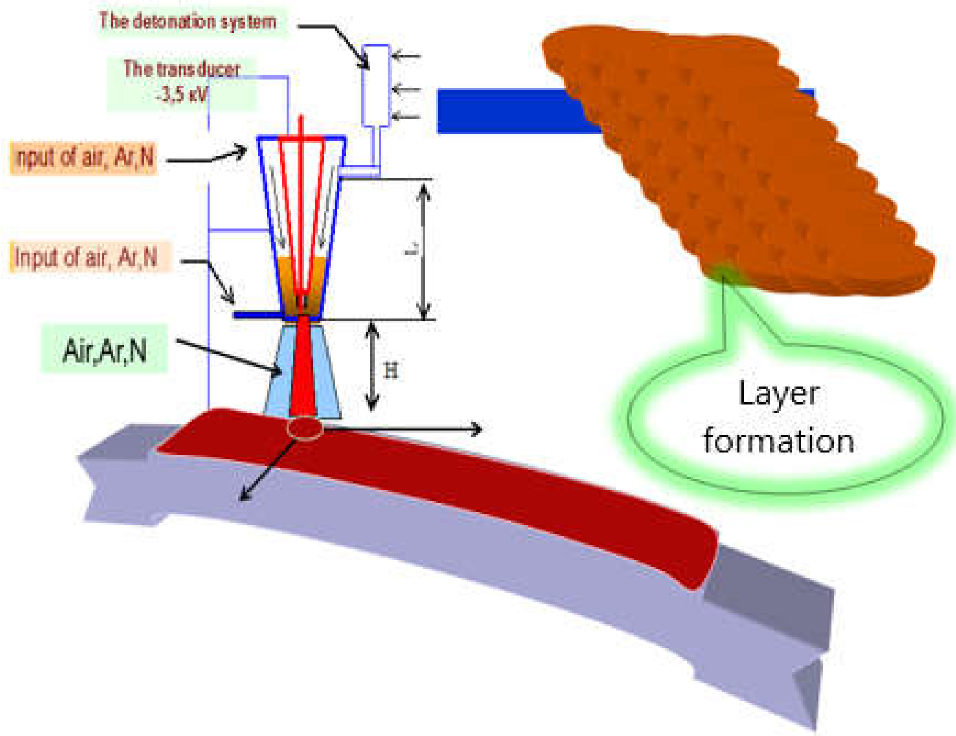

Figure 1. Scheme of pulse-plasma surface treatment

The essence of the process :

1. The part surface is treated with a pulsed plasma jet, which has a power density of 105-107 W/cm2, a speed of 5-8 km/s, a temperature of 25000-30000 K and a frequency of 2...4 Hz.
2. The technology ensures the production of a modified layer with a hardness of 14...19 GPa and a thickness of 30...100 μm
3. At the same time, a layer of nano-crystalline material is formed, which has a high: wear resistance, extreme pressure resistance, corrosion resistance

4. Possible concomitant alloying of the hardened cutting edge with alloying elements W, Mo, Ti, Cr, Ni, N, C, etc.

Results of research:

Development of innovative duplex technology for applying wear-resistant coatings

The first process is cumulative-detonation spraying of coatings(CDS)

- Coating thickness 0.2-0.3 mm.
- Roughness – Rz 10-17 µm'
- The product is heated up to 100°C.
- Productivity up to 2 kg/hour.
- The total consumption of the combustible mixture is up to 10 m3/hour.
- Standard surface preparation.
- No configuration or size restrictions.

The second process is plasma-detonation treatment of sprayed coatings(PDM)

- The product does not heat up.
- Capacity up to 300 mm2/sec.
- Installed power up to 30 kVA.
- The total consumption of the combustible mixture is up to 1.5 m3/hour.
- Only the wear surface is processed.
- There is no need to clean the surface of the coating.
- No product size restrictions.

CONCLUSION

1. Technological equipment (MCDU) for deposition of high-quality coatings and their subsequent modification (PDM) is proposed. This equipment provides low specific energy consumption and high material efficiency, up to 90%.

2. Comprehensive studies at all structural levels established the features of the emerging structure of Cr_3C_2 -NiCr coatings obtained using pulse-plasma (plasma-detonation modification).

3. The method of cumulative detonation spraying provides high-density coatings, up to 400 µm thick, with porosity mostly less than 1%, microhardness up to 13.2 GPa, and high adhesion and cohesion characteristics.

4. It has been established that a characteristic feature of the coating structure, which is formed during pulse-plasma (plasma-detonation treatment) is the formation of a substructure 100–300 µm in size and nanoparticles of strengthening phases of the carbide and oxide type, 10–80 nm in size, uniformly distributed over the volume of the structure.

5. The formation of a nanostructural state in such coatings contributes to an increase in their strength and crack resistance.

6. Analytical estimates show that a high level of hardening and crack resistance of the resulting coatings are ensured by the optimal structural-phase composition: a dispersed subgrain structure with a uniform distribution of strengthening phases and a gradient-free level of dislocation density.

7. An increase in the crack resistance of coatings is facilitated by the absence of structural zones of dislocation accumulations with their high density - concentrators of local internal stresses.

8. Plasma-detonation modification provides an increase in the hardness and density of the coating material, which is due to the passage of electric current and healing of defects, as well as accelerated mass transfer of carbon, oxygen, and an increase in the number of carbide and oxide particles in the surface layer.

9. On the basis of the conducted research, it is possible to recommend a duplex technology, including a set of technologies (cumulative detonation spraying of a coating and its subsequent plasma detonation modification) for creating coating materials on the surface of parts operating in extreme operating conditions.

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PHARMACEUTICAL COATING IN THE FORM OF A FILM FOR SOLID ORAL MEDICINES

Oral solid dosage forms (ODS) have advantages such as ease of manufacture and high patient compliance. Tablets are improved by techniques such as coating, double pressing and osmotic systems. Common coating methods include sugar, film, microencapsulation and compression coating [1].

Film coating (FC) is the most versatile method for coating tablets, capsules and granules. FC can be non-functional (to change the appearance and protect against external factors) and functional (to control the release of drugs). Microencapsulation is a modification of FC that differs in particle size and coating methods (mechanical and physicochemical) [1].

A functional coating improves product stability and changes the release pattern, while a non-functional coating improves the appearance and organoleptic properties, making it easier to swallow, especially for elderly patients with dysphagia [2].

Many active pharmaceutical ingredients (APIs) have a bitter taste, which makes it difficult to develop liquid formulations, especially for children. This can be solved by using a film coating, which creates a barrier between the taste buds and the API [3]. For chewable tablets, more complex coating methods are used to slow down dissolution in the mouth without affecting bioavailability (microcapsule coating) [4]. Product stability requires proper packaging, desiccants and moisture barriers, especially for bulk products during transport and after opening the package (Table 1). Moisture barriers stabilise water-sensitive APIs, reducing negative interactions, and should meet ICH Q3C(R6) standards [5].

Table 1

Functions of coating materials

Function	Назва матеріалу
Functional film-forming polymer	Cellulose acetate phthalate
	Hydroxypropyl methyl cellulose phthalate
	Cellulose acetate trimellate
	Ethyl cellulose
	Methacrylic acid copolymer

Non-functional film-forming polymer	Hydroxypropyl methyl cellulose
	Polyvinyl pyrrolidone
	Polyvinyl alcohol
	High molecular weight polyethylene glycol
Solvent or carrier	Water, ethanol, methylene chloride
Plasticisers	Propylene glycol, polyethylene glycols, diethyl phthalate, fractionated coconut oil, castor oil
Colourants	Water-soluble colourants (FD&C Yellow 5)
	Water insoluble colourants (FD&C Yellow 5 Lake)
	Inorganic pigments (iron oxide, titanium dioxide)
	Natural colourants (beta-carotene)

Dry technologies can replace organic solvents. To protect photosensitive APIs, titanium dioxide is used in coatings, with an optimal coating level of 2% [5].

Modification of release is achieved with the help of functional coatings, in particular enterosoluble and extended release. PH-sensitive polymers are used to delay release, and coatings soluble at pH >7 are used for delivery to the colon. Multilayer structures help to control the release [6]. Sustained-release formulations reduce the frequency of dosing, but coating defects can lead to dose drops. Alcohol can impair the effectiveness of these forms [6]. Problems can arise from tablet defects or errors in the coating process, which emphasises the importance of perfect tablet quality prior to coating. Uneven colour can be avoided by using insoluble colourants.

Innovations in pharmaceutical processes are developing coating technologies for a variety of products, including tablets, pellets, catheters and stents, which require sophisticated application methods for controlled drug release [7].

Important trends include the use of process analysis technologies (PAT) for real quality control and the concept of quality by design (QbD), which minimises risks. Continuous pharmaceutical processes reduce costs, shorten time and improve product stability [5].

Film coating (FC) is used to improve taste, dysphagia, and brand image. The choice of films with low moisture permeability improves the stability of water-sensitive APIs, while opacifying agents protect light-sensitive products. Functional films with pH-sensitive coatings improve release, although changes in pH can reduce efficacy, which can be corrected by additives such as alkalising agents or superdisintegrants [7].

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OPTIMIZATION OF THE COMPONENTS OF COMPOSITE MATERIALS USING THE EXPERIMENT PLANNING METHOD

Annotation. The results of research on the calculation of the compositions of the composite material − aerated concrete − with the use of heat energy waste and ferroalloy metallurgy are presented. Using the method of mathematical planning of the experiment, the optimal compositions of aerated concrete for the production of small wall blocks for residential and industrial construction were determined.

Keywords: *composite material, fly ash, silica dust of ferrosilicon production, mathematical modeling*

When calculating compositions, technology and studying composite materials, the majority of experimental studies are formulated as tasks related to determining the optimal ratios between components of compositions and optimal conditions of the technical process. There are different ways to optimize technological factors. Often, such tasks are solved by conducting an experiment, which consists in the sequential study of the influence of each of the factors on the properties of the compositions (the number of components, the value of the parameter, etc.). This method is associated with significant costs of time and materials, since the properties of the composite material are affected by a large number of factors. The method of mathematical planning of the experiment allows to simultaneously vary all factors and obtain quantitative indicators of the main factors and interaction effects [1]. Practical interest lies in obtaining mathematical models and establishing, on their basis, the optimal composition of aerated concrete using waste heat energy and ferroalloy metallurgy.

Currently, the most scarce means of production in the world are raw materials, and especially fuel and energy. Therefore, it is urgent to direct the production of composite building materials to the rational use of raw materials, taking into account the maximum utilization of industrial waste, and to develop, first of all, the production of the least energy- and raw material-intensive materials.

The aim of the work is to use the method of mathematical planning of the experiment to determine the optimal consumption of fly ash of the Kurakhiv thermal power station and waste during the smelting of ferrosilicon of the Zaporizhzhia plant of ferroalloys in porous concrete.

When selecting compositions of composite building materials, the consumption of components is changed under certain conditions, guided by physical considerations. Based on research on the technology, composition and properties of aerated concrete, the consumption of the variation factors was as follows: cement − from 11 to 22 %; fly ash − from 0 to 34 %; waste of ferrosilicon production − from 0 to 8 %. The response function (composite material optimization parameters) is the compressive strength of aerated concrete (**$\sigma_{com\ st}$**), MPa; flexural strength of aerated concrete (**$\sigma_{ben\ st}$**), MPa; softening factor of aerated concrete (**K_{sof}**). Tests of aerated concrete were carried out according to standard methods in accordance with state regulatory documents. The planning matrix of the composite symmetric orthogonal three-level plan of the second order and the results of experiments to determine the mechanical parameters of aerated concrete are given in the table.

Table

Experimental plan, compressive strength (Y_1) and flexural strength (Y_2) and the softening factor of aerated concrete (Y_3)

No. in order	Experiment plan			Experimental data of optimization parameters					
				Y_1		Y_2		Y_3	
	X_1	X_2	X_3	$\sigma_{ст1}$	$\sigma_{ст2}$	$\sigma_{зг1}$	$\sigma_{зг2}$	$К_{р1}$	$К_{р2}$
1	-1	-1	-1	1,91	1,93	0,49	0,51	0,76	0,78
2	0	-1	0	2,31	2,33	0,56	0,58	0,69	0,71
3	1	-1	1	2,74	2,76	0,57	0,59	0,8	0,82
4	-1	0	0	2,23	2,25	0,79	0,81	0,78	0,8
5	0	0	1	2,11	2,13	0,54	0,56	0,82	0,84
6	1	0	-1	1,77	1,79	0,47	0,49	0,75	0,77
7	-1	1	1	2,5	2,52	0,69	0,71	0,76	0,78
8	0	1	-1	2,48	2,5	0,63	0,65	0,71	0,73
9	1	1	0	1,72	1,74	0,49	0,51	0,69	0,71
10	-1	-1	1	2,00	2,02	0,83	0,85	0,83	0,85
11	1	-1	-1	3,34	3,36	0,58	0,6	0,69	0,71
12	-1	1	-1	1,58	1,6	0,47	0,49	0,73	0,75
13	1	1	1	1,76	1,78	0,59	0,61	0,7	0,72

As a result of the conducted statistical processing of the results of the experiment (by determining the regression coefficients), adequate mathematical models were obtained in the form of regression equations [2], which in the natural values of the factors have the following form:

$Y_1(\boldsymbol{\sigma}_{\mathbf{com\ st}})$ = $2{,}170833+0{,}097917X_1-0{,}21018X_2+0{,}038155X_3-0{,}35155X_1X_2-0{,}15321X_1X_3+0{,}130833X_2X_3-0{,}23625X_1^2+0{,}298274X_2^2-0{,}02661X_3^2$;

$Y_2(\boldsymbol{\sigma}_{\mathbf{ben\ st}})$ = $0{,}58696-0{,}05351X_1-0{,}01024b_2X_2+0{,}055894X_3+0{,}011065X_1X_2-0{,}06261X_1X_3-0{,}02487X_2X_3+0{,}033829X_1^2+0{,}015198X_2^2-0{,}02808X_3^2$;

$Y_3(\mathbf{K_{sof}})$ = $0{,}752822-0{,}02098X_1-0{,}01812X_2+0{,}026573X_3+0{,}004267X_1X_2+0{,}001209X_1X_3-0{,}02022X_2X_3+0{,}019674X_1^2-0{,}05604X_2^2+0{,}041698X_3^2$.

The coefficients of the regression equations reflect the relation between the studied properties of the composite material and the content of the components of the technological system. According to the regression equations, the optimal costs of the components of aerated concrete (for which the mechanical parameters meet the requirements of the state standards of Ukraine) were determined, namely: cement content − 13-14%; fly ash content − 30-34%; the content of ferrosilicon production waste is 7-8% (figure).

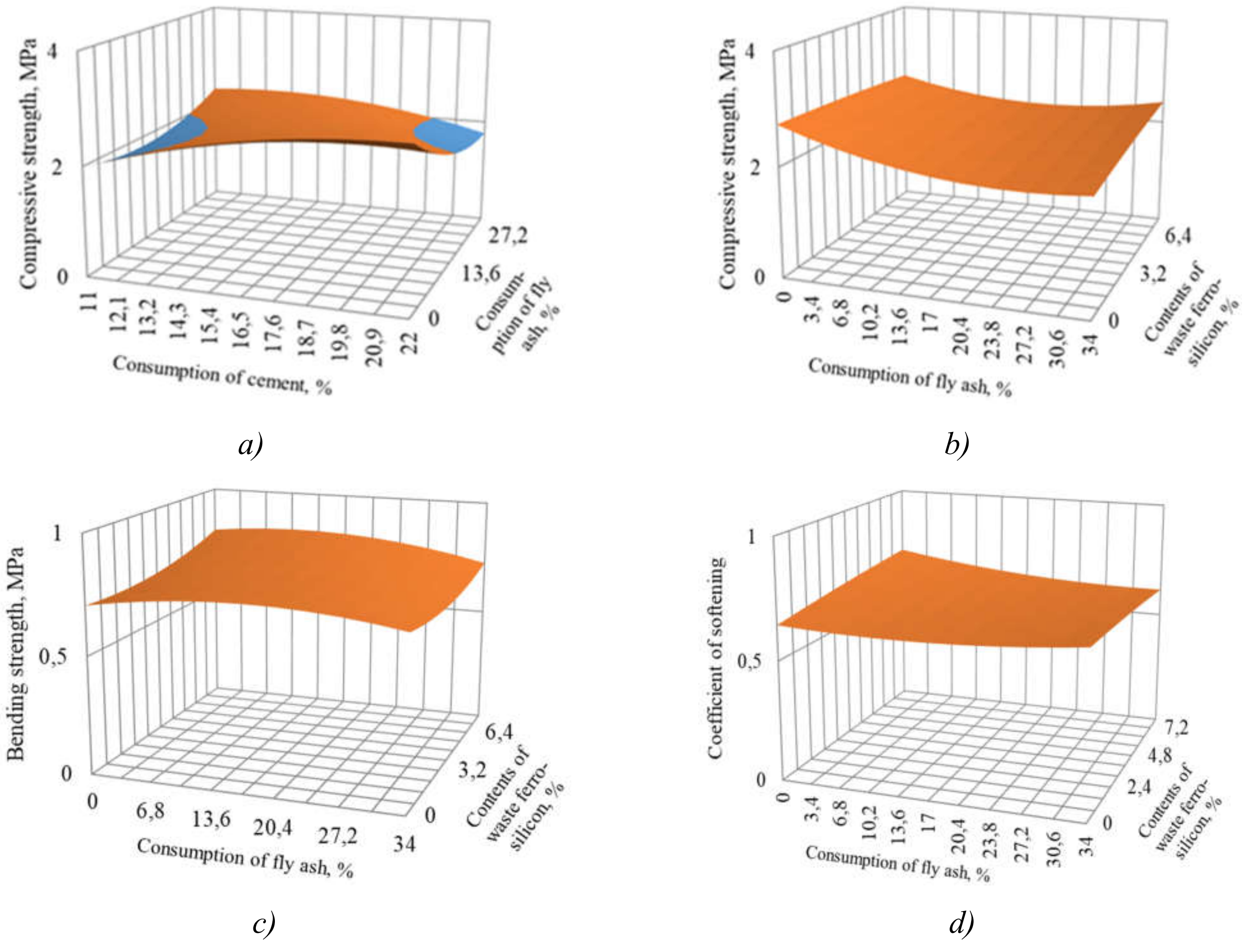

Figure – Dependence of compressive strength of aerated concrete on consumption of cement and fly ash (*a*); of compressive strength (*b*), of bending strength (*c*) and of coefficient of softening (*d*) from consumption of fly ash and of contents of waste ferrosilicon

Conclusions. Using the experiment planning method, mathematical models of composite materials − aerated concrete − were obtained from cement consumption, fly ash and ferrosilicon production waste. Mathematical models in the form of regression equations reflect the influence of the component composition on the properties of composite materials and allow to optimize their compositions. The resulting aerated concrete with the use of heat energy waste and ferroalloy metallurgy meets the requirements of the State Standards of Ukraine.

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WASTE MANAGEMENT FROM BUILDINGS AND STRUCTURES DAMAGED OR DESTROYED BY WARFARE. MAJOR ISSUES AND SOLUTIONS.

Abstract. The management of construction and demolition waste has become a pressing issue in Ukraine due to the widespread destruction caused by the war. This paper examines the primary challenges faced by Ukraine in addressing this problem and proposes potential solutions. The authors explore contemporary approaches to waste management and suggest ways to enhance their effectiveness in the Ukrainian context. Particular emphasis is placed on recycling opportunities and innovative technologies for processing construction waste, as well as the experience of other countries that have faced similar challenges.

Keywords: *construction and demolition waste management, recycling, recycling technology*.

The widespread destruction of infrastructure in Ukraine due to the war has led to a critical shortage of construction waste management solutions. Experts estimate that the country has already amassed 10-12 million tons of such waste, with the figure growing on a daily basis [1].

Ukraine's recycling rate in 2024 is estimated to be less than 10%, while experts believe that it is feasible to recycle 80-85% of waste through industrial processes [2].

Unregulated dumping and storage of hazardous materials in temporary landfills create serious environmental hazards. Major risks include contamination of groundwater and soil by toxic leachate, air pollution from hazardous particulate matter, and the worsening of sanitary and epidemiological conditions [1].

The construction waste resulting from explosions and shelling is distinct from "standard" waste due to its composition of diverse, structurally different materials, complicating its recycling.

All construction elements, materials, and objects that were located in a residential, industrial, or public building become uncontrollably mixed and deformed as a result of an explosion. Consequently, it becomes extremely difficult to separate the particles of these materials from other waste. Hazardous building materials, such as asbestos-cement sheets commonly used for roofing, pose a significant challenge. If not properly separated from other materials, all waste must be disposed of in a landfill.

According to the Ukrainian Institute of the Future, nearly 50% of all construction waste is disposed of in landfills. The situation with landfills across the country is critical, as most of them have long been operating beyond their capacity [3].

The system for managing waste from destruction consists of the following stages:

1. Nitial site clearance: Collection of demolition waste, including potential sorting of individual waste components.
2. Transportation of demolition waste from the generation site to waste processing facilities or interim storage locations.
3. Final site cleanup following demolition of damaged or destroyed structures.
4. Temporary storage of demolition waste at designated sites or waste processing facilities until final disposal or recovery.
5. Preparation of demolition waste for recycling or disposal.
6. Recycling of demolition waste as secondary material or energy resources [4].

Table 1

Construction Waste Management Strategies

Name	Advantages	Disadvantages
incineration	- Significant decrease in waste volume; - Electricity generation; - Reduced transportation expenses.	- Release of toxic substances; - Substantial financial outlay for waste incineration facilities.
burial	- Low costs; - No need for waste processing facilities; - Minimal maintenance.	- Large landfill areas; - Environmental poisoning and pollution.
recycling	- No need for large areas to establish landfills; - Conservation of natural resources; - Minimizing negative environmental effects; - Reducing production costs; - Universality of recycling management methods for various construction materials.	- Significant upfront costs; - Slow return on investment; - Imperfect regulatory framework.

Globally, only three technological approaches exist for managing construction waste (see the table 1). Classification of construction waste management methods based on processing location (table 2).

Table 2

Construction waste management by territorial factor

Type of processing	Advantages	Disadvantages
On-site recycling at the demolition site	- There are no additional transportation costs; - Discount on the recycled product.	- Low equipment efficiency; - Low product quality; - Increase in noise level; - High particulate matter.
Processing at specialized enterprises	- High equipment productivity; - Superior quality of the recycled product.	- The presence of additional costs for transporting construction waste; - High recycling cost.

The experience of using demolition waste in various countries has been analyzed.

Countries like Denmark, the Netherlands, and Germany have a mandatory requirement for new construction to incorporate a certain percentage of recycled materials.

Austria recycles approximately 87% of construction and demolition waste. Waste collection is typically carried out on-site using containers, and is handled by specialized demolition and waste management operators.

Flanders (Belgium) has taken the most radical approach to combatting construction waste landfilling, implementing a direct ban on landfills for secondary processing of construction waste fractions. This approach is driven by Flanders' high population density and the scarcity of available space in existing landfills.

The Netherlands has had a law in place for nearly a decade that prohibits the disposal of recyclable construction waste in landfills. In some other countries, official proof that waste cannot be recycled is required before it can be accepted at a landfill [5, 6].

In Ukraine, there are already companies that can process various construction materials. For example, «Metinvest», «ArcelorMittal Kryvyi Rih», and the Zaporizhzhia and Dnipro metallurgical plants handle metal recycling.

Glass recycling is carried out by companies «Region-2001», «Vetropak», and «UtilVtorProm», concrete – «Caris», «TechConstructionMechanics», «AgroIndustrialGroup», «Tereschenko Group», «Organ». Plastic – «Ecola», «TIC», «Region-2001», «The Good Plastic Company», bricks – «Actis Group», «Forest Ukraine» and «UtilTorProm». Timber is usually processed in state-owned forestry enterprises located in every region of Ukraine. [7].

In this paper, the authors analyze the challenges of waste management arising from the damage and destruction of buildings and structures caused by hostilities. The main issues we have identified are:

– There is a significant lack of specialized infrastructure and advanced technologies in Ukraine for the collection, sorting, transportation, storage, processing, and disposal of complex construction waste streams. Many communities address the problem of construction waste disposal by transporting it to landfills.

– Regulatory and standardization gaps exist. The current regulatory framework contains significant gaps in the comprehensive regulation of recycling and construction waste management. Standards for the quality and safety of construction materials made from secondary raw materials are absent.

– Lack of economic incentives. Effective financial and economic mechanisms to stimulate the collection, sorting, and recycling of construction waste have not been established. The cost of disposing of construction waste remains low, making recycling unprofitable. Secondary materials are not competitive in Ukraine, partly due to the low cost of raw materials. Primary construction materials in Ukraine are significantly cheaper than secondary ones due to low rent on mineral extraction. Therefore, it is necessary to reform the pricing of natural resources and ensure the competitiveness of recycled materials on the market.

Unresolved social aspects. There is an urgent need for widespread information and education campaigns to promote a culture of waste management among the population and businesses.

In our view, the following actions are key to addressing the effective management of waste generated by the damage and destruction of buildings and structures as a result of hostilities:

1. Development and government support for projects, startups, research, and innovation in the following areas: - improving recycling technologies; - creating new eco-friendly materials based on recycling; - addressing local recycling and disposal of 'wartime' construction waste based on best European practices.

2. The need for a comprehensive legislative framework to regulate the management of construction waste is urgent. The presence of hazardous materials such as asbestos in mixed waste from shelled buildings poses significant challenges for recycling. Specialized technologies and regulations are required for the safe handling and disposal of these materials.

3. Development of national quality and safety standards for construction materials and structures made from recycled materials. A regulatory document is needed that mandates the use of recycled building materials in reconstruction projects.

4. Training and certification of specialists in waste management.

5. Maintaining detailed records and statistics on construction waste recycling to assess the effectiveness of initiatives and plan future actions.

6. Implementation of a system of tax, customs, and credit incentives to promote the use of recycled materials in construction and industry. As a means of economically stimulating enterprises in the construction waste recycling sector, we propose the use of tax breaks for businesses, reduced-interest loans, financial risk insurance, and subsidies from various levels of government to support innovative projects requiring significant capital investment. A public-private partnership model would be instrumental in attracting increased private investment in this sector.

7. Raising environmental taxes and royalties on primary resource extraction and CO_2 emissions to boost demand for secondary raw materials.

8. Implementing an educational initiative to inform stakeholders about the benefits of green building and proper waste disposal.

9. Actively seeking international technical assistance and grants to develop modern infrastructure for sorting, recycling, and disposal of construction waste in Ukraine.

Conclusion. 1. The domestic recycling of construction waste offers a promising avenue for sustainable development. By effectively managing construction waste, we can mitigate environmental impacts, create new economic opportunities, and foster a circular economy for construction materials.

2. Effective management of waste generated from the damage and destruction of buildings and infrastructure due to hostilities is possible through collaboration between businesses, government agencies, and international financial institutions involved in Ukraine's reconstruction. This collaboration will create a transparent legal and regulatory framework, laying the foundation for a sustainable and efficient system of cooperation and enabling the launch of large-scale recovery projects based on the principles of a circular economy and eco-design.

3. Addressing the issue of waste generated from the damage and destruction of buildings and infrastructure due to hostilities will contribute to the effective reconstruction and sustainable development of Ukrainian cities, preserving the environment and saving resources.

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ТИТАНОВІ ПОРОШКОВІ МАТЕРІАЛИ НЕСФЕРИЧНОЇ ФОРМИ ДЛЯ АДИТИВНИХ ТЕХНОЛОГІЙ

У роботі показано принципову можливість використання більш дешевих порошкових матеріалів на основі титану, що за хімічним складом відповідає марці сплаву ВТ1-0, з несферичною формою частинок, що отримують за технологією гідрування-дегідрування і призначених для виготовлення об'ємних виробів різними методами адитивних технологій. Проведено металографічні дослідження зразків, отриманих з несферичних порошків, що показало високий рівень адгезії шарів без видимих несуцільностей.

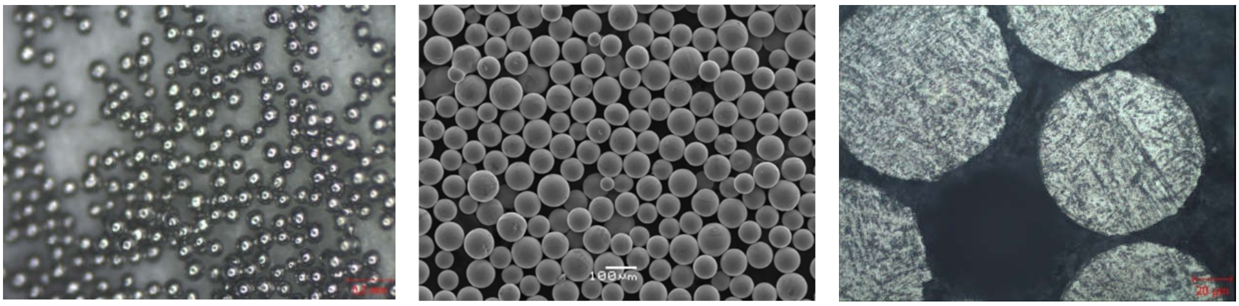
Ключові слова: *адитивні технології; титан; порошок; частинка; форма; фракція; поверхня; шар; компактування; сплавлення; структура; властивості.*

Застосування адитивних технологій є перспективним напрямком у розвитку різних галузей промисловості (особливо таких як високоточне машинобудування та авіадвигунобудування), що дає змогу одержувати готові вироби, а також виготовляти необхідне в промисловості технологічно складне оснащення. Найважливішим завданням при цьому є заміна наявних дорогих імпортних порошкових матеріалів дешевшими аналогами.

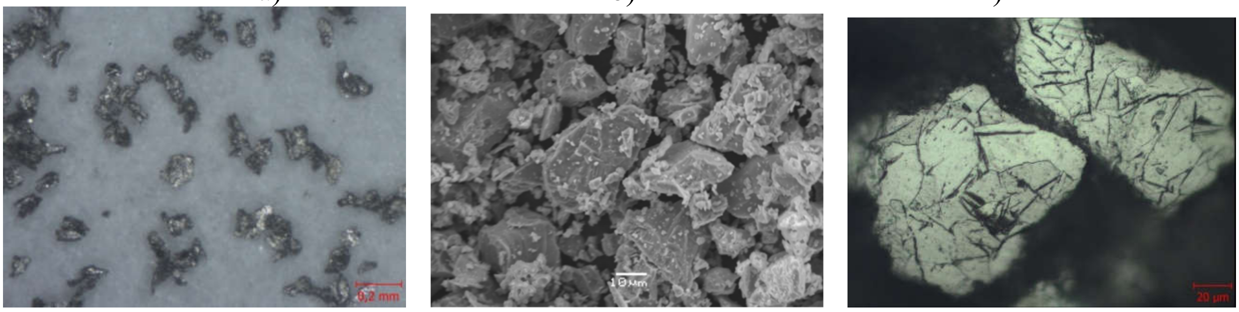
Ці технології дають змогу об'єднати в собі головні переваги таких методів отримання виробів, як порошкова металургія, ливарне виробництво та наплавлення. Зазначені технології передбачають виготовлення виробу методом пошарового додавання матеріалу [1–4].

Метою досліджень є оцінка можливості використання титанових порошків, які попередньо піддавали операціям гідрування та дегідрування в технологічному ланцюгу їх виробництва для подальшого отримання виробів різними методами адитивних технологій.

На рисунку 1 наведено реальні частинки металічного порошку (сферичного титану та порошку титану, отриманого за технологією гідрування-дегідрування [5–7]), що відповідають спрощеним моделям, представленим у роботах [8–9], різних типів укладання гіпотетичних частинок тієї чи іншої форми.



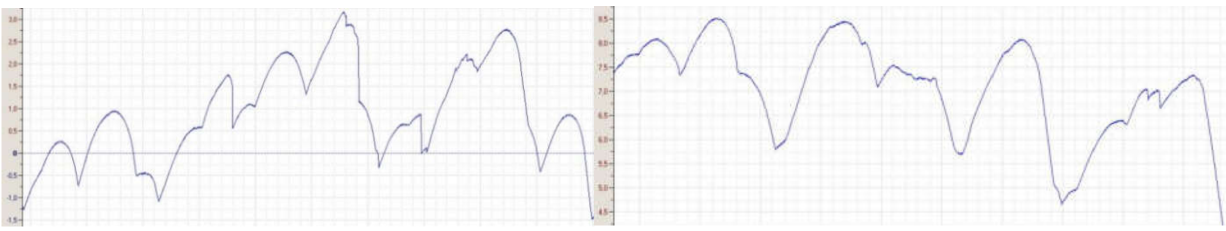
а) б) в)



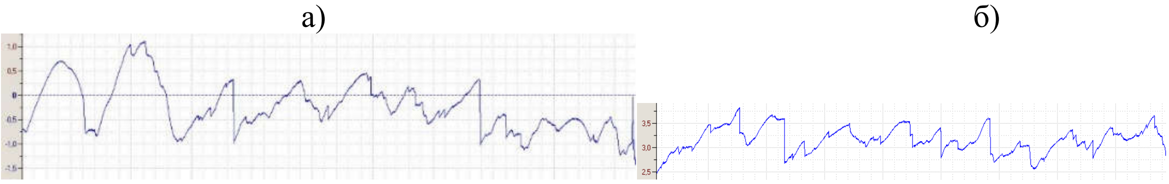
г) д) е)

Рисунок 1 – Зовнішній вигляд і структура сферичних (а, б, в) і несферичних (г, д, е) порошків титану (фракція – 100 мкм)

Методом профілювання насипаних і закріплених на підкладці порошкових шарів мінімальної товщини із застосуванням різних фракцій показано, що оптимальна зовнішня поверхня отримується за умови використання порошкового матеріалу, в якому частинки мають форму багатогранників, умовно прийнятих за об'єкти, які за формою наближаються до частинок, у вигляді гексаедрів та їх різновидів. Використання таких порошків має забезпечити більш щільну та однорідну структуру у порівнянні з порошками сферичної форми [10]. Попередні графічні результати експериментів із використанням зазначеного приладу наведено на рис. 2.



а) б)

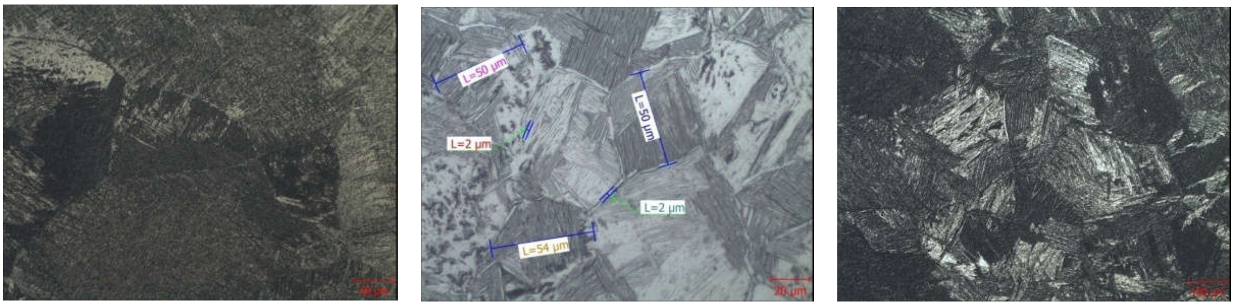


в) г)

а, б) сферичний порошок фракцією -200+100 мкм; в) несферичний порошок фракцією -250+100 мкм; г) несферичний порошок фракцією -50 мкм.

Рисунок 2 – Результати дослідження порошків на профілографі-профілометрі

На наведеній (рис. 3) мікрофотографії багатошарового зразка з нелегованого титану (отриманого сплавленням за технологією електронно-променевого сплавлення та аргонодугового наплавлення) показано досить хороший рівень адгезії шарів без будь-яких видимих дефектів, типу несуцільностей (раковин або непроплавів).



а) б) в)

а) метод електронно-променевого наплавлення б, в) метод аргонодугового наплавлення

Рисунок 3 – Мікроструктура дослідних зразків отриманих за технологією пошарового нарощування з титанового порошку (фракція -250+100 мкм)

Розглянуто можливість застосування різних джерел енергії та способів для пошарового нарощування матеріалу при формуванні виробів – автоматичне електронно-променеве наплавлення та ручне аргонодугове наплавлення. Визначено оптимальні режими процесів покрокового сплавлення тонких шарів порошкових матеріалів. Проведено металографічні дослідження зразків, отриманих з несферичних порошків, що показало високий рівень адгезії шарів без видимих несуцільностей.

Наплавлення порошку за хімічним складом, що відповідає марці сплаву ВТ1-0, здійснювали методом ЕПН (електронно-променевого наплавлення) на установці ЕПЗ-20, з попереднім насипанням порошку. Швидкість наплавлення становила 1,11 мм/с; струм наплавлення 40...50 мА; струм фокусування 605...610 мА. Аргонодугове наплавлення проводили вручну з пошаровим насипанням і оплавленням порошку в камері з контрольованим середовищем (інертний газ – аргон). Режим наплавлення був приблизно однаковий для всіх зразків (зварювальний струм до 30 А, джерело струму Fronius TT3000).

З наведених вище рисунків видно, що отриманий (сплавлений) шар матеріалу характеризується наявністю рівновісної, однорідної, щільної та безпористої структури без будь-яких видимих дефектів (у вигляді несуцільностей або пор). При цьому, структура дослідних зразків наближена до структури заготовок, отриманих методами лиття. Таким чином, можна констатувати, що відносно дешевий порошок, отриманий за технологією гідрування-дегідрування, є перспективним з погляду заміни наявних дорогих порошків титану сферичної форми.

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PROSPECTS FOR OBTAINING FINE-GRAINED AND POWDERED MATERIALS FROM DESTROYING WASTE IN THE AREA OF THEIR FORMATION

Abstract. The feasibility and efficiency of recycling of waste from demolitions by a mobile crushing and sorting line in the area of their formation are considered. The conducted studies on crushing waste on a vibrating jaw crusher with an inclined chamber show the prospect of processing with the production of marketable products.

Keywords: *destroying waste, crushing and sorting line, fine-grained and powder materials*.

As a result of military actions related to russian aggression, a huge number of completely (Fig. 1, a) or partially (Fig. 1, b) destroyed buildings and structures were formed in Ukraine.

a) completely

b) partially

Fig.1 Destroyed buildings

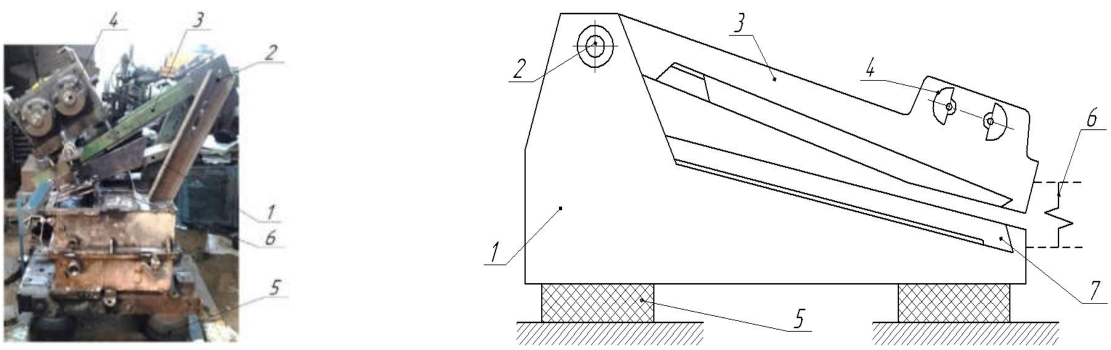
The results of a large study conducted by a group of American scientists, published in The New York Times, show that about 210 thousand buildings were destroyed in Ukraine between February 2022 and December 2023 alone. Unfortunately, this figure continues to increase. Hundreds of thousands of tons of destruction waste are added to existing industrial and construction waste, which include [1] parts (debris) of damaged (destroyed) objects, as well as materials, objects that were inside or next to such objects at the time of damage (destruction) and/or performance of dismantling works and which have completely or partially lost their consumer properties and cannot be used in the future at the place of their formation or discovery. Such a huge amount of waste generated in a relatively short period of time cannot be processed at existing plants.

The scale of the upcoming task of rebuilding devastated cities and disposing of waste in an environmentally sound manner is almost unimaginable, both for ordinary entrepreneurs and lawmakers. The Law of Ukraine "On Waste" [2], the Law of Ukraine "On Waste Management" [1] legalized the procedure for performing work and the executors, established responsibility for dismantling, sorting (if possible), removal of waste from destruction to specially created temporary storage places.

The complex process of destroying waste management begins with manual disassembly and potential initial sorting. The disassembled waste from each destroying area is taken to a sorting station, where the waste is classified based on its material composition. Due to the small area of the sorting stations, relatively small volumes are formed here, which are delivered to specialized secondary resource recovery centers. They can accumulate large volumes of secondary raw materials in their warehouses, sort them, and then sell them to factories that directly process these secondary raw materials.

Existing enterprises do not have sufficient capacity for their complete processing, obtaining marketable products and secondary raw materials, which is one of the reasons for the removal of construction waste to created landfills or existing dumps. As a result, thousands of hectares of land suitable for agricultural or industrial use are removed from rational use, the environment deteriorates, greenhouse gas and hydrogen sulfide emissions increase, and the risk of soil and groundwater contamination with harmful chemical compounds arises. The extremely serious problem that has arisen can be partially solved by using mobile and portable crushing and sorting lines directly at the site of the destroyed buildings (a rational option) or at special landfills. The use of existing mobile crushing and sorting lines is not rational for manual dismantling of destruction, since they are designed for large-tonnage production, are focused on crushing concrete and brick, have large dimensions and power. An efficient crushing and sorting line should be small in size, with a high degree of crushing, a wide range of final product sizes and an expanded range of processed materials.

At Dnipro University of Technology research was conducted on waste crushing using a vibrating jaw crusher with an inclined crushing chamber. The crusher (Fig. 2) includes a passive (lower) crushing jaw 1, mounted on elastic elements 5 and simultaneously performing the function of a body.



a) general view b) structural diagram of the crusher

Fig.2 Vibrating jaw crusher with inclined crushing chamber

The active jaw 3 is installed in the passive jaw posts by means of the suspension axis 2, relative to which it can perform rotary oscillations. The oscillations of the jaws are generated by a two-shaft inertial vibration exciter 4. The destruction of the material occurs in the crushing chamber formed by the working surfaces of the passive 1 and active 2 jaws. The design feature of the crusher allows loading the initial material and unloading the crushed product in a horizontal plane, which is especially important when processing sheet material [3].

The laboratory sample of the crusher was used to conduct research on the processing of gypsum board, sheet glass, glass containers, brick, concrete, marble, and triplex. The figures below show some of the final crushing results.

a) b)

Fig. 3. Crushed sheet glass waste at the discharge gap: a – 0 mm, b – 10 mm

The obtained fine-grained and powder fractions of sheet glass can be used for the production of fiberglass, foam glass, glass ceramics and glass ceramic tiles, facing bricks, fillers for plastics, rubber, paints and other materials.

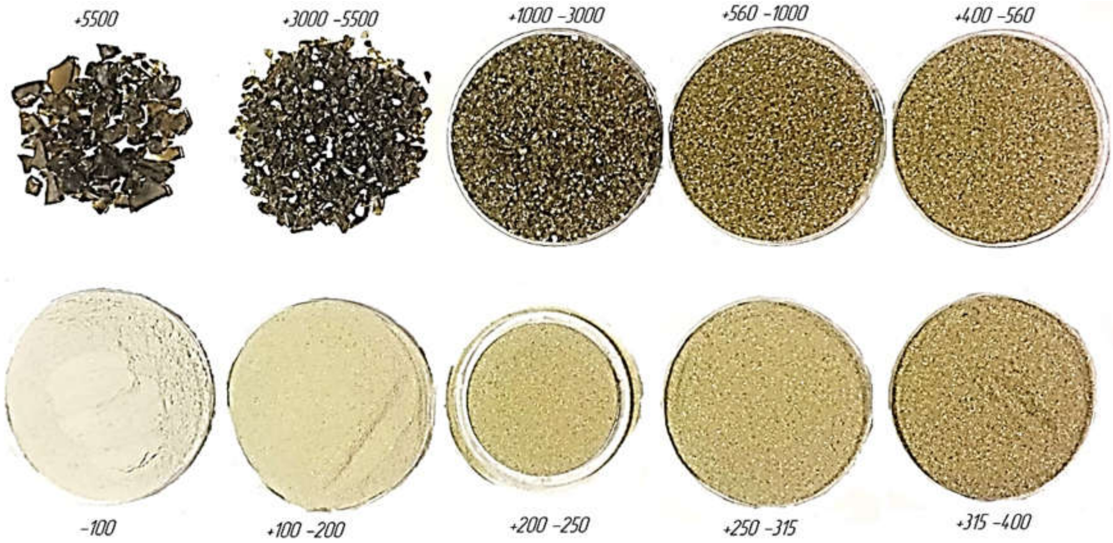


Fig.4. Distinguished size classes (μm) of brown container glass

All selected fractions of container glass are commercial products.

Fig.5. Crushed gypsum component of gypsum board

The fraction of gypsum board 0 – 200 microns after calcination restores the properties of gypsum and can be used in the production of gypsum board, building material, etc. Larger fractions, as finished commercial products, are used in agriculture, cement, landscape design, etc.

The conducted studies show the feasibility and prospects of recycling destroying waste at the place of its formation, thereby obtaining marketable products, reducing transportation costs, eliminating spontaneous dumps in forest plantations, fields, etc., reducing the load on landfills and reducing the land areas allocated for them, improving the environment, and the owners of destroyed sites using the resulting product when creating their own facilities or selling to customers.

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IMPROVEMENT OF THE DESIGN OF THE FITNESS HOOK MODEL WITH EXPLANATION OF THE MATERIAL AND MANUFACTURING TECHNOLOGY

Abstract. A modified model of J-shaped fitness hooks has been developed for performing barbell exercises such as squats, military presses, shrugs, and more, which are mounted on racks in gyms. The properties of traditional materials for the manufacture of fitness hooks and their manufacturing using 3D printing technology were analyzed. The choice of material is explained, and a model is developed that has a simplified design with fewer components and reduced material consumption. The results of modeling the design of fitness hooks are presented and a simulation study of their strength indicators is carried out through the analysis of the stress-strain state.

Keywords: *J-shaped hooks, fitness hooks, racks, load, steel, polymers, materials, additive technologies.*

The object of study for this project was the BFJ Combo Roller J-Hooks fitness hooks from BRIDGE [1]. Fitness hooks are used to fix a barbell with sports plates, the weight of which can reach 300 kg, and in some cases even more. Therefore, the main load falls on the part of the hook on which the barbell is placed.

Fig. 1. Fitness Hooks BFJ Combo Roller J-Hooks by «BRIDGE».

The use of a combination of polymer and steel structural elements was considered. As a basis (Fig. 2, b), we used strength materials that are resistant to dynamic load: stainless steel 440C, titanium alloy Grade 2 (6AI-4V) and aluminum alloy 6061 [2, 3]. The properties of these alloys are shown in Table 1.

Table 1

The properties of metals for the first version of the fitness hook design

Material	Density, kg/m^3	Young's Modulus, GPa	Strength, MPa
Steel 440C	7800	206,7	861,25
Titan Grade 2 (6AI-4V)	4510	102,81	344,5
Aluminum alloy 6061	2700	68,9	310

After comparing the materials, 440C steel with a high carbon content (0.95-1.2%) was chosen, which guarantees high strength and the ability to withstand heavy load. This steel is corrosion resistant, which makes it indispensable for use in sports equipment. Additional structural elements of the product (Fig. 2, a) are made of UHMW Black polymers.

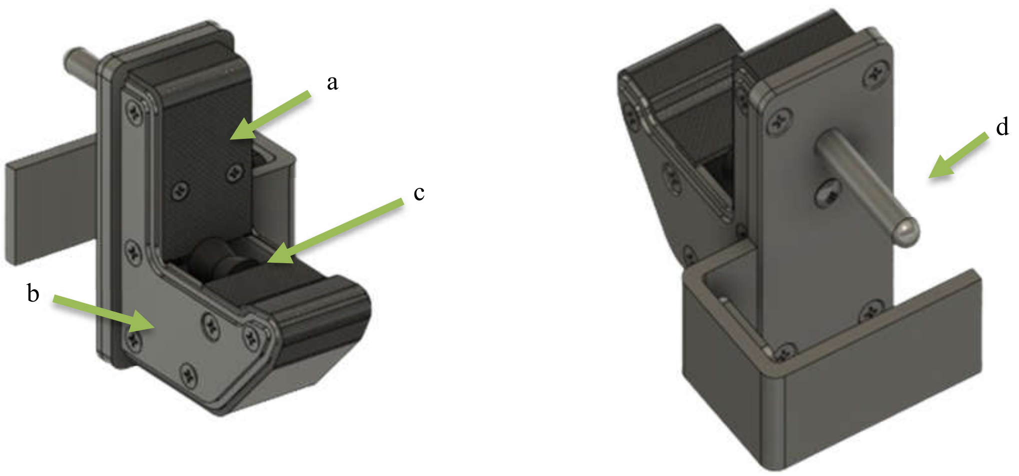

Fig. 2. Model of the first version of the fitness hook:
a - additional elements, b - base, c - roll, d - rod.

The basic concept of the fitness hook is to have a roller made of UHMW Black plastic in the middle of the structure, which allows you to adjust the position of the bar for comfort during exercise. The shaft rotates thanks to a bronze plain bearing [4] on a 440C steel rod that is fixed inside the structure and holds the fitness hook on the rack.

During the simulation [5], a loading force of 3000 N was taken. The calculation shows that the design is able to withstand the load from the barbell bar with a total weight of 300 kg. The weakest point of the structure is the bending zone and the roll (Fig. 3, a), which may undergo slight deformation with increasing load. This is confirmed by the deformation simulation model, which demonstrates the behavior of the structure under an applied load of 5000 N (Fig. 3, b).

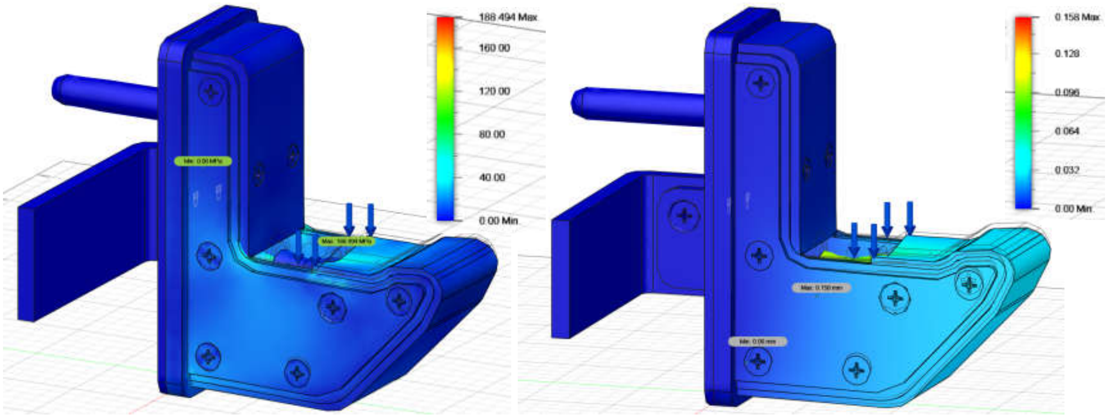

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Fig. 3. Results of simulating the load on the hook and bend point

An analysis of the traditional design of a fitness hook has revealed the presence of a significant number of components that complicate the production process and lead to increased material consumption. In this regard, a modified model of a fitness hook made of polymeric materials using 3D printing technology is proposed, which simplifies the design and reduces material consumption. The material properties for the 2nd version of the fitness hook are shown in Table 2.

Table 2

The material properties for the 2nd version of the fitness hook

Shaft material				Material of the main components			
Material	Strength, MPa	Density, kg/m^3	Young's Modulus, GPa	Material	Strength, MPa	Density, kg/m^3	Young's Modulus, GPa
EPX 150	79	1090	2,9	EPX 82	80	1,16	2,8
Thermoplastic Resin	114	1280	3,3	Nylon 12	82,8	1,13	2,93
Rubber nitrile	15	1200	0,002	Polyetherketoneketone	61	1,39	5,8

As in the previous version, the roll is rotated by a plain bearing on a rod fixed in the middle of the product, which requires lubrication. Thermoplastic Resin was chosen for the roll to provide the necessary flexibility and elasticity.

The material used for the main components is EPX 82 (Carbon), which has high strength and wear resistance. Additionally, the model provides for the use of threaded rods for attaching the fitness hook to the rack (Fig. 4), which will slightly increase production costs but increase the stability of the attachment.

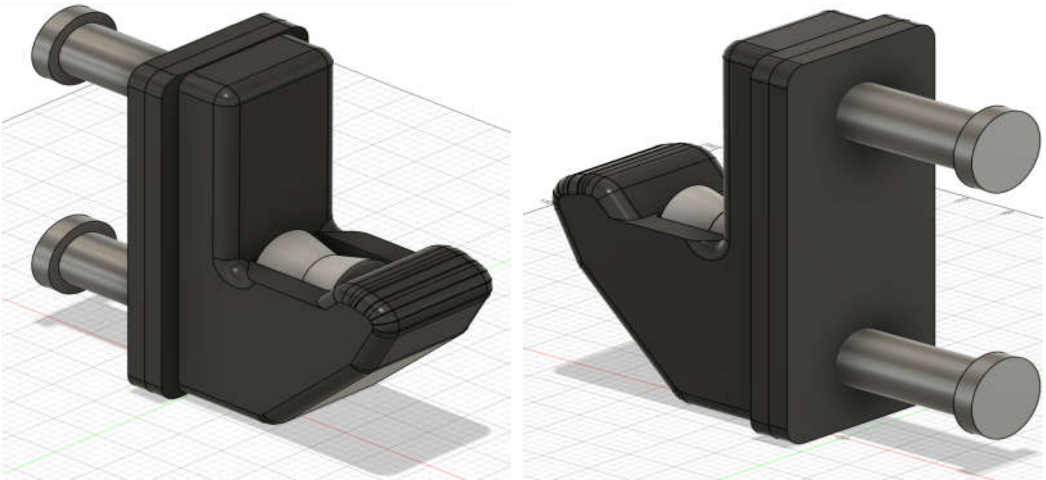

Fig. 4. Model of a 3D printed fitness hook

A simulation was developed (Fig. 5, a), which revealed that the load is carried out on the rubberized roll of the product, which can withstand a fingerboard weighing 300 kg. At higher loads, the deformation is transferred to the limbs of the fitness hook, which is insignificant and will not lead to destruction (Fig. 5, b).

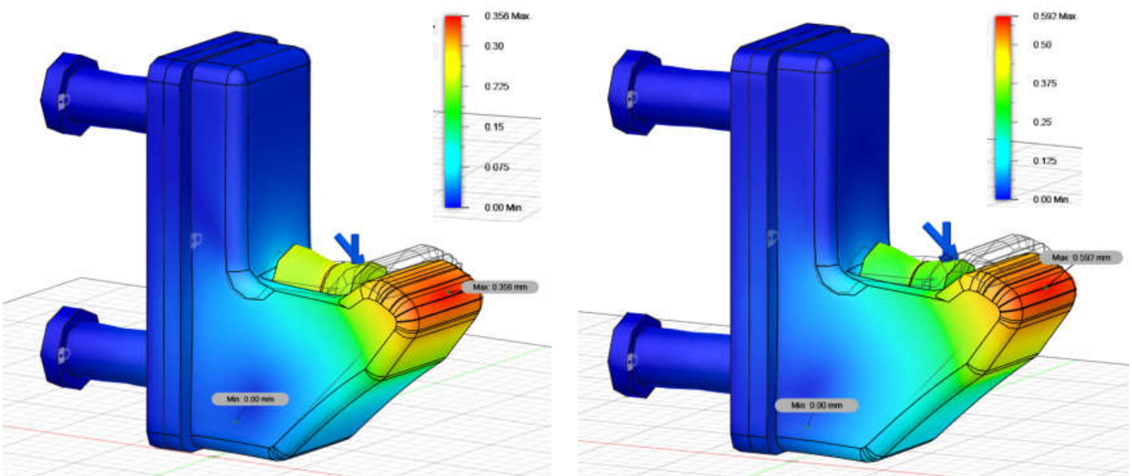

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Fig. 5. Fitness hook load simulation:

a - load 3000 N, b - load 5000 N

The analysis of the design of traditional fitness hooks has revealed the presence of a large number of components that complicate production and increase material costs. A modified model has been proposed that will reduce the number of assembly components by using 3D printing technologies to manufacture lightweight and durable structures that reduce overall production costs.

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POTENTIAL AND PROSPECTS OF USING ALTERNATIVE FUELS IN PISTON ENGINES OF HYBRID POWER SYSTEMS

Abstract. This article examines the advantages and prospects of using such fuels as biodiesel, hydrogen, and methanol. Mathematical modeling of piston engine operation with various fuel types has been conducted. Numerical methods were applied to analyze combustion processes and evaluate the performance of alternative fuels. The results demonstrate the potential for reducing energy consumption and harmful emissions.

Keywords: *biodiesel, hydrogen, methanol, engine, numerical methods.*

Introduction. Modern internal combustion piston engines, which are widely used in vehicles and industrial power systems, primarily run on fossil fuels-oil, natural gas, and coal. Burning these fuels results in substantial emissions of carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulates, which contribute to global warming, acid rain, and other environmental issues. The increasing number of vehicles exacerbates these negative impacts, underscoring the need for more environmentally safe technologies [1].

Research points to the advantages of alternative fuels over traditional ones. For instance, biodiesel exhibits higher environmental performance and lower CO_2 emissions, while hydrogen releases only water vapor upon combustion, minimizing climate impact [1]. However, each fuel type has technical limitations that must be addressed for stable piston engine operation.

The objective of this study is to analyze the advantages and prospects of using alternative fuels in piston engines within a hybrid power system and to perform a mathematical analysis of the combustion process of alternative fuels in such engines. The primary parameters considered in modeling include cylinder pressure and temperature, fuel composition and properties, reaction kinetics, and heat exchange between the cylinder walls and the working medium. The task is to create a mathematical model that allows for predicting the combustion efficiency and environmental performance of various alternative fuels [2].

Three main groups of equations are used for modeling the combustion process: mass balance, energy, and chemical reaction equations. When burning alternative fuels, it is essential to account for the mass balance of each component of the fuel mixture and the combustion products. The mass balance equation can be expressed as:

$$\frac{d}{dt}(\rho V) + \nabla \cdot (\rho u V) = \sum \dot{m}_{in} - \sum \dot{m}_{out}, \tag{1}$$

where ρ – density of the working mixture; $\nabla \cdot (\rho v)$ – divergence of mass density flow; V – cylinder volume; u – speed; $\dot{m}_{in}$, $\dot{m}_{out}$ – mass flow of input and output components.

For describing heat transfer and determining the amount of energy released during combustion, the energy equation is applied:

$$\frac{d}{dt}(E) = \dot{Q} - \dot{W}, \tag{2}$$

where E – internal energy of the system; $\dot{Q}$ – heat added to the system; $\dot{W}$ – work done by the gas.

Heat losses through the cylinder walls and the efficiency of heat transfer to the working mixture are also considered. The combustion of alternative fuels, such as hydrogen or biodiesel, involves a series of chemical reactions. These reactions are mostly described by a system of differential equations.

$$\frac{dC_i}{dt} R_i(C_1, C_2, \ldots C_n), \tag{3}$$

where C_i – concentration of the i-th substance; R_i – reaction rate for each component.

In the case of hydrogen, the main reaction is described by a formula $2H_2 + O_2 \rightarrow 2H_2O$, that ensures high combustion efficiency and minimal harmful emissions. To achieve optimal performance of the hybrid power unit, numerical modeling methods are used, allowing for the evaluation of the efficiency and environmental impact of alternative fuel combustion under various parameters. The optimization of the fuel mixture involves finding the optimal air-to-fuel ratio that will provide maximum energy efficiency and minimal levels of harmful emissions.

$$ER = \frac{m_{air}}{m_{fuel}}, \tag{4}$$

where ER – air/fuel ratio; m_{air} – air mass; m_{fuel} – mass of fuel.

Boundary conditions for temperature and pressure are set depending on the type of fuel and engine design [3]. As part of the study, we will create a model that describes the combustion processes, fuel consumption, and harmful emissions for a hybrid power unit using a piston engine. To achieve this, we will examine the fuel combustion energy equation:

$$Q = m \cdot H_u \cdot \eta \tag{5}$$

where Q – is the total thermal energy released during combustion (J); m – is the mass of fuel (kg); H_u – is the lower heating value of the fuel (J/kg); η – is the combustion efficiency, which accounts for heat losses and incomplete fuel combustion. Fuel consumption (Specific Fuel Consumption, *SFC*):

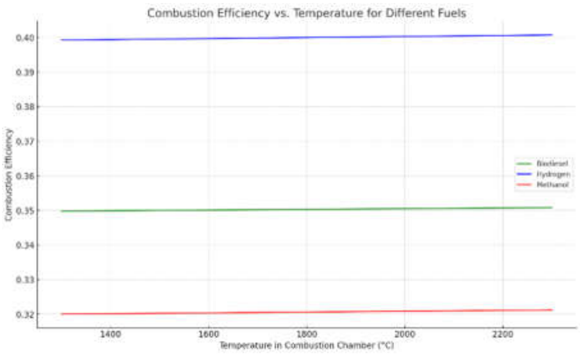
$$SFC = \frac{m}{P \cdot t}, \tag{6}$$

where *SFC* – is the specific fuel consumption (kg/kW·h); *P* – is the engine power (kW); *t* – the operating time on the selected fuel (h).

The emission level can be calculated as a function of the air excess ratio λ and combustion temperature. For example, the CO_2 emission level can be described as follows [4]:

$$E_{CO_2} = k \cdot \frac{m \cdot C}{M}, \tag{7}$$

where: E_{CO2} – the mass of emissions CO_2; *k* – coefficient depending on complete combustion; *C* – carbon content in fuel; *M* – fuel molecular weight.



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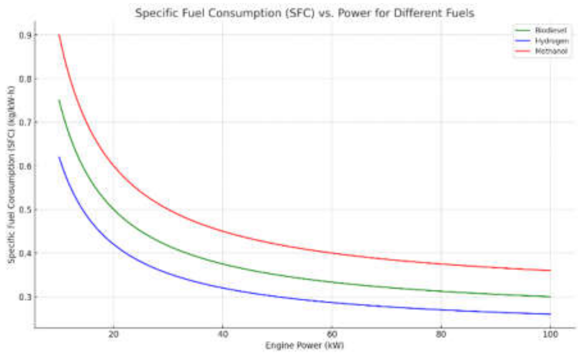

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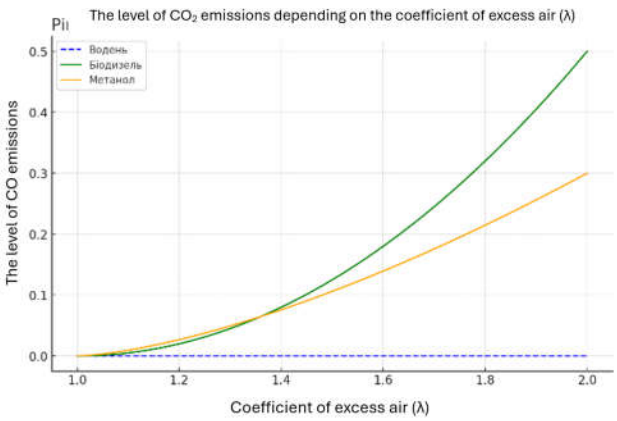

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Figure 1 – Comparison of combustion efficiency, specific fuel consumption, and CO_2 emission levels for different types of alternative fuels in piston engines

In Figure 1, graph 1 should indicate the relationship between combustion efficiency and temperature, graph 2 should show specific fuel consumption (*SFC*) as a function of engine power, and graph 3 should illustrate CO_2 and NO_x emission levels as a function of the air excess ratio.

Conclusions. The study results indicate that the use of hydrogen provides zero CO_2 emissions, high fuel efficiency, and improved performance metrics, making it ideal for environmentally oriented applications. Methanol, due to its properties, offers a balance between environmental friendliness and cost, while biodiesel serves as a reliable option for engines where fuel stability and high energy density are crucial.

The adoption of alternative fuels significantly reduces greenhouse gas emissions, improves fuel efficiency, and lowers operational costs, which are crucial factors under modern environmental regulations [5]. Future research prospects lie in enhancing existing mathematical models for more accurate simulation of alternative fuel combustion processes and a comprehensive analysis of hybrid power unit characteristics.

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FLY ASH FROM THERMAL POWER PLANTS – A VALUABLE TECHNOGENIC RAW MATERIAL IN THE MANUFACTURING OF COMPOSITE MATERIALS

Annotation. Ash and slag waste are man-made mineral formations that are produced in large quantities and pose a serious environmental hazard. On the other hand, it is a valuable mineral raw material for obtaining various materials. The presented results showed the possibility of extracting useful components (carbon, iron, aluminum, silicates from fly ash and using them in the manufacture of various composite materials.

Keywords: *composite materials, ash and slag waste, fly ash, extraction of useful components.*

Composite materials (CM) have been known for a long time in human history. Thus, reinforcing marble columns with metal rods was used back in Ancient Greece. The very first industrial composite material is considered to be reinforced concrete, widely used since the end of the 19th century. As is known, composite materials are artificially created materials and consist of two or more chemically different components that differ significantly in properties and are separated by a well-defined intercomponent boundary. They are introduced into the composition of composite materials in order to give them properties that each of the components does not have separately. By changing the size, location, mass and volume ratio of the components, it is possible to obtain materials with the necessary characteristics of physical, mechanical, operational and other properties. Any CM consists of a matrix – a component continuous in the volume of the material, and filler – a discontinuous component in the form of discrete particles of various shapes, placed in it according to a given pattern and united by a matrix. It can perform the functions of both reinforcement (in the CM design) and filler that determines the functional characteristics of the material (thermo physical, electrical, magnetic, tribotechnical, etc.). The scope of application of CM is enormous: aviation technology, astronautics, ships and mechanical engineering, defense industry, energy, construction, medicine, automation, materials for electronics, nanotechnology and much more. The advantages of CM are high strength, heat resistance, and wear resistance. However, their disadvantages should also be noted: expensive raw materials, production, and cost. Therefore, when creating and manufacturing CM, they strive to reduce the cost of products by using less expensive raw materials, obtained, for example, from man-made waste [1–5].

Every year, in the world, simultaneously with the generation of thermal and electrical energy as a result of the combustion of solid fuel at thermal power plants (TPPs) and combined heat and power plants (CHPs), ash and slag waste (ASW) is generated, which is produced in large quantities and poses a serious environmental hazard, i.e., it creates a global problem. Fuel and energy complex facilities are among the main sources of environmental pollution. The impact of toxic substances contained in ASW storage sites on the environment and the human body is analyzed in [6, 7]. At the same time, man-made waste accumulated over many years has a unique mineral composition and often has a distribution of useful components that is not typical for natural deposits. During the combustion process of fuel, chemical and phase transformations of its mineral substance occur. As a result, substances with new properties are formed – fly ash (the largest type of waste, 75–80% of ASW) and slag. The main components of ASW are oxides: SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO. A small proportion is accounted for by sulfates $CaSO_4$, $MgSO_4$, $FeSO_4$; phosphates and alkali metal oxides are present in smaller quantities. Ash includes almost all elements of the periodic table of D.I. Mendeleyev. The elemental composition of ASW varies greatly depending on the type of coal used, combustion technology and waste disposal. Ash of the same type of coal has different properties, especially from different types of coal. Almost all ashes contain carbon (under burnt) in the form of coke and semi-coke – in the form of either independent particles or inclusions in large fractions of ash.

In industrially developed countries of the world, such as the European Union, the USA and others, the utilization of ASW is an integral part of the technological process of coal thermal power plants, which involves the involvement of various types of waste in new technological cycles or their use for other useful purposes. This problem, which is the most important element in the overall chain of creating waste-free production systems, is given much attention both in our country and abroad [6, 7].

During the recycling process, ASW can be used as secondary raw materials. Based on the analysis of the review of world experience in ASW processing [6, 7], the main areas of their use are: construction (construction products, roofing granules); road works (fillers for road materials and asphalt fillers, etc. Considering the huge volumes and low degree of their utilization in our country, the world experience of ASW processing is useful and very relevant for Ukraine. The search for promising areas of using energy complex waste and new sales markets is an urgent need not only for Ukraine, but for any economically developed state.

The output of ash from Ukrainian TPPs is about 8–10 million tons/year. In the dumps of Ukrainian TPPs, 358.8 million tons of ash and slag have accumulated on an area of about 3,170 hectares. It should be noted that the ashes of coal thermal power plants in Ukraine contain carbon in an amount from 5–7% to 25–30%. The content above 5% does not allow the use of ash in the construction industry in large quantities (for concrete – prohibited by standards) [8, 9]. Therefore, technologies are needed that will provide the opportunity to use ash with a high carbon content to obtain a useful product, or to bring the quality of ash to the indicators required by standards for widespread use in the construction industry.

Fly ash with carbon content corresponding to regulatory requirements is used as a pozzolan for the production of cement, dry building mixtures, partial replacement of Portland cement in the production of concrete, concrete and reinforced concrete products, building materials. In the production of reinforced concrete and concrete mixtures, ash is introduced instead of part of the cement and sand, acting as not only an active mineral additive that increases the total amount of binder, but also micro filler that improves the granulometry of sand and actively influences the processes of concrete structure formation and its quality indicators. The introduction of ash into the concrete mixture, unlike other active mineral additives, generally improves workability, which is explained by the spherical shape of the ash particles, and helps reduce water separation of the concrete mixture. Concrete mixtures with an optimal addition of ash have a fairly high viability and are suitable for transportation over long distances. The use of ash provides greater protection of concrete from humid conditions and the effects of aggressive chemicals, reduces the minimum standard consumption rate of cement and, taking into account its cost, as a consequence, reduces the cost of concrete [6, 7].

Another component of ASW that is in demand by consumers is fly ash microspheres. These are hollow ash balls averaging 20 to 500 μm in size with solid non-porous walls 2 to 10 μm thick, filled with a mixture of nitrogen and carbon dioxide under reduced pressure (about 0.3 at) [10]. Depending on the composition of the coal, the microspheres can be aluminosilicate or Ferro silicate. The latter have pronounced magnetic properties. The unique combination of such qualities of this product as an almost ideal spherical shape, low bulk density, high mechanical strength, thermal stability and chemical inertness, ensured a wide range of applications of cenospheres abroad in the production of thermal insulation materials, radio-transparent ceramics, fillers of composite materials.

Research [10] has established the possibility of extracting useful components (carbon, iron, aluminum, silicates) from fly ash. Ash processing products have a finely dispersed fraction, convenient for further use, which eliminates expensive operations for preparing raw materials. For example, the resulting iron and aluminum powders are suitable for producing parts and units using the pressing method, as well as silicates for molding building structures.

In cases where the carbon content in the ash is higher than the standard values, it is necessary to separate it into its components (carbon-silicates). The results of studies [6, 7, 11–14] indicate the fundamental possibility of obtaining low-ash coal concentrate from TPP fly ash by fine classification by size -0.2+0.02 mm with high efficiency for narrow bands of separated classes of dry bulk materials. For these purposes, the M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine (IGTM of the NAS of Ukraine) has created a vibratory impact screen of a new design, which allows for the effective classification of bulk materials by a boundary size of 0.02 mm. These capabilities allowed the separation to produce two products: carbon and silicates (with low carbon content, meeting building code requirements). Carbon is a highly dispersed material that can be used in the production of plastics, elastomers, ceramics; intensely black dyes, varnishes and coatings; synthetic fibers, film materials. The silicate part with low carbon content can be used to manufacture construction products.

It should be noted that fly ash from coal-fired thermal power plants is a valuable potential raw material for the complex extraction of silica, aluminum oxide, iron, as well as many valuable and rare earth metals into commercial products. For example, in foreign literature there is information about the possibility of obtaining: amorphous silica ("white soot"), which is a raw material for "solar silicon" (extraction of SiO_2); commercial alumina (extraction of Al_2O_3); iron concentrate with Fe content above 65% (extraction of Fe_2O_3), including the use of oxides contained in ASW in the manufacture of composite materials. It is possible to obtain liquid glass, wollastonite, metallic gallium, vanadium pentoxide. This experience is useful and relevant for Ukraine, so specialists should study it, and this direction can be the subject of further research in this area.

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MATERIAL SCIENTIFIC FUNDAMENTALS OF THE APPLICATION OF HIGH-STRENGTH, HIGH-VISCUS STEELS FOR SPECIAL-PURPOSE STRUCTURES

Abstract. This study investigates the production of low-carbon, low-alloy steels for critical applications. The primary objective is to develop a microstructure consisting of ferrite and pearlite, eliminating the common issue of lamination, thereby enhancing the overall performance and reliability of the steel.

Keywords. *low-carbon, low-alloy steels, controlled rolling, substructure.*

Introduction. The modern development of the construction industry requires Ukrainian steel producers to manufacture high-strength, weldable steels for the creation of metal structures, including those for critical facilities.

It should be noted that the steels currently in use do not fully meet the requirements for materials in modern frameworks of responsible structures. Domestic thick-sheet metal products exhibit a significant variation in strength and ductility properties in all directions of the material volume. The anisotropy of strength and ductility characteristics is a consequence of the coarse ferrite-pearlite banded structure in the thick hot-rolled sheet. Such structural heterogeneity, along with the formation of an axial liquation zone, increases the risk of structural failure due to delamination. The use of steels with a developed ferrite-pearlite banded structure in construction is also limited due to a decrease in impact toughness values with increasing plate thickness.

Therefore, the use of competitive domestic high-strength steel in the domestic materials market is economically advantageous and, moreover, reduces the dependence of Ukrainian metallurgical plants on thick-sheet exports. Thus, obtaining and utilizing high-strength, competitive rolled steel that meets the modern requirements of both domestic and foreign consumers is a pressing task.

Main body. The primary components of a steel frame include columns, beams, floor slabs, and connections. Typical rolled, bent, perforated, and profiled sections serve as elements of the steel frame. Responsible elements that bear significant loads are manufactured from profiles welded from individual sheets. All elements of the steel frame must have a minimum mass, be well-connected to each other, to floor slabs, external and internal walls, vertical transportation means, and various engineering systems [1, 2]. When forming a steel frame, it is necessary to pre-select the types of steel most suitable for heavily loaded and massive elements of the designed structure [3].

Data analysis and current documentation requirements indicate that for structures of critical importance, subjected to loads characteristic of such structures, it is most advisable to use welded carbon steels of strength classes C245-C285. However, for the most heavily loaded elements, such as columns, higher-strength steels can be used: C345/ [4]. In the frames of high-rise buildings and for spanning large spans, the use of high-strength low-alloy steels of classes C375 and C390 is advisable. In modern buildings, the application of high-strength steels C440 and above may be justified [2,5].

Increasing the strength of steels solely through alloying significantly increases their cost and complicates the possibility of joining them together and with other frame elements. Therefore, a rational increase in the yield strength of steels to 500-900 MPa should be ensured not only by special alloying (for example, steels with so-called carbonitride strengthening) but also by the application of various methods of heat treatment and thermomechanical treatment. At the same time, all high-strength steels must also have sufficient resistance to brittle fracture, ductility, and a low cold brittleness threshold [6].

Notably absent from the provided list are high-strength ferrite-pearlite steels produced via controlled rolling. These steels, characterized by a superior set of mechanical properties, meet the standards: tensile strength (Ts) $\geq$ 500 MPa, yield strength (Ys) $\geq$ 590 MPa, and elongation (δ_5) $\geq$ 20%, classifying them as C550 grade

Initially, the primary focus in steel development was on ultimate tensile strength, with relatively little attention paid to yield strength, ductility, or weldability. This was because riveting was the most common and reliable method for joining structural elements. Alloying with carbon was the primary method for strengthening hot-rolled structural steels [7, 8].

Welding, which replaced riveting and bolted connections, necessitated a reduction in carbon content in steel. This was because welding with high carbon content steel required either a protective gas atmosphere or a flux cover, significantly increasing construction costs and reducing process efficiency. Therefore, steel strength was achieved by increasing manganese content, although the accompanying improvement in toughness was not yet recognized [9].

The brittle fracture of steel structures [10] led to the recognition of fracture toughness as a critical property. This led to further reductions in carbon content and significant increases in manganese content in steel. The benefits of high manganese-to-carbon ratios for achieving necessary impact toughness values were established, and the significant role of grain size was also discovered [11].

Strengthening mechanisms are also considered from the perspective of their impact on embrittlement. For this purpose, by considering the specific (referred to the unit of volume) mechanical energy expended on deformation and subsequent fracture of samples, it can be found that each material is characterized not only by the total amount of this energy, but also by the ratio of its constituent parts, namely: the energy expended on elastic deformation (potential energy), and the energy dissipated (irreversibly lost) during deformation.

The application of this mechanism in combination with other known strengthening mechanisms, such as solid solution strengthening, texture strengthening, dislocation strengthening, dispersion strengthening, and subgrain strengthening, allows for the production of economical, easily weldable materials that meet the increased demands of consumers in terms of both strength and toughness [11, 12].

Conclusions. The study has shown that thick sheet metal made of low-carbon microalloyed steels is the most promising material for the frameworks of modern special-purpose structures.

Based on the conducted analysis of the literature, the research objective was formulated: to form a structural and substructural state in thick sheet metal made of economical microalloyed steel that would ensure the necessary high complex of properties for modern welded metal structures of critical importance.

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THE CHOICE OF MATERIAL AND DESIGN FOR A REUSABLE BIONIC FILTER

Abstract. The paper proposes the design of a reusable bionic filter based on the whale's whisker principle and selects an economical polymeric material for its manufacture. The filter design consists of plate segments and small tendrils that provide mechanical water purification. The filter is aimed at reducing water pollution.

The paper compares polymeric materials and selects the best material for a reusable bionic filter based on the whalebone principle

Keywords: *3D model, whale whisker, polymeric materials, bionic filter, mechanical cleaning, water treatment.*

Every day, humanity creates more and more garbage that ends up in oceans, seas, rivers, lakes and other water bodies, polluting them, and therefore reusable water filters are needed to solve this problem. Water purification requires industrial and household filters with different types and degrees of water purification. There are many types of filters. The most popular are mechanical filters, which can be multi-stage and purify a suspension of different fractions.

In this work, a bionic filter is proposed that will function on the principle of a whale's whisker. The filter design consists of segments, the 3D model of which is shown in Figure 1, which repeats the shape of the whale's whisker plate. Each segment is a plate with small hairs.

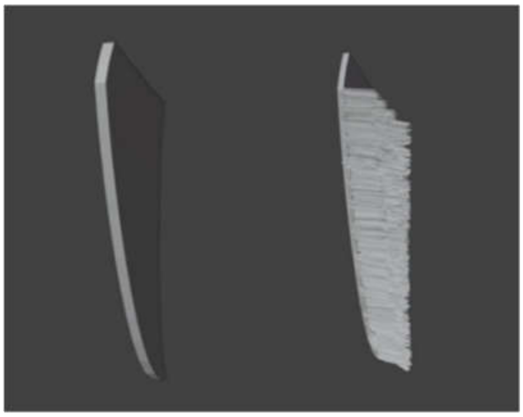

Figure 1 - Example of segments with and without hairs

The design of the filter assumes that these segments will be combined into sets of several pieces - sections, as shown in Figure 2 (shown without hairs). The sets of segments in the structure are connected to the base and create a cluster. Figure 3 shows a structure with two clusters. To increase the quality of filtering, the segments on the base are staggered. They will be connected to the base by means of grooves. The design of the base can look like a rigid or flexible substrate.

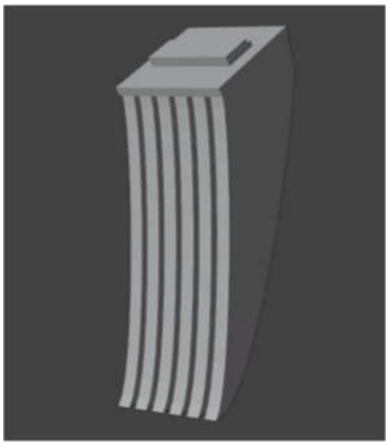

Figure 2 - Example of combined segments

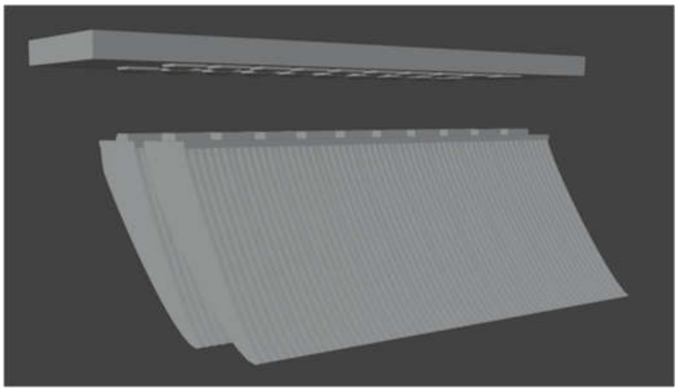

Figure 3 - Example of clusters, base and grooves

To manufacture the working part of the filter, it is planned to use 3D printing or extrusion. These methods will automate the filter production process.

The filter working part will be manufactured using a polymeric material. This material must have the following properties: high chemical resistance, strength, flexibility, affordability, the ability to be moulded using 3D printing or extrusion, and be safe for humans.

The following materials are suitable for these criteria: polyurethane (TPU), polyethylene (PE), polycarbonate (PC), high-density polyethylene (HDPE), polysulfone (PSU). Their mechanical characteristics are given in Table 1 [1].

Table 1 – Mechanical characteristics of polymeric materials

Mechanical characteristics	Materials				
	TPU	PE	PC	HDPE	PSU
Density, g/cc	0,970 - 1,20	0,91 - 0,96	1,03 - 1,26	0,933 - 1,27	1,13 - 1,66
Hardness, Rockwell R	85 - 98	38,0 - 68,0 (Shore D)	114 - 124	80,0 - 112	110 - 127
Flexural Yield Strength, MPa	25 - 50	7 -16	36,0 - 103	16,5 - 91,0	71,0 - 255
Compressive Yield Strength, MPa	10 - 15	5 - 10	18,0 - 86,2	10 - 20	13,0 - 176
Processing Temperature, °C	190 - 230	145 - 340	260 - 310	180 - 255	80,0 - 420
Nozzle Temperature, °C	200 - 240	204 - 218	270 - 320	210 - 260	335 - 380
Melt Temperature, °C	190 - 225	150 - 220	250 - 343	124 - 321	260 - 410
Mold Temperature, °C	30 - 50	20 - 70	60,0 - 120	15,6 - 65,6	65,6 - 210

Assuming that all the proposed materials are safe for humans, have the necessary physical properties and can be processed using 3D printing and extrusion, the cost of the material will also play an important role in the choice of material. The average cost per kilogram is shown in Table 2 [2-3]. After analysing the cost of polymeric materials, we choose PE for the manufacture of the filter structure.

Table 2 – Comparative cost of polymeric materials

Materials	TPU	PE	PC	HDPE	PSU
Average price (EUR/kg)	1,06	0,25	0,96	1,24	3,20

Thus, the paper proposes the concept of a reusable bionic filter based on the whalebone principle. The filter design consists of segments that mimic whalebone plates, combined into clusters and staggered for more efficient filtration. In addition, the characteristics of the materials and their relative cost for the manufacture of the working part of the filter were compared. For this purpose, it is advisable to use polyethylene, as it meets all the requirements, including being non-toxic to humans and being economically viable. The introduction of such a filter can significantly improve the quality of water treatment in domestic and industrial settings, contributing to the solution of the problem of water pollution.

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SELF-REINFORCEMENT OF HIGH-ENTROPY AlCrTiNbVB ALLOY DURING ELECTRON-BEAM SINTERING

In this work, we investigate the formation of microstructure and establish the features of in-situ formation of reinforcing phase inclusions in the process of electron beam sintering of a high-entropy powder AlCrTiNbV alloy obtained by mechanical alloying with the addition of boron.

Keywords: *high-entropy alloy; self-reinforcement; composite structure; carbide compounds; oxide compounds*

High-entropy alloys (HEAs) are one of the new classes of metal materials that possess a unique set of high characteristics: thermal stability, hardness, strength, ductility, fracture toughness, corrosion, oxidation, and wear resistance [1]. Over the past two decades, since the definition of “high-entropy alloys” and the beginning of their research, this class of materials has undergone a significant evolution from alloys consisting of simple solid solutions to more complex ones that additionally contain intermetallic and other refractory compounds (RC) [1, 2]. Among them, the most promising are self-reinforced high-entropy alloys, which, thanks to the addition of non-metallic elements such as C, B, O, N [2], significantly improves their properties, and, above all, mechanical behavior and wear resistance, due to both solid-solution strengthening and dispersion strengthening with RC particles (carbides, nitrides, borides, oxides). In addition, the formation of “in-situ” reinforcing particles provides much stronger interfacial bonds with the metal matrix of the HEA and their uniform distribution within it. One of the most interesting non-metallic elements for alloying high-entropy alloys is B [3], however, information on the effect of adding this element on such multicomponent materials is limited.

Thus, the aim of this work is to study the self-reinforcement processes of high-entropy alloys resulted from the electron beam sintering of powdered AlCrTiNbV HEA with the addition of B.

The initial powder of AlCrTiNbV HEA was obtained by mechanical alloying in a Retsch PM100 planetary mill for 20 hours in a gasoline environment in a hard alloy (WC-6Co) vial with balls of 10 mm in diameter made of the same material. The vial rotation speed was 400 rpm. Mixing of the obtained HEA powder with 1 mol of B (average particle size ~1 μm) was carried out in a ball mill for 10 hours, after which the mixture was pressed using a pressure of 100 MPa and sintered by electron beam in an electron-beam machine ELA-6 (Selmi Ltd., Sumy, Ukraine) for 1 min at temperatures from

1000 °C to 1200 °C. The HEA powder after mechanical alloying and the microstructure of the sintered samples were studied in an Axia ChemiSEM electron microscope equipped with an energy dispersive spectroscopy (EDS) analyzer of chemical composition.

The SEM image of the initial powder of AlCrTiNbV HEA is shown in Fig. 1.The initial powder alloy is an agglomeration of small particles with a size of 1 μm to 5 μm, the shape of which is mostly close to spherical. The uniform light contrast of the particles indicates the homogeneity of the resulting powder alloy, which is confirmed by local chemical analysis of individual particles. The content of each component in the alloy is 20 ± 1 at. %.

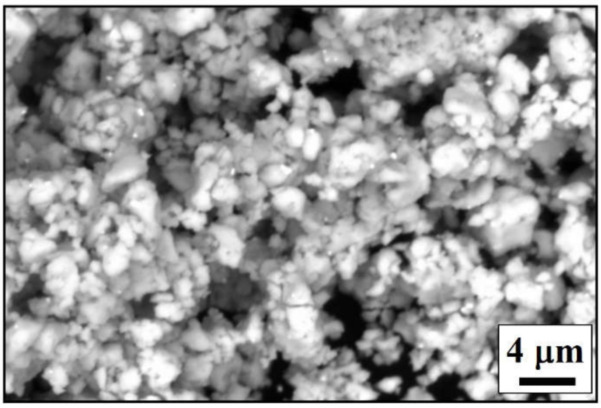
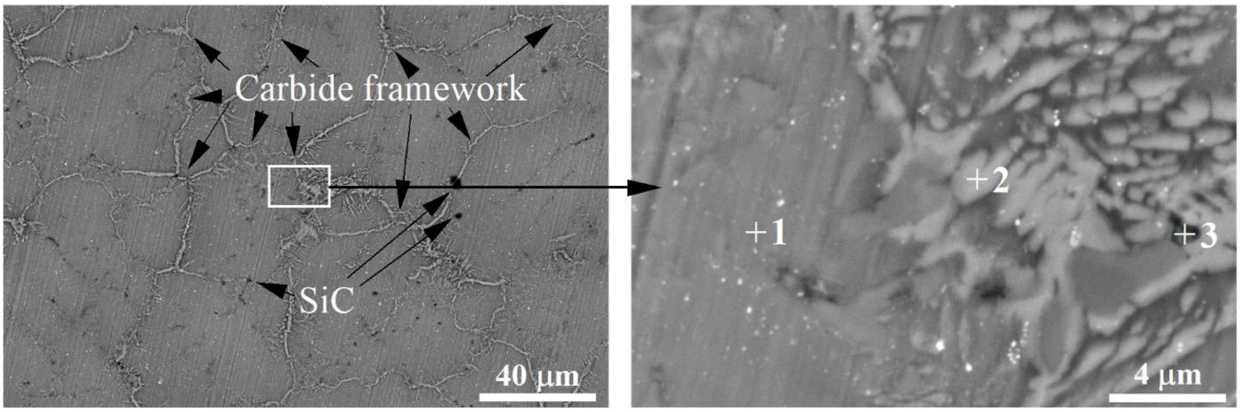


Figure 1 – SEM image of the initial powder of AlCrTiNbV HEA obtained by mechanical alloying

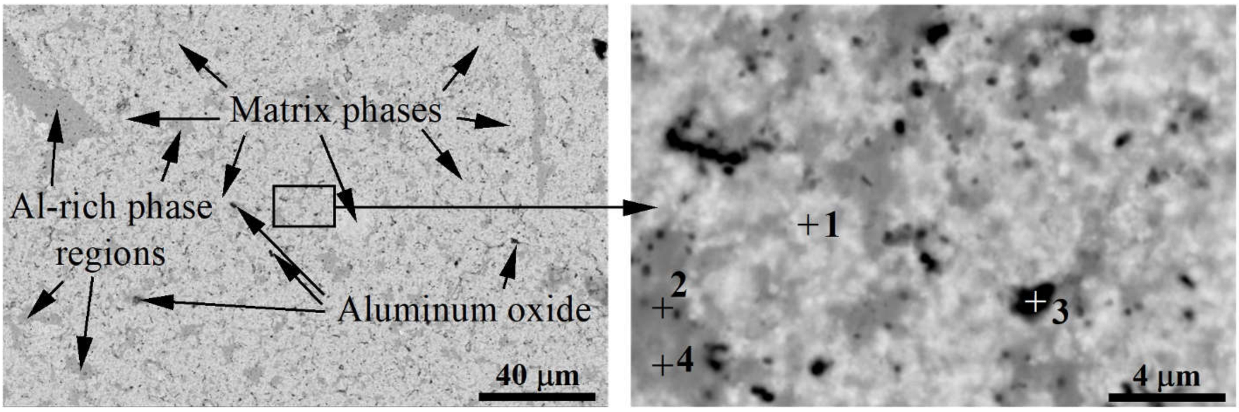
After electron beam sintering of a compressed mixture of AlCrTiNbV+B powders, in-situ formation of inclusions of carbide or oxide phases, depending on the sintering temperature, is observed. The alloy sintered at lower temperatures (1000 °C) has a composite structure (Fig. 2) consisting of large irregularly shaped grains (from 20 μm to 100 μm) of a lighter dark gray phase surrounded by a matrix of dendritic inclusions. According to the EDS analysis of the interdendritic region, the dark gray phase contains almost equal atomic percentages of Al, Cr, Nb and V (~19-20 at. %) but is depleted in Ti (13.6 at. %) and B (8.1 at. %). The dendritic region consists of small particles of 1-2 μm in size and close to spherical in shape, as well as elongated needle-like particles. The dendritic region, unlike the interdendritic region, is enriched in Ti, B, and C, which atomic content is not lower than the atomic content of Al, Cr, or V in relation to the nominal composition of the HEA. The source of carbon for the formation of the carbide framework (Fig. 2) is residual gasoline after mechanical alloying. However, it should be noted that there is certain heterogeneity in the distribution of Ti and Nb in the dendritic region. The lighter areas of the inclusions are enriched in Nb, which atomic content is 1.5 times higher than the atomic content of all other elements, while the darker areas inside some small inclusions have an increased content of Ti. Thus, in the process of carbide inclusions growth, there is competition for the interaction of Ti and Nb with B and C. Also, in some areas at the location of dendritic carbide inclusions, dark inclusions of silicon carbide SiC grains are observed (Fig. 2), which is the result of contamination with SiC grains from the sandpaper during sample preparation,



1 – interdendritic region; 2 – dendritic region; 3 –SiC

Figure 2 – Microstructure of a high-entropy AlCrTiNbVB alloy obtained by electron beam sintering at 1000 °C

When the temperature of electron beam sintering is increased to 1200 °C (Fig. 3), the microstructure of the alloy changes. First, it should be noted the absence of carbide phase particles. Instead, there is a significant redistribution between light (Al, Ti) and heavy (Nb) elements in the alloy. Similar to the sintering temperature of 1000 °C (Fig. 2), the formation of a framework from clusters of light gray phase enriched in Ti and Nb, the atomic content of which is 1.5 times higher than the content of other elements, is observed. However, the carbon content is low, up to 1-2 at. %, and the content of B is about two-thirds of the nominal one, which may be due to its high reactivity during sintering with the simultaneous reduction of impurities, primarily oxygen. This can be confirmed by the formation of a significant number of small aluminum oxide inclusions in the microstructure of the sintered alloy. Also, similarly to the sintering temperature of 1000 °C (see Fig. 2), certain heterogeneity between the Ti and Nb content is observed. In addition to the framework enriched in more refractory elements, significant areas of the dark phase enriched in Al are observed with gray inclusions enriched in Ti.



1 – Ti and Nb-enriched phase regions; 2 – Al-enriched phase regions;
3 – Aluminum oxide; 4 – Ti- enriched phase regions

Figure 3 – Microstructure of a high-entropy AlCrTiNbVB alloy obtained by electron beam sintering at 1200 °C

Thus, the addition of 1 mol of B to AlCrTiNbV HEA leads to the formation of various reinforcing inclusions, depending on the sintering temperature. At a low sintering temperature of 1000 °C, B interacts with C, Ti, and Nb, which leads to the formation of a carbide framework, while with an increase in the sintering temperature to 1200 °C, the redistribution of B, as well as low-melting (Al) and refractory (Ti, Nb) elements in the alloy occurs.

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STUDY OF MULTILAYER WEARPROOF FILM COATING OF COLD HANDIND PROCESSING TOOLS

Abstract. The general purpose of the research performed is to develop new materials for wearproof coatings with an improved set of performance characteristics. The optimum thickness of titanium nitride coating for fast-cutting tools used in the turning operation of structural steels has been established.

Keywords. *adhesion; adhesion-fatigue phenomena; multilayer wearproof coating; titanium nitride coating.*

An important reserve for significant increasing the wearproofness and operational reliability of tools and technological equipment is the application of thin wearproof films, based on transition metal nitrides and carbides.

Until now, there have been no scientifically based methods for selecting wearproof coating materials for specific operating conditions (material being processed, tool material, type of tool, working conditions).

The general purpose of the research performed is to develop new materials for wearproof coatings with an improved set of performance characteristics based on the study of the properties of thin films of nitrides and carbides of transition metals.

In conducting the study, we proceed from the following assumptions:

- there is no universal coating for a variety of working conditions of the tool and processed materials;
- each of the investigated materials of wearproof films should possess its own set of operational properties (mechanical, adhesive, thermodynamic).

As it is known, the surface areas of cutting and stamping tools operate under very severe conditions of intensive impact of the processed material, which is accompanied by such phenomena as elastic and plastic deformations, adhesive interaction and adhesion of the material, friction, vibration. Requirements for the properties of the tool (such as hardness, strength, heat resistance) are also true for surface protective films. The level of these properties (at least many of them) should be even higher. This primarily relates to heat resistance. An important property of transition metal nitrides and carbides is their thermal stability at high temperatures.

Compounds with a face-centered cubic structure have the highest melting temperatures and stability. Among transition metals, elements of group VI have the highest melting points and stability; among carbides, derivatives of elements of group V; among nitrides, derivatives of elements of group

IV. The stability of group VI nitrides decreases from CrN to MoN and then to WN, while the stability of carbides decreases in the reverse order. [1].

Numerous experimental data indicate that all values of mechanical properties decrease with increasing coating thickness [2]. The choice of optimal thickness should be based on two opposing factors:

- as the layer thickness increases, the strength properties of the films deteriorate, and wear increases due to fragility. However, with increasing film thickness, resistance primarily to abrasive wear increases, which ensures longer durability;
- the thickness of the coating affects the radius of the cutting edges. As the layer thickness increases, the rounding increase greatly, this automatically increases the cutting effort and deteriorates the quality of the machined surface.

Depending on the operating conditions of the tool, the optimal coating thickness is different. The optimum thickness of titanium nitride coating for fast-cutting tools used in the turning operation of structural steels has been established:

- on the front surface 4 μm;
- on the rear surface 2 μm.

An important property of wearproof films is the strength of their adhesion to the tool substrate. Film adhesion is caused by the interaction between the coating atoms and the substrate. One of the main factors determining the film adhesion strength is the substrate temperature during coating application. The performed studies show that the films obtained at temperatures of 500-550°C have the highest complex of operational properties, i.e. close to the zone of thermal de-hardening of tool steel [3].

Firstly, wear of coated cutting tools depends on the strength of adhesion of the film to the tool surface, the level of adhesion with the machined material, strength and thermodynamic properties of the surface layers. (Fig.1).

The intensity of wear is determined by adhesion and adhesion-fatigue phenomena in the contact zone of the cutting tool with the machined material. (Adhesion wear of the tool is defined as the separation of the smallest particles of tool material by adhesion forces in the process of friction with the processed material).

It is impossible to completely eliminate the wear that occurs under conditions of joint plastic deformation between the tool material and the machined material.

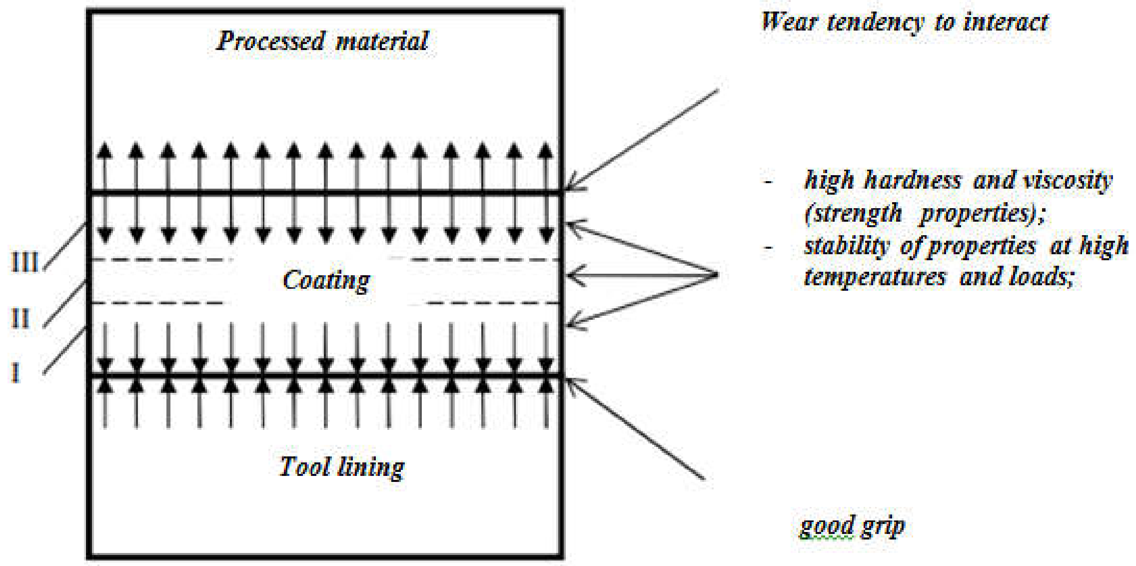

Fig.1. Scheme of wearproof coating with improved operational properties:

I – the lower coating layer adjacent to the tool base; II – transition layer;

III – the top layer of the coating is in contact with the processed material.

It is impossible to completely eliminate the wear that occurs under conditions of joint plastic deformation between the tool material and the machined material.

Conclusions. It is obvious that it is impossible to realize the whole complex of useful operational properties in the coating of unchanged chemical composition. Practical implementation of the research is the development of multilayer wearproof film coatings, successfully combining the necessary operational: high adhesion strength with the instrument base; minimal adhesion to the processed material; high hardness, strength, heat resistance of each of the components of the coating.

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PROPERTIES OF GEOPOLYMERIC MATERIALS BASED ON EXPANDED PERLITE

Abstract. Geopolymers based on expanded perlite are a perspective research object and an environmentally friendly alternative to existing thermal insulation materials. The paper investigates the properties of a geopolymeric monolithic thermal insulation material based on perlite that would meet the requirements for mechanical, physical and thermal insulation characteristics that are put forward for materials of this type. The optimum composition of geopolymer blocks based on perlite is determined, and a method of their formation is proposed.

Keywords: *geopolymer, perlite, expanded perlite, liquid glass*

The development of building materials with minimal energy consumption and a wide range of properties that meet the criteria of sustainable development and environmental friendliness is the prerogative of our time. Perlite-based geopolymer materials demonstrate significant competitiveness compared to traditional building materials, as they require less energy for their production and have a lower carbon footprint than cement or brick [1,2].

Approximately 10 billion tonnes of structural materials are produced annually in the world, accounting for more than 16% of global energy consumption and carbon dioxide emissions, with cement production accounting for almost 5% [3].

Joseph Davidowitz [4, 5]. developed the concept of creating geopolymer materials as an alternative to traditional Portland cement and laid the foundations for all modern research. Geopolymers are formed as a result of a chemical reaction between aluminosilicate materials (metakaolin, slag, perlite, fly ash) and alkaline activators, forming a three-dimensional mesh structure that determines their unique properties. In the process of well-known geopolymerization, aluminosilicates dissolve, forming silicate and aluminate gels, which polymerize into a stable structure. Thanks to this, geopolymers combine the properties of traditional cements with additional advantages, such as environmental friendliness, corrosion resistance and high heat resistance.

Perlite has long been known as an effective material in thermal insulation systems. Its low coefficient of thermal conductivity and fire resistance make it possible to manufacture building structures that do not require additional insulation, and the low density of perlite blocks ensures the lightness of building structures. This helps to reduce the amount of work and the cost of construction [6].

The introduction of geopolymers based on expanded perlite is an important step in the direction of reducing energy consumption, minimizing greenhouse gas emissions, and increasing the durability of building structures [7].

For the study of the geopolymer material, expanded perlite of the M75 brand (Berehivskoe deposit) with a fraction size of 0.7...1.2 and sodium liquid glass $Na_2O(SiO_2)n$ were used as a binder. The mixed mixture with different proportions of components was pressed into a mold with a load of 980 N to obtain a monolithic composite material of geopolymeric nature and sintered for 1 hour at a temperature of 400 °C. After heat treatment, it was removed from the oven and left in the mold for 24 hours. at room temperature. Different compositions of the composite were selected for the experiment - the ratio of pearlite: liquid glass (5:1, 5:2, 5:3, 5:4, 1:1)

The disadvantage of perlite-based materials is high water absorption, which is due to open porosity. This factor can negatively affect the mechanical properties of the material, especially in conditions of high humidity [8,9].

It was experimentally established that the minimum value of water absorption of samples (Wi = 76.5%) with a density (510 = kg/m3) has a composition with a ratio of 1:1 (perlite + liquid glass), which was formed at a temperature of 400 ° C. To reduce the degree of water absorption of perlite-based materials, various hydrophobic treatments or the addition of special additives to the mixture can be used.

Durability research took place in several stages - freezing, thawing, heating. Moistened to the humidity values in operating conditions and hermetically sealed in special polyethylene bags, the samples were exposed to cyclic temperature changes: freezing at a temperature of -22 °C → thawing at a temperature of +20 °C → heating to a temperature of +60 °C. After every tenth cycle, samples were taken in order to determine their thermal conductivity under standard conditions and to record changes in the appearance of the material.

According to the results of a visual inspection of the experimental samples after 100 cycles of climatic effects of freezing → thawing → heating, it was found that the appearance of the samples from the heat-insulating composition does not change - the change in the geometric dimensions of the samples is within the limits of permissible values, there is no noticeable change in the color and structure of the material. As a result, it was determined that the term of effective use of thermo-perlite composition for thermal insulation of buildings is at least 50 years.

The evaluation of the thermal conductivity of the samples, depending on the ratio of the components, showed that the coefficient of thermal conductivity increases with an increase in the specific content of liquid glass, which is logical, since the amount of pearlite in the composition, a component that provides low thermal conductivity, decreases, as well as the number of internal air pores decreases, the specific density of the samples increases.

The research joint of geopolymer compositions was also used in 5 variants, which have the same amount of perlite but with different amounts of binder. The highest value of the strength limit (kg/cm^2 = 21.30) has a sample made with a ratio of 5:1 (perlite + liquid glass) and was formed at a temperature of 400 °C

The strength properties allow the use of geopolymer materials based on perlite in construction, because compared to other alternative materials, such as those used by the authors [10], the strength of geopolymer filled with perlite was 2.3 MPa. It can be concluded that the strength values obtained are higher than the average values obtained in other studies [3,5].

The results of electron microscopy demonstrate that the studied samples have a uniform structure and evenly distributed pearlite particles in the matrix. Cavities are observed in all compositions, as in works [2,7]. Apparently, this was due to an insufficient amount of binder, insufficient for complete wetting of the filler, resulting in cavities up to 400 μm in size. Accordingly, cavities of these sizes are stress concentrators and significantly weaken the matrix, which correlates well with the results of the study of mechanical characteristics. In samples with a higher content of liquid glass, the number of cavities is minimal. Further research is needed to establish the relationship between compaction pressure and pore number.

The use of perlite-based geopolymers in the construction industry opens up new opportunities for creating energy-efficient, durable and environmentally friendly structures. In Ukraine, the estimated resources of perlite raw materials (Zakarpattia region) are estimated at 100 million m^3. Perlite geopolymers have the potential to become the basis for the sustainable development of the construction industry of our country and the world, providing a response to the modern challenges of the energy crisis, climate change and the growing demand for innovative solutions.

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THE CHOICE OF DESIGN AND MATERIAL OF SUN PROTECTION COATING FOR ROOFS OF SMALL-SIZED BUILDINGS

Abstract. The work proposes a method for solving the problem of overheating of small-sized buildings by applying a special sun protection coating to their roofs. Polymethyl methacrylate is proposed as a material for the coating. The use of such a coating will help reduce the heating of roofs without additional energy costs, while ensuring environmental sustainability.

Keywords: *3D model, roofs of small buildings, sun protection coating, polymethyl methacrylate.*

Given the warming trend and the increase in solar activity in recent years, the issue of cooling the premises is becoming increasingly important. When electricity and appropriate technology are available, this is usually not a problem, but in situations of limited resources, emergency situations or extreme weather conditions, alternative cooling methods are needed. These are not always radical, but may be sufficient to reduce peak temperatures or save resources. In the case of large buildings, it is often easier to insulate against external heat than to try to maintain comfortable conditions inside.

However, this option is not suitable for smaller thin-walled buildings such as small retail outlets, garages, etc., whose walls are usually poorly insulated and made of metal or plastic with metal elements. These materials get very hot in the sun, which can lead to burns if touched. The absence of thermal insulation is often due to economic expediency - a metal structure without insulation is much cheaper. The size of the facility is also an important factor: the smaller the building, the faster the heat exchange with the external environment. Combined with the lack of air conditioning, a fan or the ability to create a draft, this can lead to heat stroke.

The idea of a potential solution to this problem was suggested by the Saharan silver ants or Cataglyphis bombycina. These insects are one of the most heat-resistant animals on Earth. They survive at temperatures above 50 °C thanks to their reflective hairs. Electron microscopy has shown that the hairs covering the back of the ant's head, thorax and abdomen have a triangular cross-section. In addition, the scientists found corrugation of two surfaces of the hairs facing the sun and absolute smoothness of the third surface adjacent to the ant's body, which, together allowing a high optical reflection in the visible and near-infrared range of the spectrum while maximizing heat emissivity in the mid-infrared [1].

To reduce the heating of roofing materials and, as a result, premises, the authors propose to apply a special sun protection coating over the roofs of buildings. It is a set of triangular prisms of equal length, with a small cross-section (5-10 mm), connected together by a base (Fig. 1).

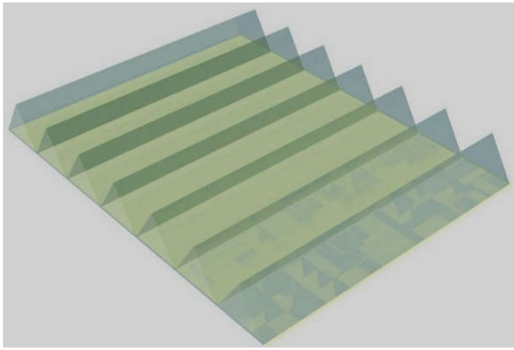

Figure 1 - 3D model of the sun protection coating

The work proposes to select a material for the construction of prisms according to the following criteria:

- The optical properties of the material should be as similar as possible to those of chitin (refractive index n = 1,56, light transmittance > 90, high transparency).
- Resistant to UV radiation (no ageing or discolouration due to sunlight).
- Resistance to mechanical damage, strength (the coating is designed for small-sized buildings, on the roofs of which people will not walk).
- Resistance to environmental influences (atmospheric phenomena, moisture, chemical environments), frost resistance.
- Range of permissible working thicknesses and material shapes.
- Affordable price.

The above criteria are met by polymethyl methacrylate (PMMA) and polyethylene terephthalate (PET). We propose to use PMMA in work.

PMMA or organic glass is a transparent synthetic polymer often used in sheet form as a lightweight or impact-resistant alternative to glass. PMMA is a cost-effective alternative to polycarbonate when tensile strength, flexural strength, transparency, polishability and UV resistance are more important than impact strength, chemical resistance and heat resistance. In addition, PMMA does not contain the potentially harmful bisphenol-A subunits found in polycarbonate. It is often preferred because of its moderate properties (Table 1), ease of use and processing, and low cost. PMMA swells and dissolves in many organic solvents. It also has low resistance to many other chemicals due to its ester groups, which are easily hydrolysed. Nevertheless, its environmental stability is superior to most other plastics such as polystyrene and polyethylene and is therefore often the choice for outdoor applications [2].

Table 1 – Mechanical properties of polymethyl methacrylate

Properties	**Polymethyl methacrylate**
Density, g/cm³	1,19
Light transmittance, %	92
Refractive index	1,49
Tensile strength, MPa (at 23 °C)	70-74
Tensile modulus of elasticity, MPa	3000-3300
Relative elongation at break % (at 23 °C)	4-5
Transition temperature, °C	95-112
Impact strength, kJ/m² at sheet thicknesses of 5-24 mm	13-15
Maximum operating temperature, °C	80-82
Molding temperature, °C	150-170
Coefficient of thermal expansion, mm/m*10°C	0,65
Thermal conductivity, W/(m*K)	0,2-0,3
Maximum water absorption by weight, %	0,3-0,4
Hardness, N/mm^2	180-190

The sun protection coating consists of two parts: the base and the triangular prisms that are attached to it. The type and material of the base depends on the shape of the roof: for a flat roof, you can use a hard, non-plastic material that allows you to make a coating in the form of tiles, while for uneven surfaces, such as slate or corrugated board, it is better to use flexible plastic materials. In both cases, the substrate can be sheet or mesh in shape. Figure 2 shows an example of a coating with a mesh base.

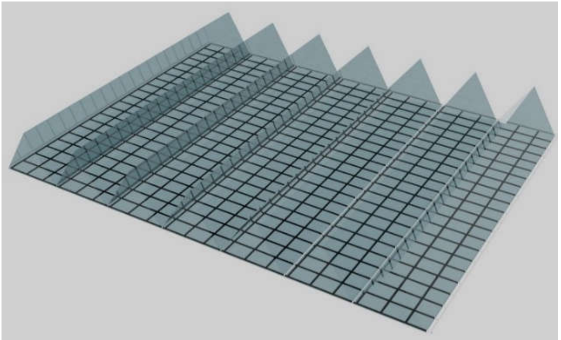

Figure 2 - 3D-model of a sun protection coating with a mesh base

As for the production of prisms, the authors propose two methods: cutting from sheet PMMA or extrusion. In the first case, a sheet of organic glass of the required thickness will be cut into triangular prisms. To do this, a cutting method needs to be chosen, and since the sheet thickness does not exceed 10 mm, the chosen method must ensure high accuracy. Laser cutting is an effective method in which a laser beam is focused on the material, heating and melting it, allowing for fast and accurate cutting of sheets to form complex shapes with minimal material loss and increased productivity [3].

However, cutting organic glass is usually difficult due to its properties. The low melting point makes it difficult to machine quickly due to localised overheating, and the same applies to laser cutting - the material can burn out and the edge quality leaves much to be desired. Moreover, the equipment and the cutting process itself are quite expensive, which directly affects the cost of the product.

An alternative to laser cutting is waterjet cutting, which allows you to cut sheet material along any straight or curved contour with minimal material waste (cutting width of just 1 mm). The fluid jet acts as a point tool, capable of cutting complex contours with any radius, without the need to create a hole beforehand. The cutting width is 0,76-2 mm, which reduces material loss, and the low force (1-100 N) and temperature (+60...+90°C) prevent deformation, melting and burning. This method does not change the physical and mechanical properties of the material, which saves on additional edge processing [4].

The second method of manufacturing prisms is extrusion, which is a process in which a material is heated to a plastic state and forced through the matrix to form a continuous profile or product. This method is widely used to manufacture a variety of plastic products such as pipes, profiles, tiles and films. Extrusion provides precision shapes, high production speeds and the ability to create complex geometries with uniform thickness along the entire length of the product.

This work proposes a method of solving the problem of overheating of small-sized buildings by applying a special sun protection coating to their roofs, which is based on bionic principles, in particular, the structure of the hairs of Saharan silver ants. The material chosen for the coating is polymethyl methacrylate, which has optimal optical, mechanical and operational properties. For the manufacture of triangular prisms, it is proposed to use the methods of extrusion or waterjet cutting of PMMA sheet. The coating base is selected depending on the shape of the roof. The use of the proposed coating will help reduce roof heating and improve comfort conditions without additional energy costs, while ensuring environmental sustainability.

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USING METALLIC GLASS IN CLOTHING TO ENHANCE ITS PHYSICAL PROPERTIES

Abstract. In the article it is shown that metallic glass, with its unique properties like superior strength, lightweight, and corrosion resistance, offers innovative uses in smart textiles and specialized apparel. This study compares it to steel, emphasizing its potential in extreme environments like firefighting and aerospace, while identifying cost-effective alloys such as Fe40Ni40B20 for advanced textile applications.

Keywords: *metallic glass, amorphous metal, advanced textiles, mechanical properties, tensile strength, specific strength, fracture toughness, density, elastic strain limit, stainless steel, vitreloy, alloy, metal, metallic glass in clothing*

Metallic glass, or amorphous metal, is an innovative material that is rapidly gaining attention for its unique properties. Its structure, unlike that of ordinary metals, is not crystalline, but amorphous, like that of glass, which provides exceptional strength, low weight, and corrosion resistance [1]. The ability to withstand high loads and extreme conditions opens up new opportunities for the use of metallic glass in various industries [2]. There are many metal glass alloys, the six most well-known of which are shown in figure 1.

Metal glass is made by cooling molten metal alloy extremely quickly - for some alloys, the rate exceeds a million degrees per second. This process prevents the atoms of the alloy from organizing into their usual crystalline structure, resulting in an amorphous, or “glassy,” structure [3]. This cooling is usually achieved using special methods, such as casting the melt onto a cooled surface [4].

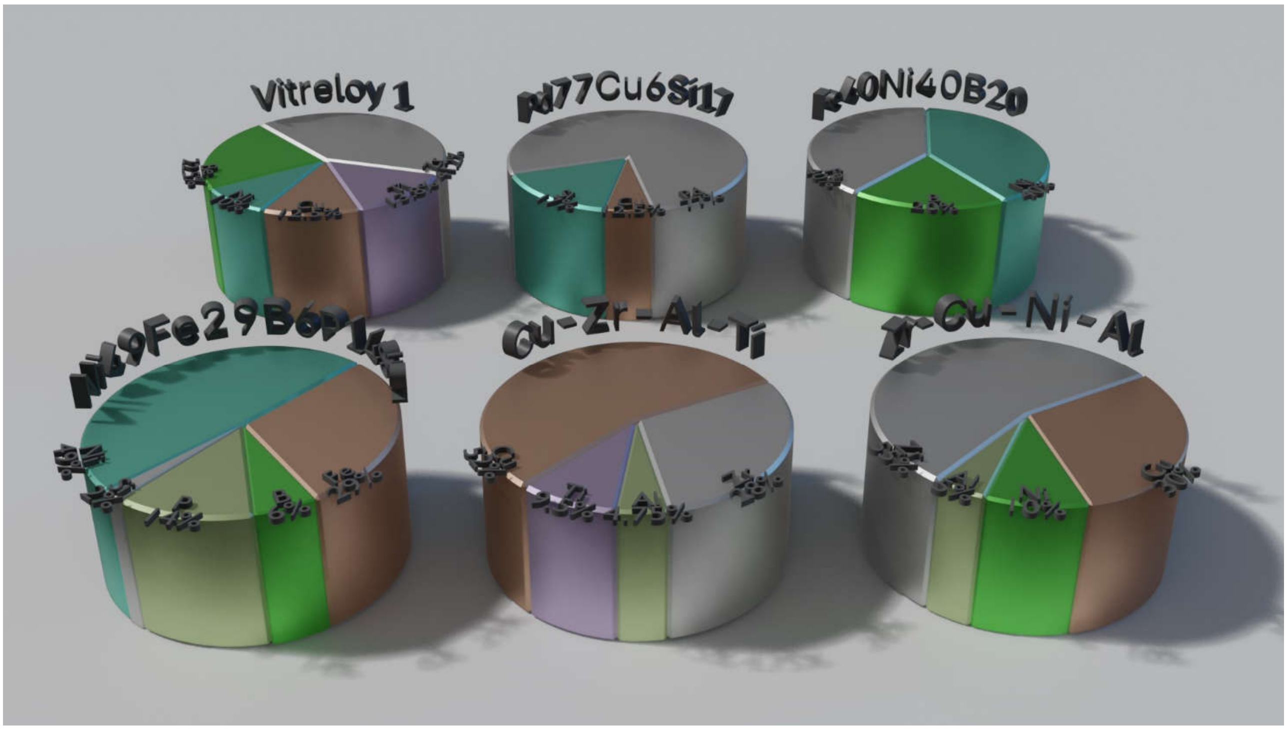

Figure 1 – Six most well-known metallic glass alloys.

Despite its many advantages, metallic glass has certain limitations that make it challenging to use widely. The production of amorphous metal is a complex and expensive process, as it requires extremely rapid cooling to maintain its amorphous structure. This requires expensive equipment and precise temperature control, which limits large-scale production. In addition, due to its brittleness, metallic glass can be prone to sudden fractures under excessive loads, which reduces its suitability in some applications. Despite these challenges, research is ongoing to optimize the production and improve the properties of metallic glass, which could expand its use in the future and reduce the cost of manufacturing.

The paper proposes to use metal glass to improve the properties of textiles. The integration of metal glass fibers into the structure of clothing can give this material 50% strength and resistance to environmental influences without increasing weight. Products made with metallic glass will not only be able to withstand significant mechanical loads, but will also remain comfortable and lightweight. A 3D-model of metal glass in the structure of the fabric is proposed (Fig. 2), the images were created in the software Blender 4.2.0. Such clothing will be extremely wear-resistant and can be used in sportswear, creating durable accessories.

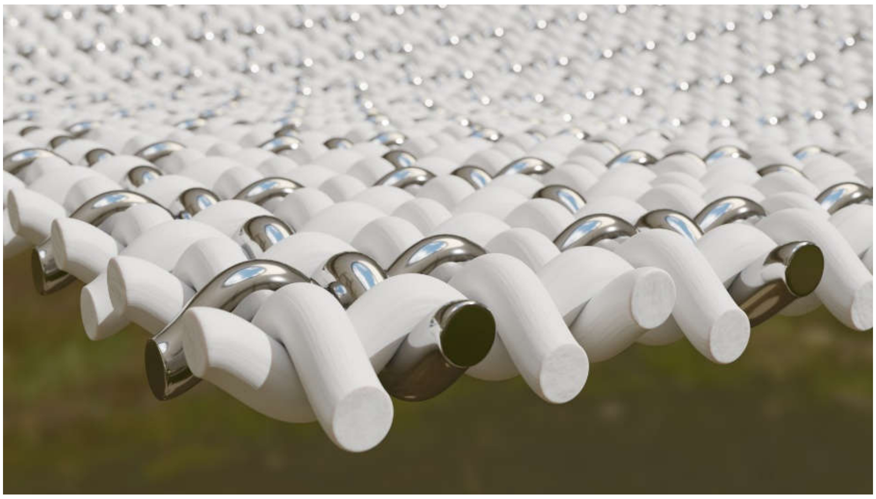

Figure 2 - 3D model of metallic glass in the fabric structure

Besides the sports industry, metal glass has great potential in the development of special clothing for occupations associated with extreme conditions. In particular, these can include firefighters, astronauts, rescuers, and workers of other fields where people face dangerous conditions on a daily basis.

For firefighters and rescuers working in high temperature and high-risk environments, clothing made with metallic glass will provide additional protection against mechanical damage and increased resistance to high temperatures. The strength and corrosion resistance of amorphous metal will protect them from damage when working in harsh environments where conventional materials can wear out quickly.

In the space industry, metallic glass can also become an indispensable material, as the conditions in which astronauts work are very demanding on the properties of clothing. Their gear must be as lightweight, durable, and radiation-resistant as possible. Amorphous metal provides the perfect ratio of lightness and resistance to external influences, which allows to reduce the weight of equipment, as well as to ensure the comfort and protection of astronauts in space.

The authors of this paper have performed a comparative analysis of metallic glass alloys. Table 1 shows the key physical and mechanical characteristics of six amorphous metallic glass alloys and compares them with the properties of ordinary steel (grade 1020) and stainless steel (SAE 304). Analyzing this data, a conclusion can be made that amorphous metal alloys demonstrate significantly higher tensile strength, elastic ultimate strain, and specific strength. In addition, most of these alloys have a slightly lower density, which is an important advantage for applications requiring high strength at low weight. However, it should be noted that amorphous metals are inferior to traditional steels in terms of critical crack resistance.

Table 1 - Comparison and properties of metallic glass alloys

Metallic glass alloys and their key characteristics	Vitreloy 1	Pd77Cu6 Si17	Fe40Ni 40B20	Ni49Fe29 B6P14Si2	Ti–Zr–Cu–Pd Alloy	Cu-Zr-Al-Ti Alloys	Zr-Cu-Ni-Al Alloys	Steel 1020	Stainless steel SAE 304
Density (g/см³)	6.6	8.5	7.5	7	5.5	6	6.4	7.85	8
Tensile Yield Strength (GPa)	1.7–2.0	1.3	1.5	1.4	1.6	1.2	1.5	0.4	0.52
Elastic Strain Limit (%)	2	2	1.5	1.5	3	1	2	0.25	0.3
Fracture Toughness (MPa·m¹/²)	25–85	Unknown (low)	30	30	Unknown (average)	40	40	50–70	70–90
Specific Strength (MPa·см³/g)	285–330	153	200	200	290	200	230	51	65
Price per kg, $	100-200	500-1500	30-80	50-100	200-600	50-150	60-120	1	2-3
Notes and comments	Suitable for lightweight, durable and wear-resistant fabrics, especially for sportswear	Limited use due to fragility and high price, but potentially useful in sensors for high-precision measurements	Low price, well suited for clothing that requires increased durability, such as for rescuers	Can be used in textiles for embedded sensors due to its balanced properties	Excellent for flexible and lightweight astronaut clothing due to its high strength and lightness	Can be used for protective clothing, in particular for firefighters, due to its temperature resistance	Suitable for specialized textiles with high strength and flexibility requirements		

The most significant factor limiting the widespread adoption of metallic glass is its cost. Even the most affordable metallic glass alloys are 10 times the price of stainless steel, while the most expensive amorphous materials can cost up to a thousand times more. This significant cost gap is due to the complexity of production processes and the use of rare elements in the alloys, such as palladium and zirconium. [5]

Considering the balance between mechanical properties and price, the most suitable choice is to use Fe40Ni40B20 and Ni49Fe29B6P14Si2 alloys. Their relatively low cost is due to the use of common chemical elements such as iron, phosphorus and silicon, which reduces the cost of the production process. In addition, they contain boron and nickel, which, although relatively abundant, slightly increase the overall cost. As a result, these alloys are promising for use in the production of high-tech materials, where the balance of price and performance is important.

Thus, the paper proposes the use of metallic glass in clothing to improve its durability and resistance, which is an extremely promising material due to its unique properties, and shows a 3D model of metallic glass in the structure of the fabric. It is also shown that Fe40Ni40B20 and Ni49Fe29B6P14Si2 alloys are proposed to be the most reasonable alloys in the fabric structure in terms of price and mechanical properties. The use of these alloys in the structure of the fabric will increase its strength characteristics by 25-30 percent, depending on the chosen alloy and structure.

The integration of this material into textiles can significantly change many industries, improving the quality of life and increasing safety in extreme conditions. In the future, this material can be used not only for clothing, but also in building materials, medical devices and other products that require increased strength and durability. Due to its unique characteristics, metallic glass can make a significant contribution to the creation of high-tech clothing that meets modern requirements. It may well become the foundation for new innovations in smart textiles and specialized clothing for jobs where every detail can play a crucial role in safety and efficiency.

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ANALYSIS OF THE IMPACT OF ELECTRON BEAM WELDING ON THE STRUCTURAL PARAMETERS OF WELDED JOINTS OF STEELS 09G2S, 10HSND, AND 10G2FB USING FACTOR ANALYSIS

Abstract. The study analyzes the influence of structural parameters on the quality of welded joints in steels 09G2S, 10HSND, and 10G2FB after electron beam welding. Applying factor analysis reveals key parameters affecting joint quality, facilitating the optimization of welding processes and enhancing the reliability of industrial structures.

Keywords: *welded joints, structural parameters, welding quality, factor analysis, electron beam welding, correlation matrix, optimization of technological processes, structural reliability.*

Main content of paper. In modern industry, welded joints play a crucial role in ensuring the reliability and durability of structures. Improving the quality of these joints is a relevant task, as defects in their structural state can lead to serious consequences, such as accidents and the failure of critical components [1, 2].

The purpose of this study is to investigate and analyze the relationships between structural parameters of welded joints and to identify key factors affecting welding quality.

The relevance of the research is driven by the need for quality control in welding, which is increasingly important within modern technological processes. The use of mathematical methods, particularly factor analysis, allows for the identification of hidden correlations between variables, aiding in the optimization of the welding process. This approach can offer significant advantages in production, including material cost reduction and increased reliability of finished products.

In the study, the impact of electron beam welding on the structural state of welded joints in steel grades 09G2S, 10HSND, and 10G2FB was analyzed. Based on experimental data, a correlation matrix was constructed, revealing relationships between ferrite grain size, the percentage content of structural components (ferrite, pearlite), and the geometric dimensions of welded joint zones [1-4].

Table 1 presents the correlation matrix, which illustrates the relationships between different structural components, essential for understanding their impact on welding quality. This enables the identification of the main factors influencing the final characteristics of welded joints, providing a deeper understanding of technological processes.

Table 1.

Correlation matrix of structural component ratios

	09G2S								
	The boundary of the welded joint – HAZ	**HAZ**	**The boundary between the heat-affected zone (HAZ) and the base metal.**	**Ferrite 2**	**Ferrite 3**	**Ferrite 4**	**Pearlite 2**	**Pearlite 3**	**Pearlite 4**
The boundary of the welded joint – HAZ	1,00	-0,33	0,45	0,05	-0,61	0,36	0,61	-0,66	0,03
HAZ	-0,33	1,00	-0,12	0,32	0,17	0,60	-0,53	0,59	-0,90
The boundary between the heat-affected zone (HAZ) and the base metal.	0,45	-0,12	1,00	-0,67	-0,91	-0,18	0,68	-0,31	0,20
Ferrite 2	0,05	0,32	-0,67	1,00	0,43	0,77	-0,20	0,15	-0,49
Ferrite 3	-0,61	0,17	-0,91	0,43	1,00	0,03	-0,83	0,20	-0,23
Ferrite 4	0,36	0,60	-0,18	0,77	0,03	1,00	-0,10	0,00	-0,82
Pearlite 2	0,61	-0,53	0,68	-0,20	-0,83	-0,10	1,00	-0,43	0,52
Pearlite 3	-0,66	0,59	-0,31	0,15	0,20	0,00	-0,43	1,00	-0,26
Pearlite 4	0,03	-0,90	0,20	-0,49	-0,23	-0,82	0,52	-0,26	1,00
	10HSND								
	The boundary of the welded joint – HAZ	**HAZ**	**The boundary between the heat-affected zone (HAZ) and the base metal.**	**Ferrite 2**	**Ferrite 3**	**Ferrite 4**	**Pearlite 2**	**Pearlite 3**	**Pearlite 4**
The boundary of the welded joint – HAZ	1,00	-0,72	-0,25	0,03	-0,03	0,51	-0,39	0,23	0,67
HAZ	-0,72	1,00	0,54	0,08	0,17	-0,24	0,61	0,39	-0,67

Continuation of Table 1

The boundary between the heat-affected zone (HAZ) and the base metal.	-0,25	0,54	1,00	-0,67	-0,67	-0,51	-0,30	-0,09	-0,62
Ferrite 2	0,03	0,08	-0,67	1,00	0,97	0,77	0,78	0,62	0,50
Ferrite 3	-0,03	0,17	-0,67	0,97	1,00	0,65	0,86	0,68	0,34
Ferrite 4	0,51	-0,24	-0,51	0,77	0,65	1,00	0,40	0,63	0,86
Pearlite 2	-0,39	0,61	-0,30	0,78	0,86	0,40	1,00	0,73	-0,03
Pearlite 3	0,23	0,39	-0,09	0,62	0,68	0,63	0,73	1,00	0,21
Pearlite 4	0,67	-0,67	-0,62	0,50	0,34	0,86	-0,03	0,21	1,00
	10G2FB								
	The boundary of the welded joint – HAZ	**HAZ**	**The boundary between the heat-affected zone (HAZ) and the base metal.**	**Ferrite 2**	**Ferrite 3**	**Ferrite 4**	**Pearlite 2**	**Pearlite 3**	**Pearlite 4**
The boundary of the welded joint – HAZ	1,00	-0,15	0,96	-0,47	-0,24	0,13	-0,49	-0,37	-0,22
HAZ	-0,15	1,00	-0,02	-0,73	-0,53	-0,72	-0,45	0,12	-0,16
The boundary between the heat-affected zone (HAZ) and the base metal.	0,96	-0,02	1,00	-0,61	-0,37	-0,10	-0,49	-0,29	-0,17
Ferrite 2	-0,47	-0,73	-0,61	1,00	0,67	0,72	0,61	0,01	0,10
Ferrite 3	-0,24	-0,53	-0,37	0,67	1,00	0,71	0,83	0,56	0,65
Ferrite 4	0,13	-0,72	-0,10	0,72	0,71	1,00	0,29	-0,18	-0,01
Pearlite 2	-0,49	-0,45	-0,49	0,61	0,83	0,29	1,00	0,78	0,83
Pearlite 3	-0,37	0,12	-0,29	0,01	0,56	-0,18	0,78	1,00	0,94
Pearlite 4	-0,22	-0,16	-0,17	0,10	0,65	-0,01	0,83	0,94	1,00

The generalized eigenvalues presented in Table 2 reflect the results of the analysis of different steel grades after welding, highlighting the importance of material selection in welding technology.

Table 2

Generalized eigenvalues of the studied steel grades after electron beam welding.

09G2S			
	Eigenvalues	**Percentage of total variance**	**Cumulative, %**
Factor 1	4,179374	46,43749	46,4375
Factor 2	2,390334	26,55926	72,9968
Factor 3	1,524795	16,94216	89,9389
Factor 4	0,703839	7,82043	97,7593
Factor 5	0,201659	2,24066	100,0000
10HSND			
	Eigenvalues	**Percentage of total variance**	**Cumulative, %**
Factor 1	4,546941	50,52157	50,5216
Factor 2	2,973983	33,04426	83,5658
Factor 3	1,058407	11,76008	95,3259
Factor 4	0,344187	3,82430	99,1502
Factor 5	0,076481	0,84979	100,0000
10G2FB			
	Eigenvalues	**Percentage of total variance**	**Cumulative, %**
Factor 1	4,419991	49,11101	49,1110
Factor 2	2,400740	26,67489	75,7859
Factor 3	1,714751	19,05279	94,8387
Factor 4	0,405599	4,50666	99,3453
Factor 5	0,058919	0,65465	100,0000

The graph presented in Figure 1 illustrates the eigenvalues for steels 09G2S, 10G2FB, and 10HSND, demonstrating their differences in behavior during welding. This clearly confirms that each steel grade has its unique characteristics that affect the quality of welded joints.

Factor analysis allowed for the reduction of the number of variables to key factors, significantly simplifying further research and optimization of technological processes. The main identified factors are the percentage content of ferrite and pearlite, which play a critical role in electron beam welding processes. This highlights the necessity of monitoring these parameters to achieve the desired level of quality in welded joints [1,2].

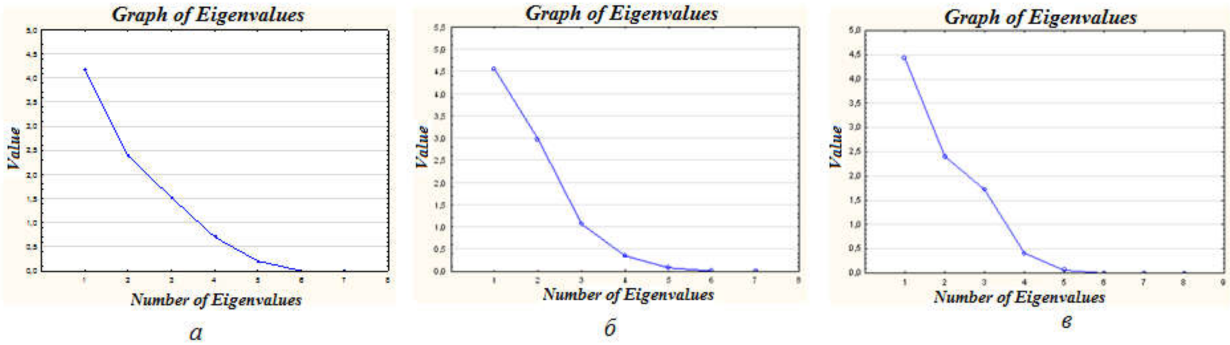

Fig. 1. Graph of eigenvalues: a – steel 09G2S; b – steel 10G2FB; c – steel 10HSND.

Conclusion. The results of this study can serve as the basis for developing a mathematical model that allows for predicting the quality of welded joints based on their structural characteristics. This could represent an important step in improving welding technologies and ensuring product reliability.

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ФОРМУВАННЯ СТРУКТУРИ ТА ФАЗОВОГО СКЛАДУ ВИСОКОЕНТРОПІЙНОГО $W_{1,5}$FECONI СПЛАВУ В ПРОЦЕСІ МЕХАНІЧНОГО ЛЕГУВАННЯ

Анотація. В роботі досліджено процеси утворення самоармованих частинок порошків високоентропійного $W_{1,5}FeCoNi$ сплаву часонками карбіду вольфраму які утворюються під час механічого легування. Показано, що відбувається формування трифазного композиту з ОЦК, ГЦК твердими розчинами та частинами WC. Середній розмір частинок WC в матриці ВЕСу складає 0,5 мкм.

Ключові слова: *високоентропійні сплави, механічне легування, структура, твердий розчин, карбід вольфраму*

Основною розвитку сучасного машино- ракетобудування, електроніки та аерокосмічних технологій є розробка нових матеріалів з підвищеними фізико-механічними властивостями (високою твердість, міцністю, модулем пружності, ударною в'язкість тощо) та високою стійкістю до дії корозійного та окисного середовища [1]. Одним з перспективних напрямків щодо реалізації нового підходу до проектування матеріалів є створення так званих високоентропійних сплавів (ВЕС) [2]. Високоентропійні сплави – це новий клас металевих матеріалів, що складаються з п'яти і більше основних елементів у приблизно рівних атомних концентраціях [3]. Їх відрізняє висока ентропія змішування, яка стабілізує однофазні структури [4]. На відміну від традиційних сплавів, де один або два основні елементи домінують, у ВЕС усі елементи мають майже однаковий вплив на властивості матеріалу. Ці сплави демонструють надзвичайно високу міцність (800-1200 МПа [5]), твердість (300-900 HV [6]), корозійну та термічну стійкість. Це робить їх перспективними для використання в аерокосмічній, автомобільній, енергетичній промисловостях, а також в інших сферах, де потрібні міцні та довговічні матеріали.

За рахунок унікальних властивостей ВЕС можуть бути використані як складові компоненти для розробки композиційних матеріалів за участі тугоплавких сполук [7]. В даному випадку отримання композиційних матеріалів може бути здійснено прямим введенням тугоплавких сполук з подальшим спіканням до заданої щільності, або ж з використанням підходів, які б забезпечували "in-situ" утворення частинок зміцнювальної фази. Найбільшого поширення набули композити на основі карбіду вольфраму. Оскільки в основі виходу з ладу твердосплавних різців є зношування матричної фази кобальту за рахунок її вимивання, застосування більш твердих та зносостійких сплавів в якості матриці може стати новим витком в розвитку металообробки. В роботах [8-9] показано, що метало матричні композити на основі карбіду вольфраму з матрицею з ВЕС дозволяють отримувати композиційні матеріали типу керметів для виготовлення ріжучого інструменту з підвищеними експлуатаційними властивостями. Було встановлено, що заміна кобальтового сполучного на ВЕС~~и~~ може призвести також до подрібнення зерен WC. Одні з найкращих значень твердості (2358 HV), тріщиностійкості (12,1 МПа·м$^{1/2}$) та міцності на стиск (5420 МПа) отримано для твердого сплаву WC – 20 мас.% AlFeCoNiCrTi ВЕС з ОЦК структурою, спеченого при 1500 °С [10].

Альтернативним варіантом композиційних матеріалів є зміцнення матриці з ВЕС~~у~~ добавками до 20 об. % частинок карбідів, боридів, нітридів чи оксидів. Проте, за рахунок поєднання високої твердості, модуля пружності та мікропластичності, найвищого ступеню зміцнення можна досягнути під час використання карбіду вольфраму як зміцнюючої фази [11]. В роботі [11] проводили отримання композитів CoCrFeNi–WC з різним вмістом зміцнюючої складової. Показано, що твердість композиту CoCrFeNi–20 мас.% WC складає 593 HV, що виявився в 3,3 рази вищим, ніж базовий ВЕС 180 HV, тоді як межа текучості збільшилася з 278 МПа для базового ВЕС до 1098 МПа для композиту CoCrFeNi–20 мас.% WC. Отримання композитів прямим змішуванням керамічних частинок з ВЕС має ряд недоліків пов'язаних із сегрегацією складових та їх нерівномірним розподілом. Рівномірність розподілу є одним з ключових структурних факторів композиційних матеріалів, зміцнених керамічними частинками, оскільки локальні флуктуації керамічних частинок значно знижують міцність матеріалу. Більш перспективним методом отримання зміцнених композиційних матеріалів на основі ВЕС-є "in-situ" синтез зміцнених порошків.

Виходячи з цього, метою даної роботи є встановлення закономірностей утворення самозміцненої структури порошків W1,5FeCoNi в умовах механічного легування елементарної порошкової суміші W-Fe-Co-Ni.

Як вихідні матеріали було взято порошки металів W, Fe, Co, Ni з розміром частинок 25–50 мкм та чистотою 99 %. Наважку порошків розміщували в твердосплавний барабан із відношенням кульок до матеріалу 10:1. Для уникнення налипання, та реакції зі стінками барабану розмелювання проводили в середовищі бензину. Механічне легування проводили за 400 об/хв протягом 20 годин. Аналіз отриманих порошків проводили методами растрової електронної мікроскопії та рентгенівського фазового аналізу.

На рисунку 1, а наведено результати рентгеноструктурного аналізу порошкового $W_{1,5}$FeCoNi ВЕС після механічного легування (МЛ). Після 20 годин МЛ формується сплав, який складається з: твердих розчинів з ОЦК і ГЦК структурою та карбіду вольфраму WC. Відповідно до теоретичних засад формування структури твердих розчинів ВЕС для $W_{1,5}$FeCoNi сплаву кількість валентних електронів (КВЕ) складає близько 8, що, відповідно до роботи [12], вказує на високу імовірність утворення двох твердих розчинів, та відповідає даним отриманим в роботі.

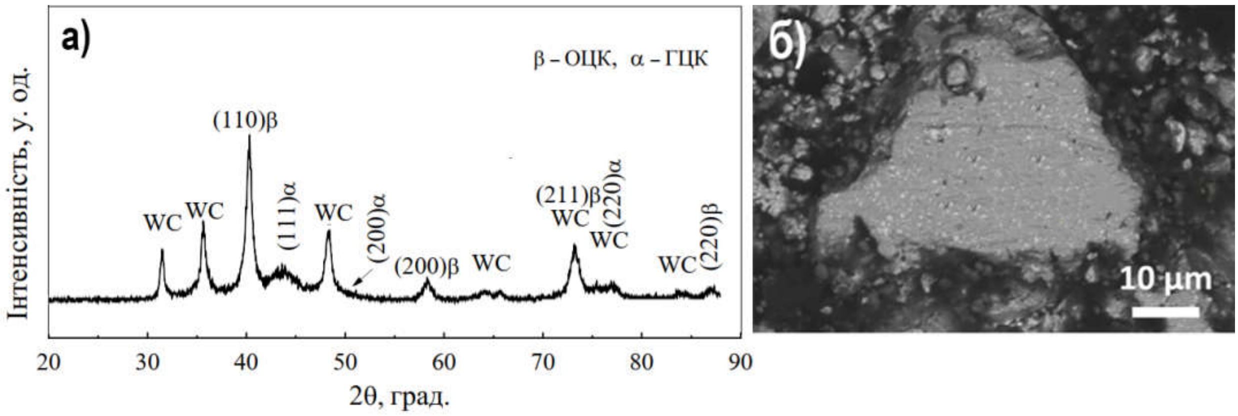

Рисунок 1 – Спектр рентгенівської дифракції (а) та мікроструктура порошку $W_{1,5}$FeCoNi ВЕС після механічного легування ОЦК

Утворення WC фази в структурі порошкового матеріалу пов’язано зі взаємодією атомів вуглецю, які не розчинилися в октаедричних та тетраедричних_порожнинах ОЦК та ГЦК кристалічних ґраток твердих розчинів заміщення, з атомами W під час МЛ та зумовлено найбільш високим, від’ємним значенням ентальпії змішування атомної пари W–C (ΔH_{W-C} = – 60 кДж·моль$^{-1}$) серед ентальпій змішування інших елементів з вуглецем в системі W-Fe-Co-Ni та наявності високовуглецевого середовища під час розмелювання. До того ж, вуглець, завдяки найменшому атомному радіусу порівняно з іншими компонентами сплаву, має найбільшу швидкість дифузії і крім розчинення в порожнинах ґраток твердих розчинів заміщення внаслідок «in-situ» реакції утворює WC.

Частинки карбіду вольфраму, які утворюються під час МЛ, синтезу мають середній розмір 0,5 мкм (рис. 1 б). За рахунок синтезу сплаву методом механічного легування первинний розподіл в сплаві атомів W як і атомів інших елементів, відбувається на атомному рівні. В подальшому під час його взаємодії з вуглецем досягається висока рівномірність розподілу змцнювальної карбідної фази по об'єму частинок порошків.

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СТРИМУЮЧІ ФАКТОРИ ВИКОРИСТАННЯ ТЕХНОЛОГІЇ 3D-ДРУКУ В БУДІВЕЛЬНІЙ ГАЛУЗІ

У роботі наведені результати проведеного аналізу щодо стримуючих факторів використання технології 3D-друку в будівельній галузі, а саме соціальних, правових, наукових, технічних та економічних бар'єрів. Запропоновані шляхи подолання вищевказаних викликів.

Ключові слова: *технологія 3D-друку, будівельний 3D-принтер, бетонні суміші для 3D-друку, стримуючі фактори, будівельна галузь*

Швидкість будівництва та простота монтажу, екологічні відновлювальні будівельні матеріали і конструкції та високий клас енергоефективності зведених будівель – такі сучасні вимоги часу перед світовою будівельною індустрією. Перспективною інноваційною технологією здатною все це забезпечити є 3D-друк будівель.

Як розглядалося в роботі [1, с. 104], внаслідок воєнних дій на території України зруйновано велику кількість об'єктів житлового фонду, соціальної та цивільної інфраструктури. Перед українськими інженерами-будівельниками постає серйозний виклик – забезпечити комфортним житлом тисячі українців в стислі терміни. За даними [2, с. 166], наприклад, будівельний принтер StroyBot або 3D-принтер Rudenko здатний звести стіни будинку площею у 100 $м^2$ протягом 48 годин. Отже, не викликає сумніву перспективність застосування 3D-друку будівель в реаліях України. Проте, станом на зараз, ця технологія не є розповсюдженою та має характер поодиноких випадків окремих забудовників, як в Україні, так і у світі. Розглянемо стримуючі фактори використання 3D-друку в будівельній галузі (рис. 1).

1. Соціальні фактори. Нові недостатньо вивчені технології завжди зустрічаються із певною пересторогою як з боку підприємців, які ризикують власними коштами у разі інвестицій в них, так і суспільством, які неготові сприймати інноваційні підходи, що не підтвердили свою ефективність роками застосування. Головна причина в цьому вбачається у низькій проінформованості широких верств населення у перевагах та технологічно обґрунтованих рішень щодо можливостей адитивних технологій. Більшість людей вважають цю ідею складною та неможливою у реалізації. Для подолання даної проблеми необхідно проводити роз'яснювальні кампанії від фахівців-професіоналів, потужну інформаційну підтримку запровадження інноваційної технології 3D-друку.

Крім того, на ринку праці бракує кваліфікованих кадрів як інженерного, так і робітничого рівня, які б могли надати фахові консультації, рекомендації та взяти участь безпосередньо у впровадженні у життя проєктів будівель, зведених за допомогою 3D-технології. Це свідчить про необхідність відкриття сучасних спеціальностей в закладах професійної (професійно-технічної) та вищої освіти із підготовки кваліфікованих кадрів даного профілю.

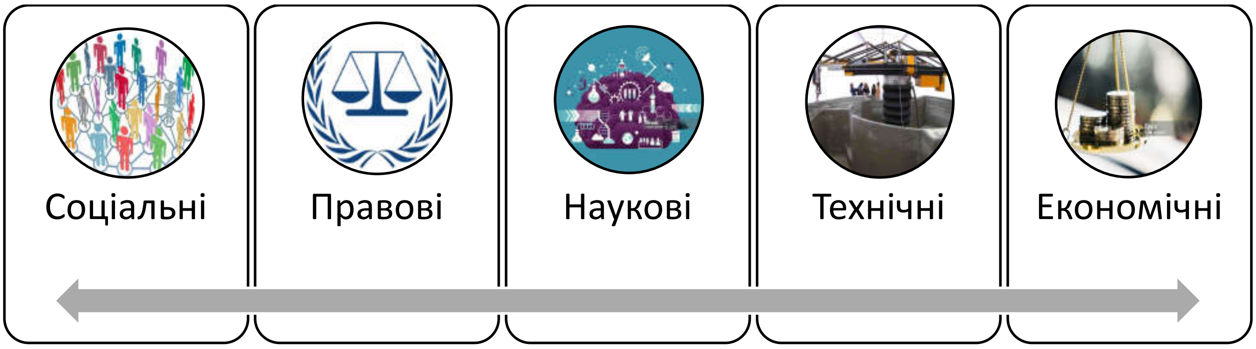

Рисунок 1. Стримуючі фактори використання технології 3D-друку в будівельній галузі

2. Правові фактори. Наразі відсутні державні будівельні норми або інші нормативно-правові документи, які б регламентували правила використання 3D-друку в будівельній галузі. Забудовники та інвестори потребують чіткого розуміння вимог до обладнання (будівельних 3D-принтерів), до будівельних сумішей, які є ефективними для використання при 3D-друці будівель різного призначення, до технічних характеристик будівельних конструкцій, виготовлених за допомогою 3D-друку та правил сертифікації зведених за цією технологією будівель.

Гарним стимулом до використання проєктів будівель, зведених за допомогою 3D-друку була б розробка та затвердження законодавчих актів щодо інвестування та певних податкових пільг при запровадженні подібних проєктів.

3. Наукові фактори. Наявний брак знань та наукових досліджень фахівців різних галузей для успішної інтеграції технології 3D-друку в будівельну галузь.

Зокрема, необхідні ґрунтовні наукові дослідження спрямовані на розробку оптимальних складів бетонних сумішей для будівельних 3D-принтерів; розробку та оптимізацію конструкції українських 3D-принтерів та комплектуючих до них із врахуванням вимог до міцності, стійкості та ефективності виготовлених конструкцій; створення віртуальних багатозадачних моделей будівельних об’єктів, які потім можуть бути відтворені за допомогою будівельного 3D-принтера; розробку та вдосконалення системи автоматизованого 3D-друку, яка покращить продуктивність і точність процесу та інше.

Тільки тісна співпраця вчених із різних галузей наук дозволить застосувати комплексний міждисциплінарний підхід до досліджень технології 3D-друку будівель та забезпечити її максимальну ефективність та популяризацію як провідної технології в будівельній галузі.

4. Технічні фактори. Технічна неготовність ринку українських забодувників також негативно впливає на нарощення темпів зведення будівель за технологією 3D-друку. Головною проблемою є відсутність вітчизняних будівельних 3D-принтерів та комплектуючих до них. При цьому наразі спостерігається достатньо високий рівень виходу з ладу закордонного устаткування, що безумовно затримує темпи зведення будівель та здорожчує їх вартість. Крім того, відсутні фахівці з ремонту та експлуатації будівельних 3D-принтерів.

Також є обмеженість в доступних будівельних матеріалах, більшість складів бетонних сумішей, які використовуються для 3D-друку є закордонною розробкою.

Автоматизована технологія 3D-друку вимагає абсолютно рівної поверхності будівельного майданчика для можливості укладання напрямних рейок та безперешкодного руху по ним будівельного 3D-принтера та забезпечення його високої продуктивності та точності [2, с. 172].

5. Економічні фактори. З економічної точки зору є проблема гострого браку коштів як окремих забудовників, так і держави на реалізацію масштабних інноваційних будівельних проєктів. Технологія 3D-друку потребує високих початкових інвестицій через використання дороговартісного закордонного тривимірного обладнання (3D-принтерів). Подальший розвиток технології та розширення використання даного устаткування у найближчому майбутньому може сприяти зниженню цих витрат прямо пропорційно зростанню конкуренції на ринку.

Проте дана технологія відкриває можливості щодо заощадження в інших аспектах: значного скорочення термінів будівництва та трудовитрат. Адже, в цьому випадку достатньо 2 – 3 осіб на будівельному майданчику: оператора, який керуватиме роботою будівельного 3D-принтера та матеріалознавця, який займатиметься приготуванням високопластичної бетонної суміші. Крім того, попередні наукові дослідження вчених [3, с. 9 – 10; 4, с. 16] дозволяють прогнозувати широке використання в якості сировини для бетонних сумішей дешевих вторинних матеріальних ресурсів (золи-виносу, доменного гранульованого шлаку, мікрокремнезему та ін). Це все в комплексі мінімізує капіталовкладення на використання технології 3D-друку.

Для старту ж використання цієї технології необхідна кооперація із європейськими партнерами, в тому числі, через залучення коштів міжнародних донорів на реалізацію подібних проєктів.

Висновки. Отже, є ряд стримуючих факторів для широкого запровадження та швидкої реалізації будівництва житлового фонду України із використанням новітньої технології 3D-друку. Вирішувати їх необхідно комплексно та в команді із фахівцями різних галузей наук і представниками різних сфер діяльності (держави, бізнесу, науки, європейських донорів). Але, у підсумку, технологія 3D-друку відкриває безліч можливостей для справжнього революційного стрибка у розвитку будівельної галузі, подолання нею викликів щодо сталого та швидкого процесу відбудови України.

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CHOICE OF ECOLOGICAL MATELIAL FOR THE CONSTRUCTION OF A MODULAR HOUSE

Abstract. This study proposes the selection of an eco-friendly material for the construction of a modular house, offering an optimal balance between cost-efficiency, durability, and sustainability. An analysis of modern nanomaterials was conducted, alongside a detailed description of the modeling and structural calculations performed using Autodesk Fusion 360. This approach enables the assessment of the strength and reliability of structural elements. The implementation of the proposed method promotes the advancement of modern sustainable construction practices.

Keywords: *Fusion 360, modular construction, sustainable construction, eco-friendliness, material properties, nanomaterials, nanoroof, nanotechnology, structural strength*.

Today, modular construction and eco-friendly materials utilizing nanotechnology are gaining popularity due to increasing demands for environmental responsibility and energy efficiency.

The aim of this work is to design a house assembled from modules made of environmentally safe nanomaterials that are harmless to human health and do not negatively impact the environment. The dimensions of the house are 10 by 10 meters, with a total area of 100 m² (fig. 1).

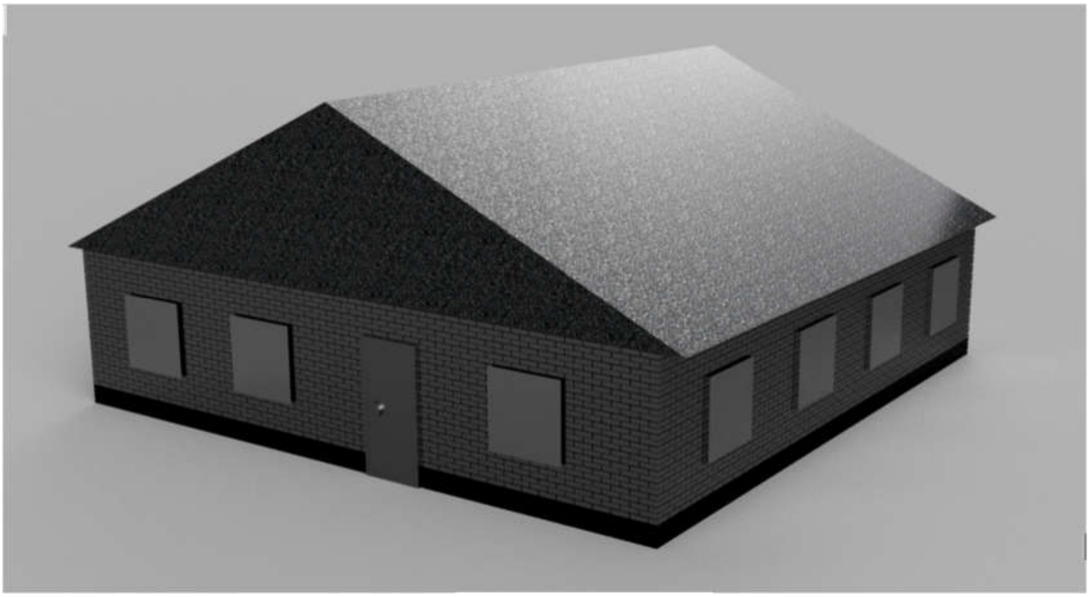

Fig. 1. – Sketch of the house

The use of eco-friendly materials in modular house construction faces several significant challenges. First, these materials require in-depth research into their durability and environmental impact. Second, their application necessitates changes in design and personnel training, as innovative approaches demand specialized knowledge and skills. Despite these challenges, eco-friendly materials remain promising due to their advantages. They contribute to reducing CO_2 emissions, conserving energy resources, and improving indoor air quality [1].

Such materials are popular in countries with high sustainability standards, particularly in Europe, the United States, and Canada, where modular houses made from eco-friendly materials are frequently used in rapid housing or office construction projects. This is due to their adaptability to different climate conditions and the ability to reuse the structures multiple times.

For the construction of modular eco-houses, environmentally friendly materials can be used, including soil blocks, nanoconcrete with improved thermal insulation properties, nano-brick for strong and lightweight structures, recycled metal, and FSC-certified wood, bamboo as a rapidly renewable resource, as well as nanocomposites to enhance the durability and stability of the building. These materials ensure energy efficiency, reduced emissions, and minimize environmental impact [2].

Nanobrick and nanoconcrete are among the most common materials in modular construction due to their unique properties. Nano-brick offers high strength with lightweight, making transportation and assembly easier. Its structure, modified with nanoparticles, provides self-cleaning, water resistance, and UV radiation resistance, extending the service life of buildings.

Nanoconcrete is distinguished by excellent thermal and sound insulation properties, which reduce the energy consumption of the building. By incorporating graphene or nanosilica, it becomes stronger and more crack-resistant, allowing for a reduction in the weight of structures without compromising reliability. These materials are not only environmentally safe but also economically efficient due to low maintenance costs and a long service life [3].

Construction using nanomaterials, such as nano-brick and nanoconcrete, can be 30-50% more cost-effective compared to traditional methods due to reduced material costs, shorter construction times, and enhanced energy efficiency. These materials also lower energy-saving expenses thanks to their excellent thermal insulation properties and reduced waste, making them a profitable choice in the long term.

To calculate the load on the roof structure, three main components were considered: the weight of the roof, snow load, and wind load. The weight of the roof is determined based on the roofing material and the beams that make up the structure. Snow load depends on local climatic conditions, particularly snow cover and maximum loads during the winter period. Wind load is calculated based on wind speed and the shape of the structure, also taking into account the type of terrain. These parameters are used to determine the maximum possible loads that could affect the safety and stability of the roof [4].

Calculation of total load:

1. Snow load per meter:

$q_{snow} = 150\ kg/m^2 \times 2\ m = 300\ kg/m$

2. Wind load per meter:

$q_{wind} = 50\ kg/m^2 \times 2\ m = 100\ kg/m$

3. Own weight of the roof per meter:

$q_{own} = 50\ kg/m^2 \times 2\ m = 100\ kg/m$

4. Total load per linear meter:

$q_{total} = q_{snow} + q_{wind} + q_{own} = 300\ kg/m + 100\ kg/m + 100\ kg/m = 500\ kg/m$

5. Conversion to newtons:

$q_{total} = 500\ kg/m \times 9.81\ N/kg = 4905\ N/m$

6. Calculation of reactions at supports:

$R_A = R_B = (q_{total} \times L)/2$

$R_A = R_B = (4905\ N/m \times 10\ m)/2 = 24525\ N$

According to the load calculations for the building, taking into account the roof weight, snow load, and wind load is essential for ensuring the reliability and safety of the structure. This allows for determining the maximum possible loads on the roof, which is crucial for maintaining its stability and longevity. Considering these factors ensures the accuracy of the calculations and enables the design of a safe roof capable of withstanding external influences [5].

Thus, modular construction using eco-friendly nanomaterials, such as nano-brick and nanoconcrete, has significant potential for the sustainable development of the construction industry. These materials offer excellent mechanical and thermal insulation properties, reducing the energy consumption of buildings and contributing to a decrease in CO_2 emissions.

Modular houses built using nanomaterials can be constructed 30-50% faster compared to traditional methods. This significantly reduces labor costs and allows for a quicker return on investment.

Load calculations for the roof, including the weight of the roof, snow load, and wind load, are critically important for ensuring the reliability and longevity of buildings. With accurate engineering calculations and the proper selection of materials, the safety and stability of the structures can be guaranteed. This makes modular houses made from nanomaterials and nano-roofs an ideal solution for the future of sustainable construction.

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STUDY OF THE RELATIONSHIP BETWEEN THE STRUCTURAL STATE AND THE FORMATION OF FRACTURE SURFACES OF LOW-CARBON MICROALLOYED STEELS

Abstract. The relationship between the structural state and the fracture mechanism of low-carbon, low-alloy steels was investigated. The results obtained in the work will allow to increase the complex of mechanical characteristics of rolled metal for building metal structures, in particular, resistance to fracture propagation.

Keywords: *structural state, fracture surface, low-carbon low-alloy steel interfaces*.

Основний зміст роботи. Повоєнний розвиток будівельної галузі України поставить нові вимоги до властивостей матеріалів, зокрема підвищення комплексу їх механічних характеристик. Особливе місце в широкому колі питань, пов'язаних з цією проблемою, посідає вивчення здатності матеріалів чинити опір руйнуванню при статичних і динамічних навантаженнях. При цьому опір матеріалу поширенню в ньому тріщин визначається його структурою, а саме морфологічними особливостями тонкої будови: розміром структурних складових, дисперсністю і розподілом неметалевих включень, типом внутрішньофазних та міжфазних границь, тобто кількістю та розподілом нанорозмірних структурних складових.

Саме тому метою даної роботи є дослідження впливу структурного стану на механізм руйнування низьковуглецевих низьколегованих сталей.

Основним матеріалом для дослідження була обрана низьковуглецева низьколегована сталь 10Г2ФБ товщиною 40 мм (клас міцності Х70 по API 5CT), хімічний склад якої наведено в табл. 1. Дану сталь було виготовлено за технологічною схемою традиційної контрольованої прокатки [1].

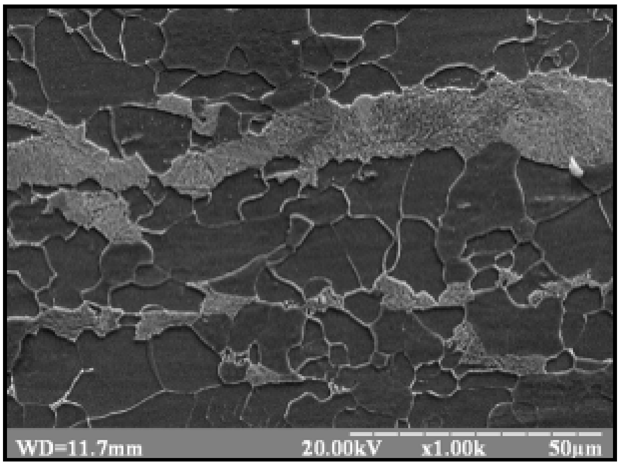
Для дослідження впливу нанорозмірних елементів на кінетику руйнування було відібрано зразки з листів товщиною 40мм на трьох рівнях: а- поверхневий шар, б- ¼ товщини, в- середина листа.

Таблиця 1

Хімічний склад сталі 10Г2ФБ

Сталь	Вміст елементів, (масс.) %						
	C	Mn	Si	S	P	V	Nb
10Г2ФБ	0,10	1,83	0,18	0,005	0,015	0,088	0,022

Результати металографічних досліджень представлено на рис. 1.



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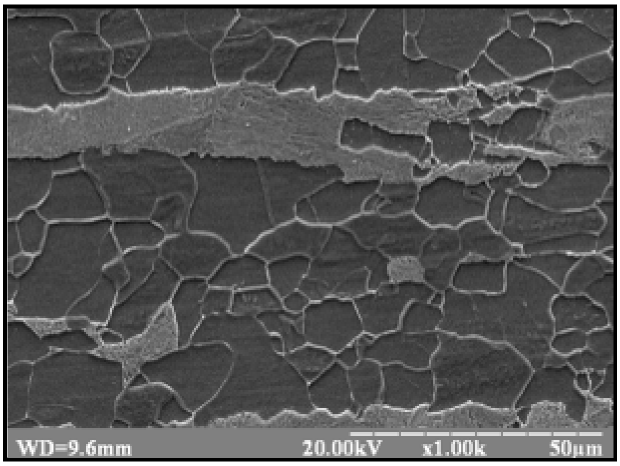

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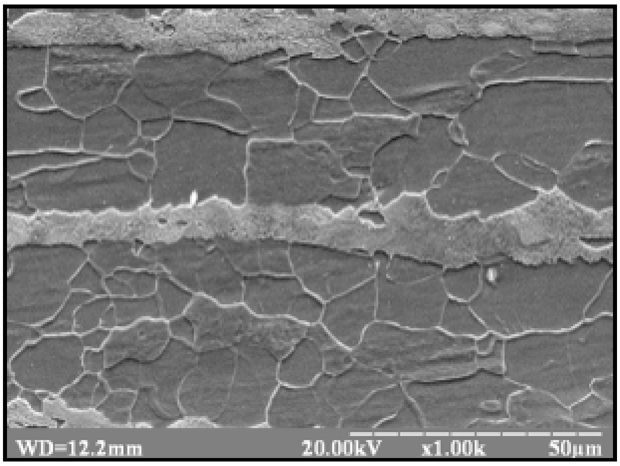

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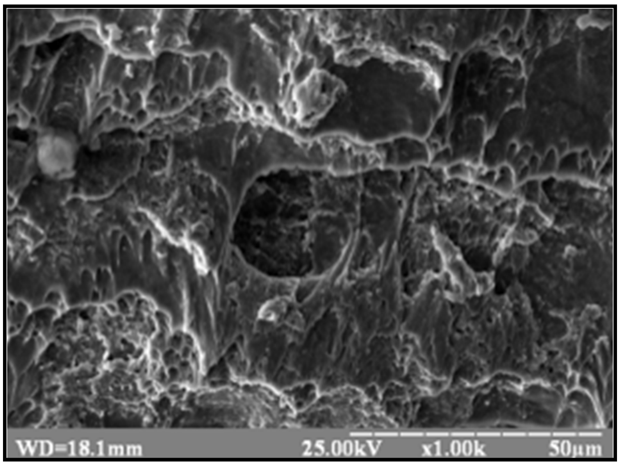
Рис. 1. Структура сталі 10Г2ФБ: *а* – поверхня листа; *б* - ¼ товщини листа; *в* - середина листа

Аналіз наведених на рисунку даних показує, що структура має змішаний поліедричний тип за загальною класифікацією типів структур [2].

Фрактограми поверхні руйнування вивчали за допомогою растрового електронного мікроскопу. Оцінку характеру зламу давали візуальним методом через його простоту та доступність спираючись на результати, які було отримано в роботі [3]. Результати фрактографічних досліджень поверхонь руйнування сталі 10Г2ФБ наведено на рис. 2.

Проведений комплекс досліджень показує, що злам майже повністю в’язкий, про що свідчить наявність характерних для цього типу руйнування ознак. При цьому слід зазначити, що зародження руйнування відбувалося на частках другої фази. Спостерігається багато пор різного розміру та на стінках великих пор можливо спостерігати пори малих розмірів.



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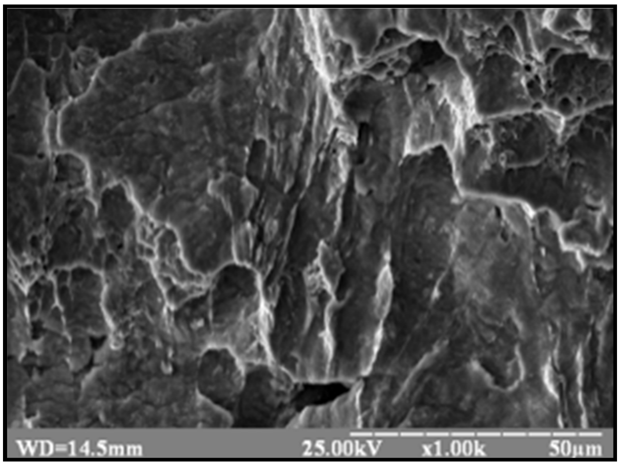

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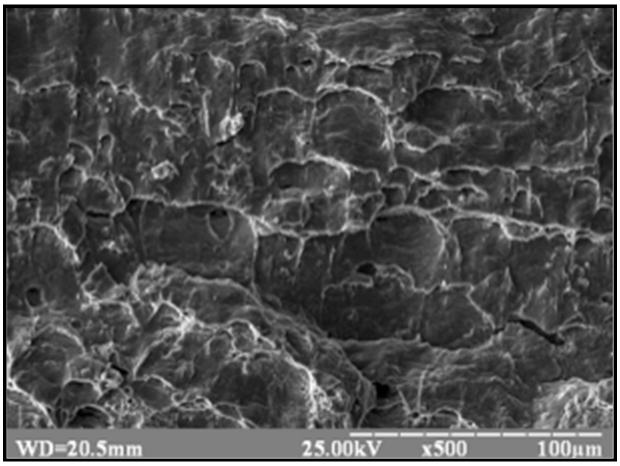

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Рис. 21. Поверхні руйнування сталі 10Г2ФБ: *а* – поверхня листа; *б* - ¼ товщини листа; *в* - середина листа

На фрактограммах присутня велика кількість неметалічних включень, які, здебільшого, знаходяться в порах різних розмірів. Пори також містять багато зруйнованих включень, що обумовлено високими ступенями пластичної деформації, яка передувала руйнуванню.

Аналіз кінетики розповсюдження руйнування через зерно граничні ансамблі показав, що біля границь спеціального типу (тип границь визначали згідно методики, представленої в роботі [4]) не спостерігаються пори. Таким чином, можливо зробити висновок, що руйнування розповсюджується, в першу чергу, по границям загального типу. При цьому, при переході через границі такого типу тріщина утворює сходинки.

Границя між зернами – область, в якій відбувається контакт двох кристалів, відмінних лише орієнтацією. Важливим питанням, яке було розглянуто в роботі, стало визначення впливу спеціальних границь на механізм розповсюдження тріщини в структурі. Так як зерна знаходяться в різних кристалографічних площинах, тріщина, підходячи до границі, втрачає певну енергію для подолання бар'єру – міжзеренної границі, і тим самим гальмується. Пройшовши певну кількість таких границь тріщина може зупинитись. Чим більше границь вона «зустрічає на шляху», тим важче їй рухатись. Але спеціальні границі, знаходячись між зернами, які відрізняються своїм положенням несуттєво і можуть лежати в схожих кристалографічних площинах, не будуть служити границями гальмування тріщини, так як тріщині легко перейти через таку границю. Тому механізм руху тріщини не просто не зміниться, а залишиться тим самим. Тобто спеціальні границі, на відміну від загальних, не будуть служити бар'єром для гальмування руху тріщини.

Висновки. Досліджено взаємозв'язок між структурним станом та механізмом руйнування низьковуглецевих низьколегованих сталей. Показано, що зародження руйнування відбувається на міжфазних границях частка-матриця. При цьому, руйнування розповсюджується, в першу чергу, по границям загального типу.

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PHYSICAL MODELING OF PLASTIC DEFORMATION PROPAGATION IN LOW-CARBON LOW-ALLOY STEELS IN THE FERRITIC-PEARLITE STRUCTURAL STATE

Abstract. Modeling the process of plastic deformation propagation in low-carbon low-alloy steels. The results obtained are aimed at improving the mechanical properties and expanding the areas of application of rolled products made of low-carbon microalloyed steels of domestic production based on establishing interdependencies between the structure and kinetics of crack propagation during dynamic mechanical fractures.

Keywords: *Plastic deformation, modeling, fracture, external loading.*

Основний зміст роботи. Аналіз економічного розвитку України, показує гостру необхідність розширення галузей використання продуктів вітчизняної промисловості, зокрема металопрокату. Одним із можливих шляхів вирішення цього завдання є використання сталей вітчизняного виробництва у будівельній галузі, насамперед при реконструкції пошкоджених внаслідок бойових дій споруд. При цьому, вітчизняний металопрокат повинен бути конкурентоздатним у порівнянні з закордонними аналогами, як за комплексом властивостей, так і за собівартістю готових виробів. Однією з найважливіших вимог, що висуваються до сучасних будівельних сталей є здатність чинити опір руйнуванню при динамічних навантаженнях будівельних конструкцій. С цієї точки зору, на перший план виходить дослідження, які спрямовано на з'ясування впливу зовнішнього навантаження на структурний стан матеріалу.

Саме тому метою даної роботи є моделювання процесу розповсюдження пластичної деформації в низьковуглецевих низьколегованих сталях.

Для вивчення впливу нанорозмірних елементів структури на механізм руйнування будівельних сталей основним матеріалом для дослідження була обрана сталь 06Х1. Хімічний склад даної сталі представлено в табл. 1.

Для проведення досліджень було виготовлено зразки з сталі 06Х1. Зразки мали циліндричну форму і одну відшліфовану поверхню, придатну для металографічних досліджень. Зразки були піддані розтягу, без досягнення стану руйнування. Розтяг зразків припинявся при різних навантаженнях, значення яких приведені у табл. 2, та на рис. 1.

Таблиця 1

Хімічний склад сталі 06Х1

Вміст хімічних елементів, %											
C	Cr	Cu	Mn	P	S	Si	Ni	Al	N	Mo	Nb
0,062	1,11	0,19	0,49	0,004	0,004	0,27	0,11	0,022	0,012	0,013	0,002

Таблиця 2

Зусилля навантаження зразків при випробуванні на розтяг

№ зразка	1	2	3	4	5
Зусилля навантаження P, Н	3033,8	3079,0	3806,3	3900,0	3981,0

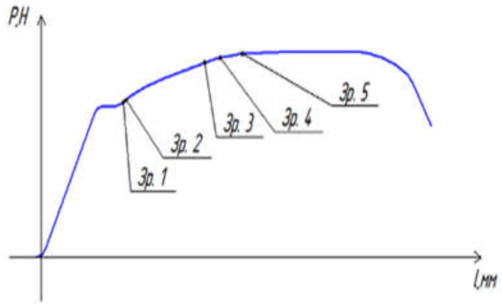

Рис. 1. Діаграма експериментального розтягу зразків

Для моделювання процесу розповсюдження пластичної деформації було використано наступну модель. Розглянемо спільну діаграму трьох суміжних зон, з яких середня відчуває пластичну деформацію, а обидві крайні знаходяться в пружному стані. Поведінку цих зон можна дослідити за аналогією із системою трьох стрижнів, з'єднаних і навантажені спільної зовнішньої навантаженням *P*. Приймемо, що стрижні виготовлені з одного і того ж матеріалу, наприклад фериту, і мають одну і ту ж границю плинності. Природно, зусилля в стержнях будуть неоднакові. З іншого боку, аналізовані три зони, виділені в обсязі полікристалічного матеріалу, працюють при одному і тому ж навантаженні, але мають різний опір пластичної деформації. Однак, при розгляді внутрішніх напружень, що діють в малих обсягах порядку розміру одного зерна, описана модель досить правильно відображає співвідношення сил, що має місце в реальному матеріалі. Середній стрижень системи несе найбільше навантаження і в ньому в першу чергу виникає пластична деформація в той час, коли в інших стержнях поки ще має місце тільки пружна деформація.

Для розрахунку була використана наступна формула:

$$\sigma_{cp} = P/(F_1 + F_2 + F_3) \qquad (1)$$

де F_1 – не деформоване зерно, а F_2 і F_3 – деформовані зерна (рис. 2).

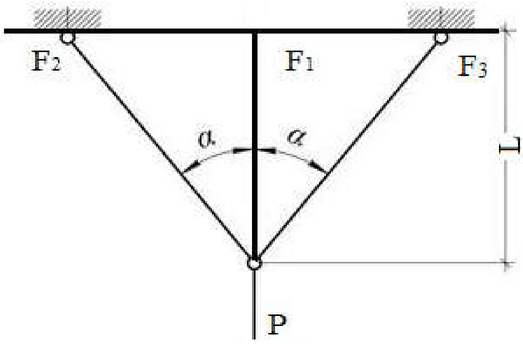

Рис. 2. Стрижнева модель для пояснення умов розповсюдження пластичній деформації

Для розрахунку згідно запропонованої моделі були використані локальні області структури, приклад яких наведено на рис. 3.

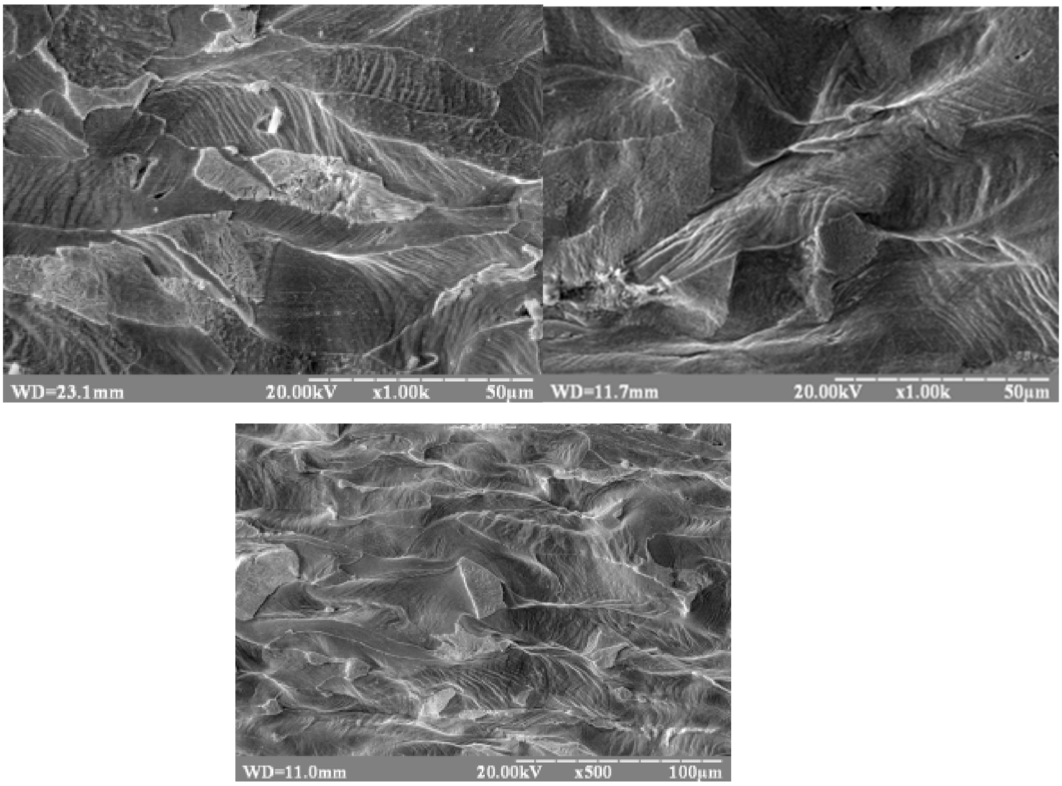

Рис. 3. Загальний вигляд конфігурацій структурних складових, які було застосовано при моделюванні розповсюдження пластичної деформації:
а – навантаження 3806,3 Н;
б– навантаження 3900 Н;
в – навантаження 3981 Н.

Результати розрахунків узагальнено та наведено на рис. 4.

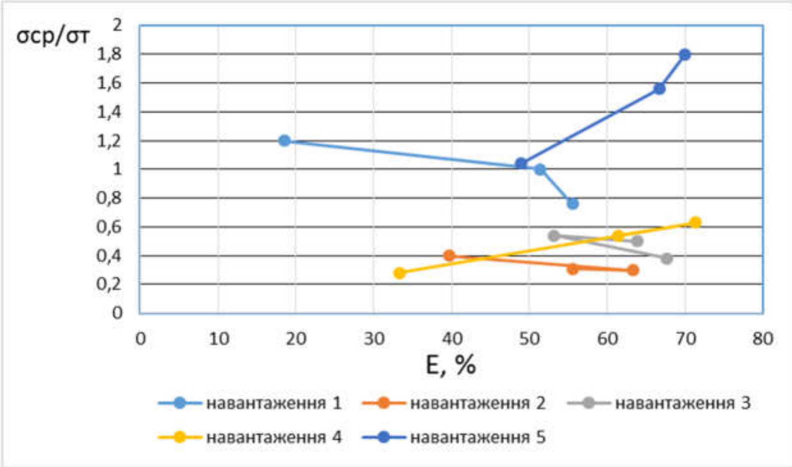

Рис. 4. Порівняльній аналіз розміра зерна при локальній деформації та співвідношення «середньої» напруги до межи плинності

Кожна вузька зона пластичної деформації протидіє пластичної деформації в суміжних зонах. При збільшенні зовнішнього навантаження значення залишкових напружень поступово зменшується, і при пластичній деформації розподіл напружень стає більш рівномірним. Таким чином, на початку пластичної деформації розподіл напружень стає більш рівномірним, проте розподіл деформації стає дуже нерівномірним.

Висновки. В роботі проведено фізичне моделювання процесу розповсюдження пластичної деформації в низьковуглецевих низьколегованих сталях. Показано, що деформації розподіляються в обсязі металу вельми нерівномірно. Це безпосередньо впливає на можливість об'єднання тріщин після досягнення певної їх щільності. . На цей процес впливає не тільки величина і напрямок напружень в області критичного перетину, але також і структура матеріалу, зв'язок і зчеплення структурних складових, їх міцність.

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THE MAIN STAGES OF BUILDING A PHYSICAL MODEL OF THE FRACTURE OF THE BAINITE COMPONENT OF THE STRUCTURE OF LOW-CARBON MICROALLOYED STEELS

Abstract. Construction of a physical model of the fracture of the bainite component of the structure of low-carbon low-alloy steels The results obtained in the work can be used in the development of technological schemes for the production of rolled metal from low-carbon microalloyed steels with an increased level of mechanical properties, namely resistance to fracture propagation.

Keywords: *bainitic structural component, low-carbon low-alloy steel, stages of fracture, physical models.*

Основний зміст роботи. Розвиток сучасного будівництва ставить все зростаючі вимоги до властивостей матеріалів для зварних будівельних конструкцій. При цьому, як свідчать дані літературних джерел (див. наприклад [1]), застосування технологічної схеми контрольована прокатка з наступним прискореним охолодженням володіє значними перевагами перед іншими способами збільшення міцності конструкційних листових сталей. Використання саме цієї технологічної схеми дозволяє досягти більш високого рівня експлуатаційних властивостей (порівняно з класичною контрольованою прокаткою) за рахунок заміни у структурі металопрокату перлітної фази на дисперсну бейнітну складову. Саме тому, вдосконалення властивостей високоміцного прокату з низьковуглецевих сталей для зварних будівельних металевих конструкцій шляхом з'ясування принципових залежностей між механізмами формування тонкої структури зазначених сталей та кінетикою розповсюдження руйнування є актуальною проблемою як з наукової так і з економічної точок зору.

Саме тому метою даної роботи є побудова фізичної моделі руйнування бейнітної складової структури низьковуглецевих низьколегованих сталей.

За класичними уявленнями [116] процес руйнування можливо в часі розглядати як три послідовні стадії:

- стадія зародження тріщини;
- стадія повільного зростання тріщини;

- стадія швидкого зростання тріщини.

Розглянемо зазначені три стадії руйнування стосовно бейнітної та/або мартенситної структурних складових.

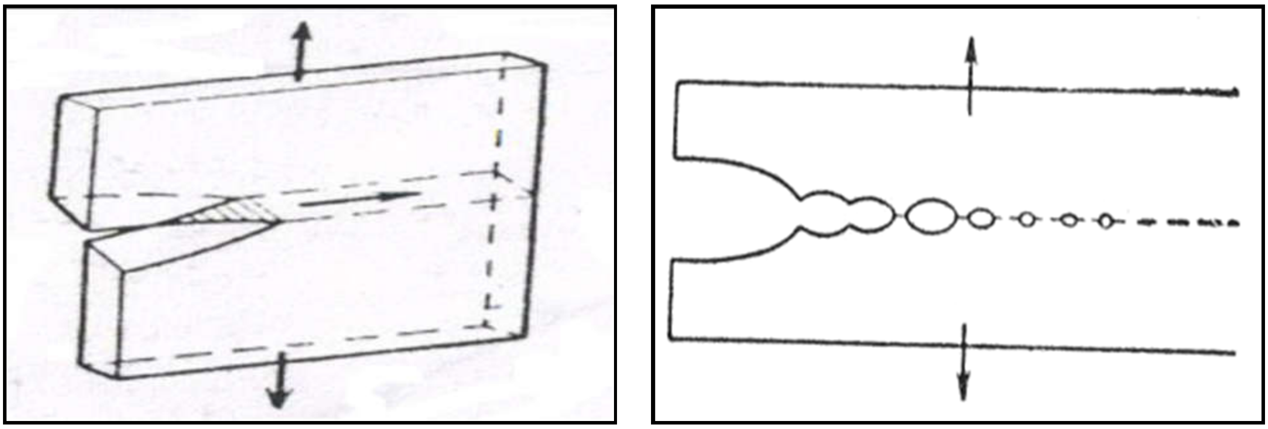
Стадія зародження тріщини.

Завдяки прискореному охолодженню, при формуванні структурних складових, частки другої фази будуть переважно виділятися на границях між пакетами бейніту, які характеризуються підвищеним рівнем вільної енергії. Частки другої фази незалежно від механізму та розвитку пластичної деформації сприяють її локалізації шляхом накопичення дислокацій на міжфазних границях. Відповідно до моделі зародження та розповсюдження в'язкої тріщини, запропонованої Броеком [2], у такому випадку навколо частки формуються дислокаційні петлі, які ініціюють появу пор. Таким чином, при зростанні пори навколо неї буде утворюватися зона локалізації пластичної деформації. В таких областях дислокації гальмуються та утворюють петлі на більшій відстані, в порівнянні з частками, які розташовані на внутрішньофазних границях з пониженими рівнем вільної енергії. Це явище небажане, тому що призводить до локалізації зони пластичної деформації між пакетами бейніту, зростанню пор та розповсюдженню в'язкої тріщини.

Стадія повільного зростання тріщини.

Для розробці моделі руйнування структурних складових, які формуються за проміжним та зсувним механізмами зробимо припущення про існування «структурної одиниці», яка буде визначати механізм зародження та розповсюдження руйнування (детально визначення поняття «структурна одиниця руйнування» наведено у роботі [3]). У випадку руйнування сталей зі структурами бейніту та/або мартенситу розповсюдження руйнування (протяжністю елементарного сколу) істотно більше ніж розмір кристалітів, які можливо спостерігати при мікроскопічних дослідженнях. Таким чином, у якості «структурної одиниці» руйнування, для нашого випадку, обираймо локальну область в структурі металопрокату, яка відділена ввід інших областей великокутовими границями – кожну окрему колонію бейніту або мартенситу. При цьому, потрібно враховувати наявність відповідних кристалографічних співвідношень як між рейками в окремій колонії так і між самими колоніями.

В межах кожної «структурної одиниці руйнування» повільний ріст тріщини відбувається за в'язким механізмом, тобто супроводжується значною пластичною деформацією. При цьому, рівень енергії, що поглинається під час цього процесу, вельми незначний і руйнування (за енергетичним критерієм) може бути віднесено до крихкого – має місце квазікрихкий злам. Специфічною характеристикою цього руйнування є концентрація пластичної деформації уздовж траєкторії руху тріщини – формування русла тріщини, яке відбувається як при плосконапруженому стані (рис. 1 *а*) так і при плоскодеформованному (рис. 1 *б*).



а б

Рис. 1. . Розповсюдження в'язкої тріщини с малою енергією:
а – плосконапружений стан; *б* – плоско деформований стан.

При цьому можливо припустити, що русло для руху тріщини формується шляхом пластичної деформації ковзанням. Як наслідок, швидке зростання тріщини (руйнування полікристалу) буде відбуватися за рахунок зсуву (зісковзування) кристалографічних площин одна відносно одної.

Ковзання в кристалі відбувається по найбільш розвиненим групам кристалографічних площин (площини ковзання), а в них – по певним кристалографічним напрямкам (напрямки ковзання). Наявність групи площин ковзання дозволяє тріщині, що рухається, при існуванні перешкод на одній площині ковзання переходити на іншу, яка відноситься до тієї ж групи площин (рис. 2). Така особливість руху тріщини спричиняє появу візерункової поверхні зламу бейнітної складової.

Таким чином, якщо в локальній області («структурній одиниці руйнування») деформації прийняти однорідною, то в межах цієї області деформація кристалографічного зсуву (див. рис. 3) буде визначатися рівнем дотичних напружень. Розповсюдження руйнування через границі цих областей, в свою чергу, буде визначатися сумісною дією нормальних та дотичних напружень, при чому за появу тріщин по границям колоній (так зване міжзерене руйнування) буде відповідати саме дотична складова напруги.

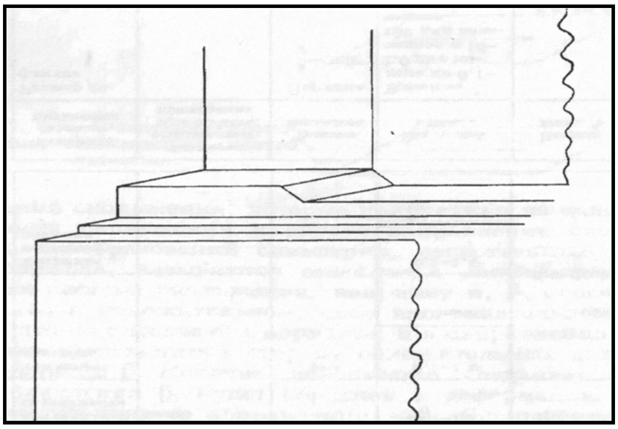


Рис. 2. Схема тонкої структури ліній ковзання.

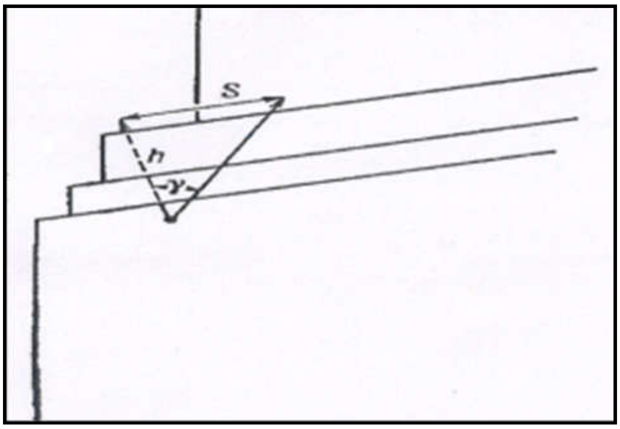


Рис. 3. К визначенню кристалографічного зсуву.

Висновки. Побудовано фізичну модель руйнування бейнітної складової структури низьковуглецевих низьколегованих сталей. Проаналізовано процес руйнування бейнітної та мартенситної складових низьковуглецевих мікролегованих сталей з точки зору проходження тріщеною трьох послідовних стадій: зарордження, повільного зростання та швидкого зростання.

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PROSPECTS FOR THE APPLICATION OF COMPOSITE REINFORCEMENT IN THE CONSTRUCTION INDUSTRY

Abstract: The ongoing conflict has highlighted the need for alternative materials in construction due to the demand for metals in military applications. This study evaluates the prospects of composite reinforcement, focusing on its mechanical properties, corrosion resistance, and efficiency compared to traditional metal reinforcement. Composite materials offer superior corrosion resistance, reduced weight, and enhanced construction efficiency. The research demonstrates their potential to improve infrastructure resilience while reducing reliance on metal resources. Practical guidelines are provided for integrating composite reinforcement into construction, promoting sustainable and resource-efficient practices, especially in resource-constrained environments.

Keywords: non-metallic composite fittings, metal fittings, building materials, innovative technologies, comparative analysis, corrosion resistance, lightweight structures, application prospects, building structures.

Modern requirements for the construction and operation of infrastructure necessitate the use of innovative materials, in particular composite reinforcement. A comparison of the properties of metal and composite reinforcement indicates significant advantages of the latter, in particular in corrosion resistance. This makes composite materials an ideal choice for use in conditions of high humidity and aggressive environments [1].

Corrosion, as is known, is one of the greatest enemies of traditional building materials. Analysis of the corrosion mechanisms of mineral building materials shows that their destruction can be significantly slowed down by effective protection methods. These methods can be used to extend the service life of reinforcement in concrete structures [2].

In view of the above, the introduction of composite reinforcement can significantly reduce the risks associated with corrosion and ensure the reliability of structures in various operating conditions. This highlights the relevance of further research in this area, as the combination of advanced materials and technologies opens up new horizons for maintaining the safety and durability of building structures [3]. Thus, composite reinforcement has significant potential for improving the quality of construction and infrastructure management.

Reinforced concrete is a cornerstone of modern construction due to its excellent compressive strength. However, traditional metal reinforcement, crucial for tensile strength, is highly susceptible to corrosion. This issue leads to reduced structural integrity, higher maintenance costs, and a shortened lifespan of buildings and infrastructure.

Figure 1. Composite reinforcement

Composite reinforcement is shown in fig 1, made from fibers such as glass, basalt, or carbon bonded with polymer matrices, offers a revolutionary alternative to metal reinforcement. Its key advantages include outstanding corrosion resistance, significantly lighter weight, and ease of handling and installation. In aggressive environments, where metal reinforcement may deteriorate rapidly, composites maintain their integrity, ensuring long-term structural performance.

The use of composite reinforcement significantly reduces the overall weight of structures, enabling more efficient construction processes. For example, in bridge construction or high-rise buildings, lighter materials decrease the load on foundations and reduce transportation costs. Moreover, the non-magnetic properties of composites make them suitable for facilities requiring electromagnetic neutrality, such as hospitals, military installations, and research laboratories.

Despite its benefits, composite reinforcement also presents certain challenges. Its lower modulus of elasticity compared to steel can result in increased deflection under load, necessitating careful design adjustments. Additionally, composites exhibit brittle failure, which occurs without warning deformation, unlike metal reinforcement. Addressing these limitations requires continued innovation and precise engineering to maximize their potential.

The relevance of composite materials is particularly significant in wartime conditions, where metals are in high demand for defense needs. Using composites in civil construction helps preserve metal resources for critical applications while ensuring the sustainability and resilience of infrastructure. Furthermore, composites open up opportunities for creating structures resistant to environmental stressors such as saltwater, industrial chemicals, and fluctuating temperatures.

Conclusions. In the conditions of war in the country, when iron is critically needed for the manufacture of weapons and strengthening fortifications, the use of composite reinforcement becomes especially relevant. This material not only demonstrates high corrosion resistance and lightness, but can also significantly reduce the dependence of the construction industry on traditional metal resources. The prospects for the use of composite reinforcement in construction are due to its strength, durability and ability to withstand aggressive operating conditions. This opens up new opportunities for improving infrastructure and reducing maintenance costs, making composite materials an element of production in modern construction.

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ANALYTICAL ESTIMATION OF ELASTIC MATERIAL STRESS STATE DURING TENSILE TESTING OF STANDARD SAMPLE

Abstract. Influence character of geometric parameters of a rubber-cable belt on tensile testing results of a standard belt sample is established and it allows considering parameters during determining maximum stresses in elastic shell of a belt butt-joint connections. Influence character of a stress-strain state of a standard sample on geometric parameters of a belt is established. The results make it possible to determine a distribution of shear stresses in elastic shell of a belt in butt-joint connections considering the structure of connections based on testing the standard samples. This increases the safety of usage of butt-joint connections of rubber-cable belts and increases their lifecycle.

Keywords: *composite tractive element, tensile testing, standard sample, elastomeric shell, stress state, analytical estimation, hoisting and transporting complex, cable-stayed structure*.

Main content of paper. Industrial usage of composite elastomer-cable tractive elements requires knowing and predicting the stress-strain state for variable modes of operation, justifying their design for safe and efficient operation in specific conditions, and considering structural defects like cable breakages or presence of butt-joint connections. Possible applications of such composite rubber-cable tractive elements are in hoisting complexes, conveyor transport and as stay ropes in cable-stayed structures.

Features of influence of rope design, mechanical properties of its components are taken into account on a basis of testing a standard sample made of a rubber-cable belt or rope. The results of these tests can be applied to butt joints only if the difference in cable placement in ropes and their joints is considered as well as mechanical properties of shell material. The tests assume pulling out a cable from a specially made sample, where d is cable diameter, b is belt sample thickness, l is sample length, t is cable placement spacing.

The solution of such a model can be obtained in the following form

$$u(y,z)=\sum_{m=1}^{M}\left(BS_m+DV_m\right)\frac{\cosh\left(q_m y\right)}{\cosh\left(q_m\dfrac{b}{2t}\right)}\sin\left(q_m z\right),\qquad(1)$$

where B, D are constant unknown coefficients; S_m, V_m are coefficients of expansion of functions $s(z), v(z)$ into Fourier series (see [1]); $q_m=\pi m$; M is the assumed (limited) amount of members in Fourier series.

It is assumed that a cable cross-section is not deformed. Respectively, the volumes of elastic shell material, that border with the cable, must belong to one plane. Displacements of these volumes of material are defined by the function $v(z)$. This plane must coincide with the plane formed by the displacement of an elastic shell by given dependency in (1).

Define displacements of volumes of material along the contact line with a cable as the average value of displacement. Error of approximation is estimated by the dispersion of deviations from the average value. Find the values of unknown coefficients by solving the algebraic system of the second order. As a result, there is

$$B=-\frac{\alpha_{1,1}}{\alpha_{0,1}\alpha_{1,0}-\alpha_{1,1}\alpha_{0,0}},\quad D=\left(\alpha_{0,1}-\frac{\alpha_{1,1}\alpha_{0,0}}{\alpha_{1,0}}\right)^{-1},$$

where

$$\alpha_{0,0}=\left(\sum_{\alpha=0}^{N}\sum_{m=1}^{M}\left[\frac{S_m}{N+1}\frac{\cosh\left(\dfrac{q_m}{2t}\left(b-\sin\left(\dfrac{\alpha}{N}\pi\right)d\right)\right)}{\cosh\left(\dfrac{q_m b}{2t}\right)}\times\sin\left(\frac{q_m\left(t-\cos\left(\dfrac{\alpha}{N}\pi\right)d\right)}{2t}\right)\right]\right);\ \alpha_{0,1}=\left(\sum_{\alpha=0}^{N}\sum_{m=1}^{M}\left[\frac{V_m}{N+1}\frac{\cosh\left(\dfrac{q_m}{2t}\left(b-\sin\left(\dfrac{\alpha}{N}\pi\right)d\right)\right)}{\cosh\left(\dfrac{q_m b}{2t}\right)}\times\sin\left(\frac{q_m\left(t-\cos\left(\dfrac{\alpha}{N}\pi\right)d\right)}{2t}\right)\right]\right);$$

$$\alpha_{1,0}=\left(\sum_{\alpha=0}^{N}\sum_{m=1}^{M}\frac{S_m}{N+1}\frac{\sinh\left(\dfrac{q_m b}{2t}\right)}{\cosh\left(\dfrac{q_m b}{2t}\right)}\left(\cos\left(q_m\frac{t-d}{2t}\right)-1\right)\right);\ \alpha_{1,1}=\left(\sum_{\alpha=0}^{N}\sum_{m=1}^{M}\frac{V_m}{N+1}\frac{\sinh\left(\dfrac{q_m b}{2t}\right)}{\cosh\left(\dfrac{q_m b}{2t}\right)}\left(\cos\left(q_m\frac{t-d}{2t}\right)-1\right)\right).$$

Deformation distributions, tangential stresses for different values of relative parameters are determined with the use of defined unknown constants.

Tangential stresses of interaction of cables during testing are transmitted along the boundary $z = 0$. The considered force is applied from the side of one cable. The force of pulling out the cable is

$$T = 4G\Delta l\sum_{m=1}^{M}\left(BS_m + DV_m\right)\frac{\sinh\left(q_m\dfrac{b}{2t}\right)}{\cosh\left(q_m\dfrac{b}{2t}\right)}. \quad (2)$$

The distribution of stresses is characterized by a coefficient of their concentration. Extreme values of shear stresses occur along the boundaries of a sample $z = 0$ and $z = b$ and on a surface of attachment of an elastic shell material to the cable at coordinate points $y = t/2$. For various values of relative thickness of a belt and cable placement spacings in it, coefficients of shear stress concentration (K) are determined. Concentration coefficients are determined as a relation of extreme stress to average stress along the surface $z = 0$.

Belt test results can also be used to determine the maximum stresses in butt-joints of belts and belts of other constructions. This can be performed by determining the difference of influence of changing the geometric parameters of a belt by the ratio of maximum stresses.

The proportionality index for coefficients of stress concentration in a cross-section of a sample as a consequence of change in rigidity of an elastic shell is determined as a relation

$$k_1 = \frac{\sum_{m=1}^{M}\left(B_2S_{2,m} + D_2V_{2,m}\right)\cos\left(q_m\dfrac{t_2 - d}{2}\right)q_m}{\sum_{m=1}^{M}\left(B_1S_{1,m} + D_1V_{1,m}\right)\cos\left(q_m\dfrac{t_1 - d}{2}\right)q_m}, \quad (3)$$

where indexes 1 and 2 indicate the values relating to an experimental sample and a sample in which geometric parameters are changed.

Displacements of cables and internal forces that occur in them as a result of loading the standard belt sample by a force equal to one unit can be determined by expressions obtained from a condition of equilibrium of cables in a belt

$$u(i,x) = \sum_{n=1}^{N-1}\left[\left(A_n e^{\beta_n x} - C_n e^{-\beta_n x}\right)\left(\beta_n EF\right)^{-1}\cos\left(\mu_n(i-0.5)\right)\right] + \frac{1}{3EF}, \quad (4)$$

$$p(i,x) = \sum_{n=1}^{N-1}\left(A_n e^{\beta_n x} + C_n e^{-\beta_n x}\right)\cos\left(\mu_n(i-0.5)\right) + \frac{1}{3}, \quad (5)$$

where $u\left(i,x\right)$ is displacements of a cable i $\left(1\le i\le 3\right)$ in a cross-section x; N is amount of cables in a sample; A_n, B_n are unknown constants; $\mu_n=\frac{\pi n}{3}$; $\beta_n=\sqrt{\frac{2Gk_Gb}{(t-d)EF}\left(1-\cos\left(\mu_n\left(i-0.5\right)\right)\right)}$; d, t are diameter and cable placement spacing in a belt, respectively, G is reduced shear modulus of an elastic shell of a belt; EF is reduced tensile rigidity of a cable; k_G is coefficient that considers the influence of a shape of an elastic shell material located between the cables.

There are three cables in a sample (N = 3), then dependencies in (4, 5) consist of four unknown constants. Values of unknown constants can be determined from boundary conditions. In a cross-section x = 0 assume that the middle (second) cable is loaded with a unit force. Equate the distribution of forces to distribution of forces in a cross-section x = l. Get three more equations

$$A_n e^{\beta_n l}+C_n e^{-\beta_n l}=\frac{1}{3}\left(\cos\left(0.5\mu_n\right)+\cos\left(2.5\mu_n\right)\right).$$

Solutions of systems of equations

$$C_n=\frac{1}{3\left(e^{-2\beta_n l}-1\right)}\left(\frac{\cos\left(\mu_n(1-0.5)\right)+\cos\left(\mu_n(3-0.5)\right)}{e^{\beta_n l}}-2\cos\left(\mu_n(2-0.5)\right)\right);A_n=\frac{2}{3}\cos\left(\mu_n(2-0.5)\right)-C_n.$$

Characteristic index is $\beta_n=\sqrt{\frac{4G}{EF}\sum_{m=1}^{M}\left[\left(BS_m+DV_m\right)\tanh\left(q_m\frac{b}{2t}\right)\left(1-\cos\left(\mu_n(i-0.5)\right)\right)\right]}$.

Tensile force acting in the elastic shell between the first and second cable is

$$T=\sum_{n=1}^{2}\left[A_n e^{\beta_n x}+B_n e^{-\beta_n x}\right]\left[\cos\left(1.5\mu_n\right)-\cos\left(0.5\mu_n\right)\right]\frac{2G}{EF}\sum_{m=1}^{M}\left(BS_m+DV_m\right)\tanh\left(q_m\frac{b}{2t}\right).$$

Tangential forces are distributed unevenly. They reach maximum values when x = 0 and x = l. The relation of maximum stresses in the cross-section x = 0 is an indicator of influence of rigidity on redistribution of forces along the belt. It has a form

$$k_2=\frac{\sum_{n=1}^{2}\left[A_{1,n}+C_{1,n}\right]\left[\cos\left(1.5\mu_n\right)-\cos\left(0.5\mu_n\right)\right]\frac{2G}{EF}\sum_{m=1}^{M}\left(B_1S_{1,m}+D_1V_{1,m}\right)\tanh\left(q_m\frac{b_1}{2t_1}\right)}{\sum_{n=1}^{2}\left[A_{2,n}+C_{2,n}\right]\left[\cos\left(1.5\mu_n\right)-\cos\left(0.5\mu_n\right)\right]\frac{2G}{EF}\sum_{m=1}^{M}\left(B_2S_{1,m}+D_2V_{1,m}\right)\tanh\left(q_m\frac{b_2}{2t_2}\right)}.$$

Product of influence indicators $k = k_1 k_2$ allows considering the influence of distribution of tangential stresses in butt-joint connections with a cable placement spacing that is different from the spacing of cables in a belt.

Conclusion. Analytical dependencies of rigidity, parameters of a stress-strain state of elastic shell material are obtained in a closed form, in particular the values of characteristic indicators, which can be used in mathematical models of rubber-cable conveyor belts, their butt joints and flat ropes. The obtained models can be used to determine the condition of strength of elastic shell in a butt joint connection based on results of cable tear out testing in belt samples.

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IMPACT ASSESSMENT OF COMPOSITE STAY ROPE DESIGN WITH POSSIBLE BREAKAGES AND NON-LINEAR REINFORCEMENT DEFORMATION ON ITS STRESS STATE

Abstract. A model and algorithm for calculating the stress-strain state of a rubber-cable rope of arbitrary design, considering the nonlinear deformation of the ropes and the presence of a discontinuity of an arbitrarily located cable, has been developed. The model was built using the methods of the mechanics of composite materials. It is solved analytically in a closed form. The resulting algorithm can be considered sufficiently reliable and such that it allows you to reasonably determine the conditions for the safe use of rubber-cable ropes in case of damage to an arbitrary rope.

Keywords: *cable-stayed bridge, hoisting machine, composite tractive element, damaged structure, elastomeric shell, stress state, analytical solution.*

Main content of paper. Application of composite materials in the industry assume studying the stress-strain state occurring in the structure of created elements and parts and justifying their parameters depending on the machine it is used in and operational features.

We accept the following calculation scheme. a system of M parallel, flexurally rigid elastic rods of length L interacts through an elastic continuous medium in which tangential stresses arise. Deformation occurs within the linear law. One cable (j^{th}) has a distance discontinuity l $(0 < l < L)$ from the section of fixing the cables. The force P acts on the rope.

The solution to the problem looks like this [1, 2]

$$u_i = \sum_{m-1}^{M-1} \left(A_m e^{\beta_m x} + B_m e^{-\beta_m x} \right) \cos\left(\mu_m \left(i - 0.5 \right) \right) + \frac{Px}{EF} + \varepsilon, \tag{1}$$

where A_m, B_m, ε – unknown constants; M – number of cables in the rope; P – tensile strength of the cable; $\mu_m = \pi m/M$; $\beta_m = \pm\sqrt{2\frac{G b k_G}{h E F}\left(1-\cos\left(\mu_m\right)\right)}$; b – rope thickness; c – the step of the arrangement of the cables in the rope; d – cable diameter; G – shear modulus of the rope rubber shell material; k_G – coefficient that takes into account the cross-sectional shape of the rubber shell; h – the minimum distance between adjacent cables of the rope; E, F – composite modulus of elasticity for tension of the cable material and their cross-sectional area.

Rope loading

$$p_i = EF\sum_{m=1}^{M-1}\left(A_m e^{\beta_m x} - B_m e^{-\beta_m x}\right)\beta_{m,k}\cos\left(\mu_m\left(i-0.5\right)\right)+P. \quad (2)$$

Ropes are attached to structural elements of lifting complexes, capital structures. The connection conditions depend on the design of the connection nodes. We will solve the problem of determining the stress-strain state in a general way – without specifying the conditions for connecting the ends of the rope. According to the task, the rope has a break in the continuity of the rope. This makes it impossible to make decisions (1) and (2) for the rope as a whole. We will apply separate solutions for two parts of the rope. For the first $0 \le x \le l$ and the second $l \le x \le L$ parts of the rope. We will give them the numbers 1 and 2. We will indicate the numbers in the lower index of the value that applies only to the specified part. We will formulate the displacement and load of the cables of the second part in the following forms

$$u_{i,2} = \sum_{m-1}^{M-1}\left(A_{m,2}e^{\beta_m x} + B_{m,2}e^{-\beta_m x}\right)\cos\left(\mu_m\left(i-0.5\right)\right)+\frac{P x}{E F}+\varepsilon_2, \quad (3)$$

$$p_{i,2} = EF\sum_{m=1}^{M-1}\left(A_{m,2}e^{\beta_m x} - B_{m,2}e^{-\beta_m x}\right)\beta_{m,k}\cos\left(\mu_m\left(i-0.5\right)\right)+P. \quad (4)$$

The parts of the rope form a single rope of length L. In the section $x = l$, the conditions must be fulfilled

$$p_{i,1} = p_{i,2} \qquad \left(1 \le i \le M\right), \quad (5)$$

$$p_{j,1} = p_{j,2} = 0. \quad (6)$$

The size of the gap between the cables in the section of the break depends on the load on the rope. Let's conditionally accept it equal to one. The condition for the occurrence of a single gap between the ends of the damaged cable

$$u_{i,1} - u_{i,2} = \begin{cases} 0 & (i \neq j), \\ 1 & (i = j), \end{cases} \tag{7}$$

where j – cable number with a break in continuity in the section $x = l$.

We equate the last condition with the δ-function. It is given by the Fourier series on the discrete axis of the numbers of cables of limited length

$$u_{i,1} - u_{i,2} = \frac{2}{M}\cos\left(\mu_m\left(i - 0.5\right)\right) + \frac{1}{M}. \tag{8}$$

From conditions (5) and (7), we have the following relations

$$A_{m,1} - B_{m,1}e^{-2\beta_m l} - A_{m,2} + B_{m,2}e^{-2\beta_m l} = 0, \tag{9}$$

$$A_{m,1} + B_{m,1}e^{-2\beta_m l} - A_{m,2} - B_{m,2}e^{-2\beta_m l} = \frac{2}{Me^{\beta_m l}}\cos\left(\mu_m\left(j - 0.5\right)\right), \tag{10}$$

$$\varepsilon_1 - \varepsilon_2 = \frac{1}{M}. \tag{11}$$

After simplifying the expressions (9), (10), we obtain

$$A_{m,1} = A_{m,2} + \frac{\cos\left(\mu_m\left(j - 0.5\right)\right)}{M\,e^{\beta_m l}}, \tag{12}$$

$$B_{m,1} = B_{m,2} + \frac{\cos\left(\mu_m\left(j - 0.5\right)\right)}{M}e^{\beta_m l}. \tag{13}$$

Let's assume that there are no displacements of the first part $\varepsilon_1 = 0$. Then

$$\varepsilon_2 = -\frac{1}{M}. \tag{14}$$

We consider expressions (9) and (10). Let's write down the value of the loading force of the j^{th} cable in the section $x = l$. According to (6), the internal load force of the cable should be zero. To do this, multiply the first component of expression (2) by the ratio of the real value of the gap between the ropes and the one taken in condition (7). Consider expressions (12), (13)

$$p_{i,1} = EF\sum_{m=1}^{M-1}\begin{pmatrix} A_{m,2}e^{\beta_m x} + \dfrac{\cos(\mu_m(j-0.5))}{M} - \\ -B_{m,2}e^{-\beta_m x} - \dfrac{\cos(\mu_m(j-0.5))}{M}\end{pmatrix}\beta_{m,k}\cos(\mu_m(i-0.5))Q + P, \quad (15)$$

where

$$Q = -P\left[\frac{EF}{M}\sum_{m=1}^{M-1}\begin{pmatrix} A_{m,2}e^{\beta_m l} + \cos(\mu_m(j-0.5)) - \\ -B_{m,2}e^{-\beta_m l} - \cos(\mu_m(j-0.5))\end{pmatrix}\beta_{m,k}\cos(\mu_m(j-0.5))\right]^{-1}. \quad (16)$$

The law of decreasing internal load forces of maximally loaded ropes is given by the product of Fourier series in continuous coordinates on the first and second parts in the intervals $0 \le x \le l$ and $l \le x \le L$ and in discrete coordinates of cable numbers, limited by their number. Thus, the model of the deformed state and the obtained dependencies for the case of linear deformation of the rope (1), (3) remain unchanged. Ratios (12), (13) obtained from the conditions of simultaneous deformation remain unchanged. Expression (14) will depend on the quantity ψ of cables adjacent to the damaged one

$$\varepsilon_2 = -\frac{\psi}{M}. \quad (17)$$

Expressions of internal load forces of cables (2), (4) are written in the following forms

$$p_{i,1} = EF\sum_{m=1}^{M-1}\left[\begin{pmatrix} \left(A_{m,2} + \dfrac{\cos(\mu_m(j-0.5))}{Me^{\beta_m l}}\right)e^{\beta_m x} - \\ -\left(B_{m,2} + \dfrac{\cos(\mu_m(j-0.5))}{M}e^{\beta_m l}\right)e^{-\beta_m x}\end{pmatrix}\beta_{m,k} - \\ -\sum_{k=0}^{K}C_{k,1}\cos\left(\frac{\pi k x}{l}\right)\begin{pmatrix}\cos(\mu_m(j-1.5)) + \\ +\phi\cos(\mu_m(j+0.5))\end{pmatrix}\right]\cos(\mu_m(i-0.5)) + P, \quad (18)$$

$$p_{i,2} = EF\sum_{m=1}^{M-1}\left[\begin{matrix}\left(A_{m,2}e^{\beta_m x} - B_{m,2}e^{-\beta_m x}\right)\beta_{m,k} - \\ -\displaystyle\sum_{k=0}^{K}C_{k,2}\cos\left(\frac{\pi k x}{L-l}\right)\begin{pmatrix}\cos(\mu_m(j-1.5)) + \\ +\phi\cos(\mu_m(j+0.5))\end{pmatrix}\end{matrix}\right]\cos(\mu_m(i-0.5)) + P, \quad (19)$$

where $C_{k,1}$, $C_{k,2}$ – coefficients of the Fourier series, which take into account the difference between the linear modulus of elasticity of the cable and the real one, depending on the load; ϕ – the coefficient of proportionality of the load forces of the $(j + 1)^{\text{th}}$ cable relative to the $(j – 1)^{\text{th}}$.

From the condition of equality of forces (5), the condition of equality between the coefficients must be ensured

$$\sum_{k=0}^{K} C_{k,1}\cos(\pi k) = \sum_{k=0}^{K} C_{k,2}\cos\left(\frac{\pi k l}{L-l}\right). \quad (20)$$

The value of the Q coefficient will change. It will be determined by the following dependence

$$Q = -P\left[\sum_{m=1}^{M-1} EF\left(\begin{pmatrix} M A_{m,2}e^{\beta_m l} + \cos\left(\mu_m(j-0.5)\right) - \\ -M B_{m,2}e^{-\beta_m l} - \cos\left(\mu_m(j-0.5)\right)\end{pmatrix}\frac{\beta_{m,k}}{M} - \atop -\sum_{k=0}^{K} C_{k,1}\cos(\pi k)\begin{pmatrix}\cos\left(\mu_m(j-1.5)\right) + \\ +\phi\cos\left(\mu_m(j+0.5)\right)\end{pmatrix}\right)\cos\left(\mu_m(j-0.5)\right)\right]^{-1}. \quad (21)$$

Note that expression (20) is obtained for the general case when not the outermost cable is damaged. For the damaged extreme (first) cable, expression (20) lacks an element $\cos\left(\mu_m(j-1.5)\right)$. In case of damage to the cable number M, the element is missing $\phi\cos\left(\mu_m(j+0.5)\right)$.

The coefficient Q is determined considering the difference in force distributions determined for the conditions of linear deformation and taking into account nonlinear deformation. The first components of the distribution of deformations and forces must be multiplied by it.

Finally, the calculation algorithm consists in determining the tension-deformed state of the rope under the conditions of linear deformation of the ropes using expressions (1) – (4), (9), 10, (12) – (14), (16). Determine two unknown constant vectors from the conditions of connecting the ends of the rope to the structure or elements of the lifting machine. According to the determined distributions of forces in the ropes adjacent to the damaged one, choose the laws of force change. It should compensate for the excess of the calculated (linearly dependent) efforts over the actual ones, determined taking into account the differences in the values of the linear and non-linear modulus of elasticity. According to the defined laws, determine the coefficients of the Fourier series $C_{k,1}$, $C_{k,2}$. Substitute the values of the coefficients into expression (21). Find the value of the coefficient Q. Multiply by it the first components of the values of the internal load forces of the cables in expressions (19), (20) and displacements in expressions (1), (3). To obtain the desired displacements of the cables and the distribution of forces between them in a rope of a given design with a damaged arbitrary cable under the given conditions of connecting the ends of the rope.

Conclusions. Analytical expressions are constructed in the paper, which allow determining the quantitative indicators of influence of the turns of the cross-sections of rope connection to the elements of the cable-stayed bridge or hoisting machine and the vessel rotation around its longitudinal axis on a stress-strain state of the rubber-cable rope.

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Modern Methods for Designing Materials Based on Cermet Powders

Annotation: The design and development of materials based on cermet powders have revolutionized industries requiring high-performance composites with superior mechanical and thermal properties. This paper explores advanced methodologies in cermet material engineering, focusing on computational modeling, powder metallurgy innovations, and applications in various industrial domains.

Keywords: cermet powders, computational modeling, powder metallurgy, additive manufacturing, sintering techniques, surface engineering, and high-performance composites.

Cermet materials, which combine ceramic and metallic phases, play an essential role in various industrial applications requiring materials with excellent mechanical strength, wear resistance, and thermal stability. These composite materials are particularly useful in sectors such as aerospace, automotive, and tooling industries, where high-performance materials are vital. Recent advancements in the design of cermet materials, particularly those based on cermet powders, have focused on enhancing the properties and performance of these materials through computational methods, innovative manufacturing techniques, and precise material processing strategies [1].

One of the most significant advancements in cermet material design is the integration of computational modeling and simulation techniques. Computational tools such as finite element analysis (FEA) and molecular dynamics (MD) simulations have become crucial in predicting how cermets will behave under stress, temperature changes, and other operational conditions. These methods allow researchers to study stress distributions, phase formation, and material interactions, offering deeper insights into how to optimize the material's microstructure and performance. For example, simulations can help predict the effects of varying particle sizes and distributions of ceramic and metal phases on the final properties of the cermet [2].

Machine learning (ML) and artificial intelligence (AI) are increasingly used to process large datasets from these simulations, enabling faster optimization of material compositions. This data-driven approach can identify previously unknown correlations between material properties and microstructural features, significantly reducing the trial-and-error methods that were historically used in material design.

In addition to computational approaches, innovations in powder metallurgy techniques have significantly enhanced the production and design of cermet materials. Traditional powder metallurgy processes, such as conventional sintering, are being supplemented with more advanced techniques like spark plasma sintering (SPS) and hot isostatic pressing (HIP). SPS, in particular, allows for finer control over the densification and phase distribution of the cermet, achieving more uniform and reliable material properties [3].

Additive manufacturing (AM) technologies such as selective laser sintering (SLS) and binder jetting are also being integrated into cermet production. These methods provide the ability to fabricate cermet components with complex geometries and tailored properties. Through AM, it is possible to print cermet parts layer by layer, ensuring that the material composition and microstructure are optimized for specific applications. This not only improves the performance of the final product but also allows for quicker prototyping and reduced manufacturing costs [4].

Surface engineering techniques are another area of significant development for cermet materials. Cermet components, especially those used in harsh environments such as turbine blades or cutting tools, often require enhanced surface properties to improve wear resistance and extend service life. Physical vapor deposition (PVD) and chemical vapor deposition (CVD) are widely used to apply thin, durable coatings to cermet surfaces, enhancing their corrosion resistance, hardness, and thermal stability [5].

These coatings can be tailored to match the specific operating conditions of the component, offering precise control over the material's properties and significantly improving its performance. Additionally, recent advances in nanotechnology have enabled the development of nanostructured coatings that offer superior mechanical and thermal properties compared to conventional coatings.

Cermet materials are integral to several industries that demand high-performance materials capable of withstanding extreme conditions. In the aerospace sector, for instance, cermets are used in turbine engines and heat shields, where their resistance to high temperatures and thermal cycling is critical. Cermets are also widely employed in tooling applications, where their hardness and wear resistance make them ideal for cutting, drilling, and machining hard materials [6].

In the automotive industry, cermets are used in engine components and brake systems, where high wear resistance and durability are essential. Biomedical applications, including dental and orthopedic implants, have also benefited from the biocompatibility and mechanical properties of cermet materials.

By tailoring the material properties, researchers can develop cermet-based solutions that meet the specific demands of each application.

Conclusion. The design and development of materials based on cermet powders are at the forefront of materials science and engineering. The combination of advanced computational methods, innovative powder metallurgy techniques, and cutting-edge surface engineering approaches has transformed the way cermets are designed and produced. These advances enable the creation of materials with superior properties that are optimized for specific industrial applications. As research continues to evolve, the potential for cermet materials to meet the growing demands of industries requiring high-performance materials will only increase, offering new possibilities for improving efficiency, reducing energy consumption, and extending the service life of critical components.

In the future, the integration of eco-friendly production methods and the development of more sustainable cermet materials will play a key role in reducing environmental impacts, further enhancing the material's importance across a wide range of industries.

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