Edited by
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The monograph is devoted to the actual scientific and practical problems of materials science, foundry production and engineering and architectural solutions, which are of great importance for the industrial development and post-war reconstruction of Ukraine. The book comprehensively combines research in the field of creation of new metal materials with increased operational properties and development of inclusive and sustainable engineering approaches in construction and environmental design.
The book is addressed to scientists, practicing engineers, foundry specialists, architects and designers, as well as scientific and pedagogical workers and higher education students in the specialties of materials science, metallurgy and civil engineering.
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ABSTRACT

The monograph is devoted to the actual scientific and practical problems of materials science, foundry production and engineering and architectural solutions, which are of great importance for the industrial development and post-war reconstruction of Ukraine. The book comprehensively combines research in the field of creation of new metal materials with increased operational properties and development of inclusive and sustainable engineering approaches in construction and environmental design.

The first chapter substantiates the rational compositions of chromium-manganese alloys and investigates the regularities of formation of their structure, phase composition and properties in the cast state. The possibilities of reducing the energy intensity of casting processes and increasing the wear resistance of products compared to traditional alloys-analogues are shown. The prospects of using the developed materials to increase the operational stability of piercing mandrels of pipe rolling mills are determined, provided that the heat treatment regimens are optimized and metastable self-strengthening structures are formed.

The second chapter is devoted to the integration of the principles of inclusive engineering and artisanal technologies in the design of public catering establishments in the conditions of post-war reconstruction of Ukraine. The choice of environmentally friendly building materials and architectural solutions that ensure accessibility, safety, energy efficiency and compliance with sanitary and hygienic requirements (HACCP) is justified. The proposed approach contributes to the sustainable development of communities, reducing the environmental load and preserving local cultural identity.

The third chapter considers promising high-entropy alloys based on the FeNiCrCuAl and FeNiCrCuMn systems as heat-resistant casting materials of a new generation. Based on thermodynamic calculations, structural-phase analysis and research of thermophysical, mechanical and casting properties, their high structural stability and feasibility of use in conditions of elevated temperatures are confirmed.

The fourth chapter highlights the scientific and technological prerequisites for obtaining steel hollow castings with composite and reinforced non-metallic fillers by the casting method using gasified models. A mathematical description of gas-hydrodynamic processes has been developed, computer modeling and experimental verification of technological solutions that are important for the manufacture of special and protective casting products have been carried out.

The book is addressed to scientists, practicing engineers, foundry specialists, architects and designers, as well as scientific and pedagogical workers and higher education students in the specialties of materials science, metallurgy and civil engineering.

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CIRCLE OF READERS AND SCOPE OF APPLICATION

The materials of the monograph will be useful for a wide range of specialists and organizations. The results of research in the field of chromium-manganese and high-entropy alloys are focused on enterprises of the metallurgical and foundry industries, in particular, manufacturers of heat- and wear-resistant parts for pipe rolling mills, energy equipment, mechanical engineering, defense and special equipment. The proposed materials and technological solutions can be used when designing new products, modernizing casting processes and reducing material and energy consumption in industrial production.

The chapters devoted to steel hollow castings with composite and reinforced non-metallic fillers are of practical interest to developers and manufacturers of foundry products for special and protective purposes, as well as for enterprises of the defense-industrial complex, where a combination of high strength, reliability and reduced mass of structures is important.

Engineering and architectural research aimed at integrating the principles of inclusive design and artisanal technologies will be relevant for architects, civil engineers, design organizations, local governments and public initiatives involved in the post-war reconstruction processes of Ukraine. The proposed approaches can be used in the creation of public catering establishments, social infrastructure and public spaces focused on the needs of veterans, people with disabilities and internally displaced persons.

The publication is of particular value for scientists and scientific and pedagogical workers, postgraduates and students of higher education institutions in the specialties "Metallurgy", "Materials Science", "Foundry", "Mechanical Engineering", "Construction and Architecture", since the results presented can be used in the educational process, during the performance of qualification work and further scientific research.

INTRODUCTION

The current stage of development of science and technology is characterized by increasing requirements for materials, their manufacturing technologies and engineering solutions used in industry, construction and social infrastructure. In the context of global challenges caused by resource depletion, increased energy intensity of production, environmental restrictions and the consequences of the full-scale war in Ukraine, the development of innovative materials and technologies that can combine high performance characteristics, economic feasibility and social orientation is of particular relevance.

Metallurgy and foundry production remain basic industries that ensure the functioning of mechanical engineering, energy, transport and defense sectors. In this context, an important scientific task is the creation of new alloys with increased wear and heat resistance, improvement of their chemical composition, structure and phase state, as well as optimization of technological processes of casting and heat treatment in order to reduce energy consumption and increase the reliability of finished products. Along with this, the development of engineering approaches to the formation of a safe, accessible and environmentally responsible environment that meets modern social challenges is relevant.

The first chapter of the monograph examines the scientific foundations of the creation of chromium-manganese alloys with rational alloying. The optimal ranges of chemical composition are substantiated, the features of the formation of the structure and phase composition in the cast state are investigated, and the thermodynamic and technological characteristics of the melting and crystallization processes are analyzed. The results of comparative tests for friction and abrasive wear are presented, which confirm the increased wear resistance of the developed alloys compared to traditional analogue materials. The directions for further increasing the operational stability of products by optimizing heat treatment modes and forming metastable structures are outlined.

The second chapter is devoted to the issues of integrating the principles of inclusive engineering and craft technologies into the design of public catering establishments in the conditions of post-war reconstruction of Ukraine. The chapter analyzes the environmental, thermophysical and operational characteristics of natural and low-carbon building materials, as well as architectural and planning solutions aimed at ensuring accessibility, safety, hygiene and energy efficiency. A methodological approach to the creation of socially oriented, culturally authentic and sustainable public infrastructure facilities is proposed.

The third chapter presents the results of research into promising high-entropy alloys based on the FeNiCrCuAl and FeNiCrCuMn systems, designed for operation at elevated temperatures. The features of their production in vacuum induction furnaces are considered, thermodynamic prediction of the phase composition and experimental confirmation of the structural state are carried out. The thermophysical, mechanical and casting properties of the alloys are studied, and their heat resistance is also assessed, which allows us to consider these materials as a promising alternative to traditional steels and cast irons.

The fourth chapter presents the scientific and technological principles of obtaining hollow steel castings with composite and reinforced non-metallic fillers by the method of casting according to

gasified models. A mathematical description of gas-hydrodynamic and thermal processes is proposed, computer modeling and experimental verification of the influence of fillers on the quality of castings are carried out. The prospects of using the developed technological solutions for the manufacture of special and protective casting products, in particular for the needs of the defense sector, are shown. Thus, the monograph comprehensively covers modern approaches to the creation of new materials, the improvement of casting technologies and the implementation of inclusive engineering solutions. The results obtained have both scientific novelty and practical value and can be used in industry, design activities, scientific research and the educational process.

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1 CHROMIUM-MANGANESE ALLOYS ON OCHOBI IRON WITH INCREASED TRIBOLOGICAL PROPERTIES

ABSTRACT

In this work, the rational compositions of the chemical composition of established and substantiated chromium-manganese alloys in the following ranges were: C = 2.6-3.0%; Cr= 10.0-20.0%; Mn = 10.0-15.0%; Ni = 0.5-1.7%; Si≤ 1.3%; V≤ 0.3%; Cu≤ 0.3%. It has been determined that an additional increase in the complex of properties of chromium-manganese alloys can be achieved by the additional introduction of molybdenum, titanium, barium and calcium in small amounts.

The peculiarities of the formation of the structure, phase composition and properties of the investigated chromium-manganese alloys in the cast state were. The change in the temperature intervals of the beginning and end of melting/crystallisation of alloys with different alloying systems was determined by thermal analysis. A comparative analysis of the melting/crystallisation temperature intervals revealed that the developed chromium-manganese alloys are characterised by lower energy consumption of the production process, and, therefore, are more technologically advanced in terms of achieving the required superheat temperature, subsequent casting into moulds and crystallisation.

According to the results of comparative tests for friction wear (temperature up to 950°C, load 500 N) and abrasive wear of chromium-manganese alloys with traditional analogue alloys in the cast state, it was found that the experimental material containing 3.10% C 13.10% Cr; 15.75% Mn; 1.15% Ni; 0.90% Si; 0.25% V and 0.15% Cu, has higher wear resistance in contrast to high-chromium cast iron 300Cr32Ni3V and alloy chromium-nickel "nikorin" (36.0 – 38.0% Cr; 57.0 – 59.0% Ni). The results of the study indicate that further development of effective heat treatment regimes for the proposed chromium-manganese alloys will increase the operational stability of the piercing mandrels of pipe rolling mills while reducing the material costs of their manufacture.

KEYWORDS

Chromium-manganese alloys, chemical composition, phase composition, thermal analysis, crystallization, wear resistance, heat treatment, structure, alloying, operational durability.

1.1 THEORETICAL PRINCIPLES OF UNDERSTANDING AND PRACTICE OF APPLYING RISK MANAGEMENT

It is known that the activity of mankind in the conditions of risks has always been in the past, is now, and in the future, post-industrial, entrepreneurial era will only grow. It is necessary to state with pleasure that to date, knowledge about risks and management in their conditions have achieved significant success, including with the participation of the authors of this article. Thus, the following have been newly defined: the stages of their development, methods of management in the conditions of risks, the essence, the content of risk — as the unity of two basic elements (uncertainty and certainty); the concept of "risk management" has been clarified — as a composition of new concepts "risk economics", "risk engineering", "risk administration"; a new concept of "risk management" was introduced — as a composition of risk management and risk production and as "management under risk conditions" instead of the erroneous one — "risk management" [1, 2]. The need to increase the effectiveness of risk management was also proven, primarily by establishing a new, basic, general and professional criterion for dividing types of risks into economic, engineering, administrative and production. The interpretation of risk as a unity of two main elements: certainty and uncertainty was also clarified. However, the authors believe that among the types of certainty and uncertainty, the idea of the existence of complete certainty and complete uncertainty (inside the risk) is erroneous? Therefore, the very formulation and solution of this problem becomes an exceptionally relevant problem of risk management.

The authors of this section conducted a scrupulous and capacious analysis of a significant number of literary sources on the basic concepts of risk management [3–6]. It shows that there are various interpretations of the concepts of risk, certainty, uncertainty, complete and incomplete certainty, complete and incomplete uncertainty.

But the main result of the analysis is the conclusion that the literature assumes the existence of three different separate phenomena: risks, complete certainty and complete uncertainty. The authors of the article consider the idea of the existence of complete certainty and complete uncertainty (inside the risk) to be a mistake. Let's give a few quotes that clearly illustrate this mistake.

Thus, in [4] it is stated: "Complete uncertainty is a type of uncertainty characterized by close to zero predictability of events. In conditions of complete uncertainty, economic entities are completely unable to predict in any way both the prospects of their own development and the market as a whole… Complete certainty is characterized by a predictability of an event close to 1 and allows economic entities to predict not only their strategy in the market, but also its development trends with a 100 percent probability". But an enterprise is a phenomenon created by man, and therefore there can be neither complete certainty, nor the absence of fluctuations in the magnitude of results, nor can there be complete uncertainty (this follows from the risk principle).

A similar point of view is present in [7–9]. Here the author is sure that "… one can talk about the conditions of certainty, risk, and uncertainty in decision-making". That is, it is also asserted that certainty and uncertainty exist separately, outside of risk. At the same time, it follows from the whole context that here we are also talking about complete certainty and uncertainty.

Analysis of recent research and publications as a whole shows that the most important unresolved component of the problem. In contrast, the authors of this study, based on their personal many years of experience in researching risks as a subject of risk management, or more precisely, as a subject of all risk management as a whole, put forward a hypothesis about the lack of complete certainty and complete uncertainty in general in the phenomena created by mankind.

1.2 RESEARCH METHODOLOGY

To achieve the aim, the following methodological approach will be followed in the study:

– the meaning of the risk principle is revealed;

– the absence of complete certainty and complete uncertainty outside the risk is proven;

– the absence of complete certainty and complete uncertainty within the risk is proven.

When solving the first problem, which was to establish the risk principle, the authors drew attention to the fact that risks are an integral part of any human activity. This is due to the fact that every phenomenon that arises as a result of human activity always carries a certain risk. Risks have accompanied humanity at all times, since the beginning of the development of civilization, and will remain an important component of our existence in the future. Any phenomenon created by humanity cannot exist without risk, and at the same time there is no risk without a phenomenon. In other words, these two concepts are inseparable.

The principle of inseparability of risk and phenomenon emphasizes: if there is a phenomenon, then it is necessarily accompanied by risk. This applies not only to complex technical or innovative processes, but also to everyday actions. For example, the invention of the car brought with it the risks of road accidents, and the development of digital technologies gave rise to the risks of cyber threats. At the same time, if there is no risk, this means that the phenomenon to which this risk is associated also does not exist. This dependence is explained by the fact that risk is not just a random component, but a natural property of any phenomenon that arises as a result of human activity.

Given this inseparability, a logical question arises: how exactly is risk related to the concepts of certainty and uncertainty? It is especially important to explore these relationships in cases of absolute certainty and absolute uncertainty. After all, it is these extremes that are most often used as theoretical concepts for analyzing complex situations. The answer to this question became the basis for solving the second problem.

The second task was to prove that beyond the risk there is neither complete certainty nor complete uncertainty. To do this, the authors relied on the risk principle established during the solution of the first task. According to this principle, if there are risks, then there must be corresponding phenomena. Among these phenomena there may be such extremes as complete certainty and complete uncertainty.

However, let's imagine a situation where there is no risk at all. In this case, there are no corresponding phenomena, since they are always associated with risk. This means that beyond the risk, it is impossible to exist either absolute certainty or absolute uncertainty. This statement is explained by the fact that the phenomena of complete certainty and complete uncertainty are theoretical constructs that exist only in connection with risk. Without risk, these constructs lose their meaning and cannot actually be realized.

This conclusion is important for understanding the nature of risk and its role in shaping human activity. Outside the risk, the world becomes "empty" in terms of certainty or uncertainty, because their presence is possible only in interaction with risk. Therefore, the statement about absolute certainty or absolute uncertainty in a world where there are no risks makes no sense.

Additionally, the authors considered the question of whether phenomena of complete certainty or complete uncertainty can exist in the risk itself. To do this, they turned to the analysis of the content of risk, which consists of two main elements — certainty and uncertainty. This means that risk by its nature is a simultaneous combination of these two components.

From the content of risk, it follows that if risk exists, then both of its components must necessarily exist: certainty and uncertainty. This conclusion is based on the concept of "content", which means the set of basic elements of the phenomenon. If even one of these elements disappears, the entire structure of risk collapses. Thus, risk is impossible without the interaction of certainty and uncertainty.

The key point is that none of these elements can completely disappear or become absolute. In other words, certainty cannot be reduced to zero, but it cannot completely replace uncertainty either. Similarly, uncertainty cannot fill the entire risk space, but it cannot be completely absent either. This means that it is impossible to achieve a state of absolute certainty or absolute uncertainty in risk itself.

Risk is a complex phenomenon that is inextricably linked to phenomena created by mankind [10]. Its content is determined by the simultaneous presence of certainty and uncertainty, which cannot exist separately. Outside the risk, neither absolute certainty nor absolute uncertainty is possible, and inside the risk they always coexist in a certain balance. These conclusions emphasize the importance of the risk principle as a key tool for understanding complex processes and phenomena.

The principle of inseparability of risk and phenomenon is a fundamental concept that emphasizes that any phenomenon created by man is always accompanied by a certain degree of risk. This dependence is due to the fact that human activity is always associated with uncertainty, and therefore with the potential for adverse or unpredictable consequences. That is why risk cannot be separated from any human project, discovery or process.

For example, the development of transport technologies, such as cars or airplanes, opened up new opportunities for humanity to move quickly, but at the same time brought with it the risks of accidents, technical malfunctions and security problems. A similar situation is observed in the field of information technology: the creation of computer networks has greatly facilitated the exchange of information, but at the same time the threats of cybercrime have arisen [11]. Even such everyday phenomena as housing construction or agricultural activities involve risks — from possible natural disasters to man-made accidents.

Thus, the established principle of the inseparability of risk and phenomenon is of profound importance for understanding the nature of human activity. It emphasizes that no progress or change can be absolutely safe or completely predictable. Humanity is always left to seek a balance between positive development opportunities and managing potential risks that inevitably arise in the process of creating new phenomena.

The proof of the absence of complete certainty and complete uncertainty outside the risk boundary is based on the principle of the inextricable link between phenomena and risks. Outside the risk boundary, where potential threats or opportunities are not considered, it is impossible to speak of absolute predictability or complete chaos. This is explained by the fact that any phenomenon that is not accompanied by risk actually ceases to exist as a real process or event.

Complete certainty implies the existence of an ideal state in which all factors affecting an event or phenomenon are fully known and controlled. However, in the real world, this is not possible, since there are always unknown variables, even in the simplest situation. For example, even in a stable production process, unforeseen circumstances may arise, such as equipment breakdowns or external economic changes. The absence of risk here becomes a theoretical abstraction that has no practical meaning. Similarly, complete uncertainty means a state of absolute chaos, where there is no predictability or structure. However, in nature and society, there are always certain patterns and regular relationships that exclude complete chaos. Thus, both complete certainty and complete uncertainty outside the limits of risk become absurd concepts.

Within risk, it is also impossible to achieve a state of absolute certainty or absolute uncertainty. This is explained by the nature of risk itself, which includes the simultaneous interaction of two main components – certainty and uncertainty. It follows from the content of risk that these components are its inseparable components.

Certainty within risk means the presence of partial information about the possible outcomes of an event or process, while uncertainty reflects the inability to predict all possible consequences. None of these components can completely disappear or become absolute. If certainty disappears completely, risk as a phenomenon ceases to exist, since any logical basis for forecasts is lost. On the contrary, if uncertainty disappears, risk also disappears, since all outcomes of the event become predictable.

Thus, neither absolute predictability nor complete chaos are possible even within risk. Risk always functions as a balance between a certain share of certainty and a share of uncertainty, which complement each other.

Effective risk management allows to identify, assess and minimize existing risks by developing response strategies and preventing potential losses. An important tool is the construction of risk forecasting models based on data analysis and the implementation of contingency plans to ensure resilience, in particular supply chains.

The financial sustainability of an organization is characterized by the ability to maintain solvency, ensure continuous operations and meet financial obligations even in crisis conditions. In the logistics sector, this includes cost control, inventory optimization, and management of receivables and payables.

Risk management in this context helps to form financial reserves to cover unforeseen costs, maintain flexibility in financial flows and avoid significant losses from logistics failures. For example, the use of insurance mechanisms or hedging currency risks are practices that support the financial sustainability of logistics operations.

The readiness of a logistics system to develop lies in the ability to quickly adapt to market changes, introduce new technologies and management methods. The assessment of such readiness includes an analysis of financial indicators, organizational flexibility and risk management strategy.

Risk management in this context contributes to effective planning of the expansion of logistics capacities, development of scenarios for adaptation to changes and reduction of the probability of failures during the implementation of innovations. In addition, it allows to avoid overspending of resources and to increase the overall efficiency of management, in particular logistics.

The object of the study is to assess the financial stability and readiness of logistics activities in organizations for development. The proposed two-component methodological approach makes it possible to optimize the assessment of the readiness of organizations for development based on determining a sufficient level of investment, on the one hand, and a balanced level of activity costs, on the other. Thus, for the first component, it is proposed to use an integral indicator of investment adequacy, the calculation method of which is based on combining the dependencies between the volumes of capital investments and other resource parameters of the activities of enterprises (depreciation deductions, long-term loan capital, non-current assets, equity, etc.). The second component reflects the ratio of material and other operating costs to the total income of logistics activities in organizations.

The study was carried out on the example of motor transport enterprises. The proposed methodological approach was tested, which showed low resource capacity of enterprises. The dynamics of the integral indicator of investment adequacy showed that in general for enterprises engaged in road freight transportation, its level is significantly lower than the normative value, which is equal to 3. Its value on average fluctuated at the level of 1.2—1.7, that is, it was in the range of the absence or limited resources for economic development. This indicates the dominance of survival strategies, not development, among motor transport enterprises, and weak state policy, which does not stimulate investment activity in a legal transparent environment.

The results obtained can be used both at the level of individual logistics organizations and organizational networks, and for an aggregated assessment of the industry as a whole. An additional advantage of the developed two-component methodological approach to assessing the state and readiness of an enterprise for development is the possibility of using different components for each component, differentiating their importance in an integrated assessment, and adjusting target ranges.

As a result of the study, several possible strategies for managing the development of logistics activities in organizations were identified, such as a reserve management strategy, an asset diversification strategy, a profit reinvestment strategy, a strategy for optimizing liabilities and obligations, a risk-oriented liquidity management strategy, and an active liquidity management strategy.

1.3 ASSESSMENT OF SUSTAINABILITY AND READINESS OF LOGISTICS ACTIVITIES IN ORGANIZATIONS FOR DEVELOPMENT: PROBLEMS AND SOLUTIONS

The difficult period of adaptation to modern conditions and requirements for the transport sector will accelerate the processes of transition to a new level of competition in the freight transportation market. Digital transformation is accelerating, consumer preferences are changing, new business models are being introduced [1]. In the future, the competitive environment will be determined by technological modernization, in fact, the restart of infrastructure in general, and transport in particular.

Most organizations have weak financial stability. Despite overcoming the ongoing crisis of unprofitability of motor transport enterprises in the freight transportation market, their profitability remains low, which does not allow forming enough capital to finance development [2].

This situation has led to the emergence of economic and social problems: aggravation of the deficit of working capital; low level of competitiveness and attractiveness for foreign investment; lack of effective policies aimed at stimulating the growth of financial resources; insufficient level of financial potential and economic base.

The negative impact of the ongoing processes has significantly increased the requirements for ensuring the sustainability of commodity supply chains, and in this market the processes of logistics optimization, mergers and acquisitions of transport companies have intensified. A growing trend is the development of e-commerce, wh ich stimulates the control of transport and logistics companies at all links of the supply chain – manufacturer, warehouse, sales centers [3–5]. Increasing investments in modern technologies of logistics supply chains is considered as a tool for improving the quality of transport services, reducing operating costs, and reducing environmental impact.

European initiatives on transport development strategies are supported by large-scale financial resources and various financial instruments for the restoration of the transport sector. The budget of the relevant funds for these purposes is estimated at over 1.8 trillion euros. This further emphasizes the conclusions of this study that the success of the transport sector development critically depends on a consistent state incentive policy, supported by the formation of powerful financial funds and instruments [6–8].

The priority innovative direction of the transport industry development is its digitalization. Accordingly, investments in the implementation of digital technologies in the business processes of transport enterprises will become increasingly important to ensure the maintenance of competitive positions in the market. At the same time, there is a wide range of digital technologies and tools, and their application depends on the type and functional area of logistics activities in organizations. In general, two main models of their activity can be distinguished:

1) organizations that provide goods transportation services;

2) organizations that manage a fleet and provide rental or outsourcing services.

For the first type of organizations, the priority areas of investment in digital technologies are digital tools that allow real-time receipt of data on the delivery of goods, possible obstacles and delays, etc. Such technologies are needed for a quick and timely response to possible problems or changes in the needs of service consumers to avoid delays and unplanned expenses.

For organizations of the second type, investments in digital solutions for monitoring the condition of their vehicles, their intended use, location, etc. are a priority. Such investments are necessary both for control and for the ability to meet modern standards of safety and environmental friendliness of the use of road transport.

Scientific research on the topic under study is important because the economic development of organizations cannot be achieved without innovative development. Low efficiency of spending on technological innovations does not provide opportunities for development. Therefore, it is necessary to take into account not only equipment and technology, but also the organization of the production process. The introduction of innovations requires an increase in sources of capital investment, the expansion of which is impossible without the use of state innovation policy instruments: public-private partnership programs, technological development, and preferential taxation [7, 8].

The current task is to develop a methodological approach to assessing the readiness of organizations for development and recommendations for expanding investment opportunities. The results of such studies are needed in practice, because they are determined by the need for organizations to update fixed assets, the need to transition to modern technologies, the introduction of innovative products and the growth of demand for qualitatively new transport services.

1.4 SCIENTOMETRIC ANALYSIS OF EXISTING PUBLICATIONS ON THE DEVELOPMENT OF METHODOLOGICAL APPROACHES TO ASSESSING THE SUSTAINABILITY AND DEVELOPMENT OF ORGANIZATIONS

International experts note that the development of sustainable transport infrastructure will be based on four dimensions of sustainability: environmental (climate change resilience), social (inclusiveness), institutional (technological development) and economic (productivity and flexibility) [9]. According to their estimates, by 2040 the need for investment in transport infrastructure will amount to up to 2 trillion USD. This is considered a "golden era" of transport infrastructure.

Among the main trends that will determine the development of transport in the EU countries for 2021–2024, the following are highlighted [10]:

1) prioritizing the transition to alternative fuels;

2) ensuring competition in the aviation industry;

3) a modal-neutral approach that promotes sustainable transport development;

4) green financing to increase the sustainability of the EU transport sector.

It should be noted that the current action plan for the implementation of the Transport Strategy provides for the development of multimodal transport technologies and infrastructure complexes to ensure interaction between different modes of transport. And, in particular, paragraph 21 of the plan provides for the partial reorientation of road freight transport to rail and inland waterway transport [11].

In general, the trend in the development of intermodal and multimodal transport also determines the priority for road transport enterprises to invest in projects that will allow them to quickly adapt and integrate into such technologies. The objective priority for investing in development is projects to prepare for the transition to renewable fuels through the renewal of the transport fleet and ensuring compliance with new environmental standards.

The complexity and multifaceted nature of economic development determine the presence of a wide range of scientific interpretations and understandings of such development, for the disclosure of which various algorithms and methods of its assessment are developed and applied. Domestic and foreign researchers use various methodological approaches to assess the financial condition of enterprises, their readiness to implement various strategies of economic development. Thus, the author of the work [12], systematizing methodological approaches to enterprise development, distinguishes the following types: innovative, economic, strategic, marketing and competitive. The author concludes that each of the above approaches or their combination has its own advantages for application, but at the same time reflects only a separate specific effect associated with the development of the enterprise. But the effectiveness of their application will depend primarily on the readiness to implement development strategies on an alternative basis and adapt to new operating conditions. This occurs under the influence of internal and external changes, which complicates the process of assessing the readiness of enterprises for development.

Considering the functioning and development of an enterprise through the prism of competitiveness, methodological approaches are developed to assess the level of such competitiveness. Thus, some researchers note that the competitiveness of an enterprise depends on many factors: technical and technological, organizational and managerial, financial and economic, socio-psychological, natural and geographical, transport, environmental, industry and market. Therefore, competitiveness cannot be measured by a single statistical indicator [13]. Accordingly, the authors' approach to the need to apply different assessment methods, which are systematized according to two criteria: the degree of objectivity/subjectivity and the type of assessment (quantitative and qualitative), is justified. They thus distinguish 4 groups of methods for assessing competitiveness: objective-quantitative (calculated and calculated-graphic), objective-qualitative (models of structural and strategic analysis), subjective-qualitative and subjective-quantitative.

Different methods have their advantages and disadvantages, and accordingly, their application must correspond to the goals and possibilities of their effective use. Difficulties arise due to the fact that some assessment methods require complex algorithms for calculating performance indicators, and hence more costs for their application. Other methods are less complex, but also with a lower probability of accuracy and validity of their results. This complicates the choice of the optimal method.

Often, the development of an enterprise is considered in the context of assessing its potential. The implementation of this approach is based on the application of various methods for assessing such potential, which, in turn, is also considered by its individual types, in particular: innovative, investment, technological, competitive, marketing, labor, etc.

In the work [14], the author singled out the following principles for assessing the potential for economic development of an enterprise:

1) determining the key properties of the enterprise;

2) considering the potential for economic development of an enterprise as a set of its properties;

3) identifying a criterion functional property;

4) identifying the controllable basic properties of both the enterprise and its components;

5) identifying the uncontrollable basic properties of the enterprise and its components;

6) taking into account external environmental factors;

7) organizing the process of searching for reserves for the enterprise's economic development.

Despite the rather broad interpretation of these principles, they show the systematicity and complexity of the enterprise's potential and, accordingly, methodological approaches and tools for its assessment.

The author also emphasizes the need to use three levels of potential assessment indicators: partial, general, generalizing. Partial will characterize the possibilities of improving the basic properties of the enterprise (in particular, consumer properties of products or services). General will characterize key properties (in particular, financial results, sales volumes, etc.). Generalizing will characterize the criterion properties of the enterprise (for example, its market value).

The author's grouping of methods for assessing the potential of economic development of enterprises includes: the use of individual indicators or their combination; quantitative and qualitative assessment; absolute and comparative assessments; different levels of the hierarchy of assessment indicators, etc. Such diversity opens up wide possibilities for finding effective tools and indicators for assessing the current state or potential of the enterprise at the appropriate stage of its development. But the issue of determining the optimal methodology remains unresolved due to the fact that excessive overload can blur the accuracy and validity of the results of their application when making management decisions regarding strategic and tactical tasks of enterprise development.

In the context of assessing the potential of enterprises, traditional methods are to determine the effectiveness and feasibility of investments, investment projects for individual enterprises. In particular, this involves assessing the payback period of investments, the level of net present value, investment profitability, and systematization of risks for the relevant industry or market of goods/services. Undoubtedly, assessing the effectiveness of investments is critically important for the development of an enterprise, but it is advisable to apply it to specific investments, relevant target goods, services, and markets. The problem remains that such methods should be preceded by an integrated assessment of the state and readiness of the enterprise for development. But investments should serve as the basic criterion and indicator for conducting such assessments.

A number of studies are aimed at developing methodological tools for assessing the state and potential of development, which take into account industry specifics and aspects of the functioning of business entities. In particular, such an approach is disclosed in the works: [15] on the development of agricultural enterprises, [16] on the development and livelihoods of food industry enterprises, etc. There is no single methodological approach to assessing the development of motor transport enterprises, so this issue remains relevant.

In general, it should be noted that the development of methodological approaches to assessing various aspects of the activities and development of enterprises is carried out in accordance with the theoretical basis of the issues under study. And, accordingly, the application of existing and new criteria, indicators, characteristics should be adapted to management tasks, the existing information base for the use of such methodological approaches and tools.

Most researchers justify the need to combine different assessment methods that will provide an acceptable level of validity of conclusions and recommendations regarding the analysis of the current and potential state of development of the enterprise, but this issue remains unresolved.

All this allows to argue that it is advisable to conduct a study dedicated to optimizing the assessment of the readiness of enterprises for development based on the development of a two-component methodological approach that takes into account investment adequacy and material costs. This methodological approach determines the logic of monitoring the sustainability of motor transport enterprises based on the consistency of key economic indicators with the level of investment and achievement of target parameters of structural cost balance. The advantage of this methodological approach is the possibility of using different components for each component, the possibility of adjusting target ranges and establishing different specific weights in the integral assessment [17].

1.5 RESULTS OF THE DEVELOPMENT OF A METHODOLOGICAL APPROACH FOR ASSESSING THE SUSTAINABILITY AND DEVELOPMENT OF ORGANIZATIONS

The aim of the study is to optimize the assessment of the readiness of road transport enterprises for economic development based on a two-component methodological approach. This will make it possible to investigate the level of investment adequacy and balance of the enterprise's costs, as well as develop recommendations for solving existing problems and outlining strategies for further development.

To achieve the aim, the following objectives were set:

– to propose a methodological approach to assessing the readiness of enterprises for development based on the calculation of an integral indicator of investment adequacy and the level of material costs;

– to test the proposed two-component approach to assessing the state and readiness of enterprises for development;

– to develop strategies for managing the development of enterprises.

The object of the study is to assess the financial sustainability and readiness of road transport enterprises for development. Enterprises engaged in freight transportation chronically lack working capital, which increases risks for current activities and blocks investment opportunities in their development strategies. Thus, in general, net working capital for such enterprises has been negative for the last 10 years, which requires the introduction of modern instruments for financing their activities, which will be accessible and effective [18].

The imbalance in the financing model of motor transport enterprises is further exacerbated by the dominance of material intensity of cost price and operating costs. The share of material costs and services takes up about 80% of all operating costs of the enterprise, which forms a dependence on working capital and the settlement system at enterprises. But the problem of settlements for the provided services for cargo transportation is acute for the studied industry enterprises, whose current assets consist of accounts receivable on average by 2/3. About 20% is accumulated in inventories, highly liquid assets are quite limited [18]. Such a cost structure requires additional working capital to pay VAT and excise duties when making material costs, although it reduces the real burden of value added tax. At the same time, it increases the dependence of enterprises on the level of tax burden by direct taxes – on profit, on property, on the payroll.

The study used methods of generalization (to systematize modern mechanisms for the formation and implementation of economic development), statistical observations (to structure data on the financial activities of motor transport enterprises in Ukraine), a systematic approach (to study the principles of implementing economic development), and the method of expert assessments (to determine the criteria for the economic development of motor transport enterprises and internal indicators of the effectiveness of their activities).

The proposed methodological approach to assessing the state and readiness of motor transport enterprises for development consists, on the one hand, in determining a sufficient level of investment for development, and on the other, a balanced level of activity costs. To take into account the first component, it is proposed to use an integral indicator of investment adequacy, compliance with the minimum regulatory level of which will confirm the accumulation of a sufficient and sustainable level of investment at the enterprise. The components of the integral indicator of investment adequacy are the ratio of capital investments with such parameters as: depreciation, long-term loan capital, non-current assets and equity. The normative minimum level of the integral indicator of investment adequacy of the enterprise will depend on the specified parameters of its components, which allows for multivariate calculations. The proposed integral indicator can be used both at the level of individual enterprises and for an aggregated assessment of the industry as a whole. Taking into account the second component involves determining the level of material costs as the ratio of material and other operating costs to the total amount of income from all types of activity at the enterprise.

1.6 RESULTS OF RESEARCH ON THE USE OF THE PROPOSED METHODOLOGICAL APPROACH BASED ON A TWO-COMPONENT MODEL

The methodological approach to assessing the state and readiness of motor transport enterprises for development consists in determining two components: a sufficient level of investment for development and a balanced level of activity costs.

Definition of the integral indicator of investment adequacy.

The integral indicator of investment adequacy is calculated as follows

$$IS_t = \sum_{i=1}^{n} \frac{CI_t}{SD_{it}} \cdot P_{it} + \sum_{j=1}^{m} \frac{SD_{jt}}{CI_t} \cdot P_{jt}, \tag{1.1}$$

where IS_t – integral indicator of investment adequacy in the t-th period; CI_t – capital investment in the t-period; P_{it} – weight of the i-th type of resource for the integral indicator of investment adequacy for development in the t-th period; $i = 1, 2, ..., n$; SD_{it} – indicators of the i-th type of development resources in the t-th period; SD_{jt} – indicators of the j-th type of development resources in the t-th period; P_{jt} – weight of the j-th type of resource for the integral indicator of investment adequacy for development in the t-th period; $j = 1, 2, .., m$.

One of the options for the normative level of the integral indicator of investment adequacy is given in **Table 1.1**.

Table 1.1 Normative level of the integral indicator of investment adequacy

Components of the integral indicator of investment adequacy	Calculation of indicators	Minimum level	Weight	Contribution to the integrated indicator
1	**2**	**3**	**4**	**5 (gr.3*gr.4)**
Depreciation adequacy	Ratio of capital investments to depreciation deductions	2.5	0.25	0.625
Adequacy of long-term loan capital	Ratio of capital investments to long-term debt capital	4	0.25	1.0
Production adequacy	Ratio of non-current assets to capital investments	3.5	0.25	0.875
Equity adequacy	Ratio of equity to capital investments	2	0.25	0.5
Integral indicator of investment adequacy	–	–	1	3.0

Source: compiled by the authors.

The first component of the integral indicator of investment adequacy allows to assess depreciation adequacy through the ratio of the annual volumes of capital investments of the enterprise and the volumes of depreciation deductions. The target minimum level for this ratio is set at 2.5, based on the logic of the formation of its components. Thus, depreciation deductions show only the actual level of wear and tear of existing means of production (fixed assets) formed in previous years. Accordingly, capital investments at the level of depreciation deductions will not ensure even a simple reproduction of fixed assets. Especially in conditions of their fairly rapid depreciation, both moral and technological, and physical.

Therefore, capital investments should not be less than 2.5 times higher than the annual volumes of depreciation deductions. There are certain risks for enterprises that have practically worn out fixed assets and, accordingly, minimal depreciation deductions. This can lead to a wide range of values for this component. This feature is generally inherent in indicators that reflect the ratio between different financial and economic indicators of the activities of enterprises. Therefore, it is advisable to use limit levels of the ratio, in particular, if they exceed 3–4 times the minimum target standard, then such a three-fold minimum is applied, and not the actual result.

The second component of the integral assessment allows to assess the adequacy of long-term loan capital through the ratio of annual volumes of capital investments and accumulated long-term liabilities of the enterprise. Similarly to the previous ratio, capital investments should exceed such liabilities several times, which will indicate an active investment strategy aimed at the economic development of the enterprise.

The next component of the integral assessment is aimed at determining production adequacy through the ratio of the cost of non-current assets and capital investments. The inverse ratio is used here, since this allows to apply comparable weighted rates and target standards. The proposed target standard may be a 2–4-fold excess of assets over capital investments and will depend on the need for fixed assets for the production of goods or the provision of services. Thus, for motor transport enterprises, especially medium and large ones, the presence of a modern transport fleet and its renewal is a critically important condition for maintaining competitiveness, market positions and implementing development strategies.

The next component of the integral assessment is the adequacy of equity, which is assessed through the ratio of equity and capital investments. Similarly to the previous ratio, compliance with the parameters of financial autonomy requires an adequate level of equity. Accordingly, a multiple excess of equity over capital investments is acceptable.

In general, the use of different regulatory limits allows for multivariate calculations and evaluation of results in accordance with the goals and strategies of economic development of enterprises.

To calculate the integral indicator of investment adequacy, the same specific weight of its individual components (ratio) was used, i.e. each of them was 25% (0.25). At the same time, different specific weights can be used for research, as well as expanding the components of the integral indicator. Four components of the integral indicator were used. Accordingly, the minimum normative value of the integral indicator of investment adequacy is 3. And the higher the value of this indicator, the better the potential of the enterprise to implement its economic development strategy, and therefore, a more effective mechanism for managing its economic development is used.

In this case, it seems appropriate to supplement the minimum target level with a sufficient level, in particular, which will be twice as high as the minimum. Conceptually, this is shown in **Fig. 1.1**.

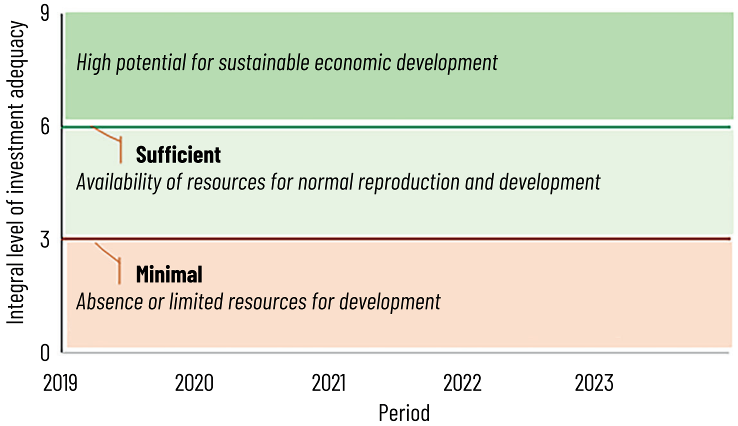

Fig. 1.1 Ranges of the level of the integral indicator of investment adequacy
Source: developed by the authors

This will allow to obtain three ranges for the integral indicator:

1) less than the minimum level – the actual value in this range will indicate the absence or significant limitation of resources for development at the enterprise;

2) between the minimum and sufficient levels – the actual value in this range will demonstrate the availability of resources for normal reproduction and development of the enterprise;

3) above the sufficient level – the actual value in this range will demonstrate a high potential for sustainable development of the enterprise.

Determining the level of material costs.

Taking into account the second component of the methodological approach to assessing the state and readiness of enterprises for development involves determining the level of material costs, the calculation of which is proposed to be carried out as follows

$$CL_t = \frac{MC_t + OC_t}{I_t} \cdot 100\%, \tag{1.2}$$

where CL_t – level of material costs in the t-th period; MC_t – volume of material costs and costs for payment of services used in production in the t-th period; OC_t – volume of other operating expenses in the t-th period; I_t – total amount of income from all types of activities in the t-th period.

Thus, the level of material cost is the ratio of material and other operating expenses to the total amount of income of the enterprise. As with the first component, it is possible to apply only the minimum target standard or to apply several ranges (**Fig. 1.2**).

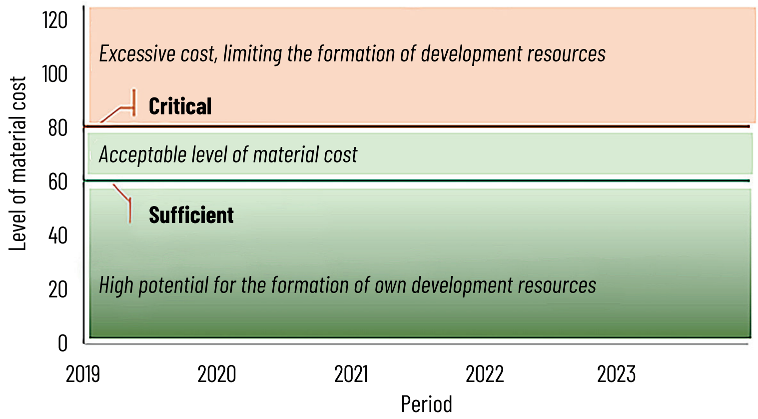

Fig. 1.2 Ranges of material cost level

Source: developed by the authors

So, actual values of the material cost level less than 50% will indicate the presence of a high potential for the formation of the enterprise's own development resources. Values at the level of 50–75% will indicate an acceptable level of material cost, and above 75% will mean a critical level and excessive cost, which limits the formation of sufficient development resources at the enterprise.

The information base for calculating the material cost level is the data of the report on the financial results of the enterprises [19]. Sources of input data for applying the proposed methodological approach to assessing the state and readiness of enterprises for development are given in **Table 1.2**.

Table 1.2 Input data for assessing the state and readiness of enterprises for development

No.	Indicator	Reporting form	Line code
1	**2**	**3**	**4**
1	Integral indicator of investment adequacy		
1.1	Capital investments	Notes to the reporting	–
1.2	Depreciation and amortization	Financial statement (form 2)	2515
1.3	Profit before tax		2290/2295
1.4	Non-current assets	Company balance sheet	1095
1.5	Equity		1495
1.6	Long-term debt capital		1595

Continuation of Table 1.2

1	2	3	4
2	Level of material costs		
2.1	Material costs and costs of services	Financial statement (form 2)	2500
2.2	Other operating expenses		2520
2.3	Net income from sales of products (goods, works, services)		2000
2.4	Other income from operating activities		2105, 2110, 2111, 2112, 2120, 2121, 2130, 2180
2.5	Income from financial activities		2200, 2220
2.6	Other income		2240

Source: compiled by the authors

A certain problem for assessing the state and readiness of enterprises for economic development for external experts and researchers is the rather veiled data on investments in general, and capital investments in particular, in the financial statements of enterprises. On the one hand, such data are quite confidential and require proper protection of commercial interests.

1.7 TESTING THE PROPOSED TWO-COMPONENT METHODOLOGICAL APPROACH TO ASSESSING THE READINESS OF ORGANIZATIONS FOR DEVELOPMENT

The testing of the methodological approach showed low resource capacity of the studied enterprises.

Thus, the dynamics of the integral indicator of investment adequacy showed that in general for enterprises engaged in road freight transportation, its level is significantly lower than the target normative value.

In particular, in 2013 it was 2.1 points with a minimum level of 3 points. And during 2015–2023 its value on average ranged from 1.2 to 1.7, that is, it was in the range of absence or limited resources for economic development [18]. This confirms the widespread practice of domestic enterprises in general to rely on internal resources for financing investments. In particular, in 2020, only 6.6% of capital investments in the economy as a whole were financed by bank loans and other loans [18].

The calculation of the second component of assessing the state and readiness of enterprises for development based on aggregated data for freight road transportation enterprises in Ukraine showed the following. The overall level of material costs of the specified type of economic activity is quite moderate and during 2013–2023 did not exceed 40% [18]. This confirms the presence of the potential for ensuring the efficiency and profitability of providing freight transportation services by road transport. At the same time, the application of the developed approach to the reporting of individual motor transport enterprises showed results that differ from industry-wide calculations.

The calculations were carried out using data from three motor transport enterprises from different regions of Ukraine and with different potential: Kyiv Production Company Rapid, PJSC ATP 11263, Dnipro, PJSC Chernihiv Motor Transport Enterprise 17462. The calculation of the integral indicator of investment adequacy showed that during 2018–2023 the studied enterprises did not reach the target regulatory level (**Table 1.3**).

Table 1.3 Average level of indicators for assessing the state and readiness for development for individual enterprises during 2018–2023

Indicators / enterprises	Value
Integral indicator of investment adequacy	Standard level > 3
PJSC "Kyiv Production Company "Rapid", Kyiv	2.4
PJSC "Chernihiv Motor Transport Enterprise 17462"	2.0
PJSC "ATP 11263", Dnipro	2.7
Level of material costs of the enterprise's activities	Standard level < 60
PJSC "Kyiv Production Company "Rapid", Kyiv	63.9
PJSC "Chernihiv Motor Transport Enterprise 17462"	54.5
PJSC "ATP 11263", Dnipro	74.3

Source: compiled by the authors based on enterprise reporting [19]

In addition, more powerful enterprises from Kyiv and Dnipro generally have a higher level of the investment adequacy indicator, which confirms the feasibility of building potential and investment opportunities. Analysis of the integral indicator of investment adequacy by individual components in the context of the studied enterprises shows significant differences in their business models and ability to implement development strategies (**Table 1.4**).

Table 1.4 Assessment of compliance with the regulatory level of individual components of the integral indicator of investment adequacy for individual enterprises during 2018–2023

Indicators / enterprises	Depreciation adequacy	Long-term debt capital adequacy	Production adequacy	Equity adequacy
Standard level	> 2.5	> 4	> 3.5	> 2
PJSC "Kyiv Production Company "Rapid", Kyiv	4.79	2.24	1.36	0.91
PJSC "Chernihiv Motor Transport Enterprise 17462"	1.23	2.13	5.03	3.41
PJSC "ATP 11263", Dnipro	0.98	0.40	5.47	3.68

Source: compiled by the authors based on enterprise reporting [19]

So, PJSC "Kyiv Production Company "Rapid" in 2018–2023 has a high level of depreciation adequacy, which was achieved primarily due to active investment activity. The enterprise, while maintaining a traditionally low share of depreciation deductions in the structure of operating expenses for the industry, directs resources to capital investments that are several times higher than the annual depreciation of fixed assets. The enterprise also uses long-term loan resources more actively, although their volumes are somewhat lower than capital investments.

The greatest influence on the formation of the integral indicator of investment adequacy for PJSC "Chernihiv Motor Transport Enterprise 17462" and PJSC "ATP 11263" was production adequacy and equity adequacy. In particular, during the period under study, these indicators exceeded the target standard. Probably, enterprises are serious about maintaining an appropriate level of financial autonomy and minimizing risks associated with obligations to creditors.

Analysis of financial statements of transport enterprises showed that most of them do not provide open data on their capital investments, which complicates the analysis of their activities by external experts. Therefore, their investment activity can be evidenced by data on the renewal of fixed assets, cash flows from investment and financial activities, etc.

For PJSC "Chernihiv Motor Transport Enterprise 17462", the results of assessments of the integral indicator of investment adequacy by components are largely comparable with the studied enterprise from the city of Dnipro. In general, it should be noted that an important aspect of applying the developed methodological approach is a sufficient information base, primarily regarding the volumes of capital investments or another aggregate indicator of investment volumes.

The assessment of the studied enterprises showed that the problem of excessive cost is quite relevant. Thus, the level of material costs for enterprises is almost twice as high as that calculated for the freight road transportation industry as a whole. In particular, for PJSC "ATP 11263" it is almost 75 %, that is, the costs of fuel, spare parts and other material costs make up almost 3/4 of the total revenue of the enterprise. The minimum target standard of the level of material costs is not observed for PJSC "Kyiv Production Company "Rapid". And only PJSC "Chernihiv Motor Transport Enterprise 17462" has a level of material costs lower than 60 %, but also significantly exceeds the average industry level.

Calculation of the integral indicator of investment adequacy and the level of material costs for individual ATPs confirms the conclusions obtained about their weak investment readiness to implement ambitious strategies of economic development in the freight transportation market. This increases the risks of further technological lag of enterprises in the industry, the preservation of non-equivalent exchange and pressure of the transport sector on all other related sectors of the economy and markets, and the limitation of the resource base for the formation of budgets at various levels.

DISCUSSION OF THE RESULTS OF IMPLEMENTING A TWO-COMPONENT METHODOLOGICAL APPROACH TO ASSESSING THE READINESS OF ORGANIZATIONS FOR DEVELOPMENT

A methodological approach to assessing the sustainability of organizations based on a two-component assessment is substantiated, which consists, on the one hand, in determining a sufficient level of investment for development, and on the other, a balanced level of activity costs.

For the first component (2.1), it is proposed to use an integral indicator of investment adequacy. The methodology for its calculation is based on combining the dependencies between the volumes of capital investments and other parameters of activity (depreciation deductions, long-term loan capital, non-current assets, equity, etc.). The normative minimum level of the integral indicator of investment adequacy will depend on the specified parameters of its components, which allows for multivariate calculations. One of the options for the normative level of the integral indicator is given in **Table 1.1**. The calculation was carried production adequacy, adequacy of equity. Under these conditions, the integral indicator of investment adequacy is determined at the level of 3.0. The ranges of the level of the integral indicator of investment adequacy are proposed: minimum, sufficient, high (**Fig. 1.1**).

The second component (2.2) reflects the ratio of material and other operating costs to the total income of the enterprise. It is possible to apply the minimum (critical) target standard, which is set at 60%, or to apply several ranges (**Fig. 1.2**): sufficient, acceptable, critical.

An assessment of the dynamics of volumes and the level of material costs for freight road transportation enterprises in Ukraine was carried out, based on the results of which it can be concluded that during 2013–2023 the level of material costs did not exceed 40%. This confirms the potential for ensuring the efficiency and profitability of providing freight transportation services by road. At the same time, the application of the developed approach to reporting by individual road transport enterprises showed results that differ from industry-wide calculations.

The sustainability of road transport enterprises was monitored based on the consistency of key economic indicators with the level of investment and the achievement of target parameters of the structural balance of its costs. It was found that the majority of road transport enterprises have weak financial stability.

Three road transport enterprises from different regions of Ukraine and with different potential were selected for the study: PJSC "Kyiv Production Company "Rapid", Kyiv, PJSC "ATP 11263", Dnipro, PJSC "Chernihiv Road Transport Enterprise 17462".

Testing of the proposed two-component assessment of the state and readiness of enterprises for development showed their low resource capacity and the presence of the problem of excessive cost (**Table 1.3**). Thus, the level of material costs for enterprises is almost twice as high as that calculated for the freight road transportation industry as a whole. The assessment of compliance with the regulatory level of individual components of the integral indicator of investment adequacy for the studied motor transport enterprises in 2018–2023 is presented in **Table 1.4**.

The dynamics of the integral indicator of investment adequacy showed that, in general, for enterprises engaged in road freight transportation, its level is significantly lower than the normative value. This indicates the dominance of survival strategies among enterprises, rather than development, and weak state policy that does not stimulate active investment in a legal transparent environment.

It is proposed to take into account the developed approach in the implementation of state support for enterprises that actively invest, increase legal turnover, income and labor costs. Benefits can be introduced for enterprises that have higher than the normative values of the developed indicators and will adhere to such conditions for a long period. In particular, if they are fulfilled for three or more years, such enterprises may be exempted from paying income tax if they are invested in development.

The developed two-component methodological approach makes it possible to optimize the assessment of the readiness of motor transport enterprises for economic development. Based on the interpretation of economic development as a transition to a new qualitative state and new possibilities for the functioning of the enterprise, the basis for its implementation is a sufficient level of investment and the availability of sources of their financing. And the necessary result of the success of such investments should be a more balanced structure of operating costs, which will confirm the systematicity, long-term nature and durability of changes.

The development of research using the proposed methodological approach is that its use will allow rationalizing the mechanism of economic development management and more clearly identifying the correspondence of current and projected performance indicators of both domestic and foreign enterprises to their development goals.

The limitations of the developed methodological approach include the impossibility of including profitability as the main internal resource for financing the development of the enterprise in the integrated assessment of the adequacy of profitability. This component quite organically corresponds to the task of assessing the integral indicator of investment adequacy. But its practical application is complicated by possible losses of the enterprise or minimum profit values. This is a fairly typical situation for many motor transport enterprises, which will actually lead to excessive values of this ratio and distortion of the results obtained. Therefore, its application requires the availability of adequate data on the profit of enterprises and their proper calibration.

The disadvantages include the fact that the problem for assessing the readiness of enterprises for development for external experts is the rather veiled data on investments in general and capital investments in particular in financial statements.

STRATEGICALLY-ORIENTED MANAGEMENT OF ORGANIZATIONAL DEVELOPMENT

Strategically-oriented management of organizational development is a scientifically substantiated influence of management on the socio-economic development of an organization, which ensures long-term, sustainable growth of the results of production and commercial activities. The development management system consists of interconnected subsystems: production, technological, financial, innovation, communication, structural and organizational, marketing, personnel, legal support, economic, socio-psychological, motivational subsystems [20].

The main tools of strategically-oriented management of development in order to achieve the main target benchmarks are the development and implementation of appropriate strategies. Organizations that have a strategy and implement strategically-oriented management of activities always have the opportunity to act consistently and systematically both in the internal environment and in the conditions of a changing external environment, which increases the likelihood of achieving the set goals for further development.

Let’s consider the strategies that can be implemented by an organization to ensure financial stability and optimize resources:

1. The reserve management strategy involves an active process of accumulating and managing financial reserves to ensure financial stability its obligations. The main provisions are presented in **Fig. 1.3**.

2. The asset diversification strategy consists of distributing investments between different asset classes in order to reduce risk and ensure greater liquidity. The main provisions are presented in **Fig. 1.4**.

3. The profit reinvestment strategy involves the redistribution of profit received from activities in order to maintain or increase the organization's liquid assets. The main goal is to use the cash that the enterprise already has to generate additional profit. The main provisions of this strategy are presented in **Fig. 1.5**.

4. The strategy of optimizing liabilities and obligations is aimed at balancing the structure of the organization's liabilities and assets in order to ensure an optimal balance between the liquidity of assets and their financial stability. This strategy can help reduce financial costs, increase profitability and improve financial risk management. The main provisions of the strategy are presented in **Fig. 1.6**.

5. The risk-based liquidity management strategy emphasizes control over risks associated with liquidity, in particular ensuring financial stability in a changing financial environment, and helps manage the liquidity of assets in conditions of increasing risk. The main provisions of the strategy are presented in **Fig. 1.7**.

6. The strategy of active asset liquidity management involves active investment and management of liquid assets to ensure maximum efficiency and profitability, as well as optimization of the organization's risk. The main provisions of the strategy are presented.

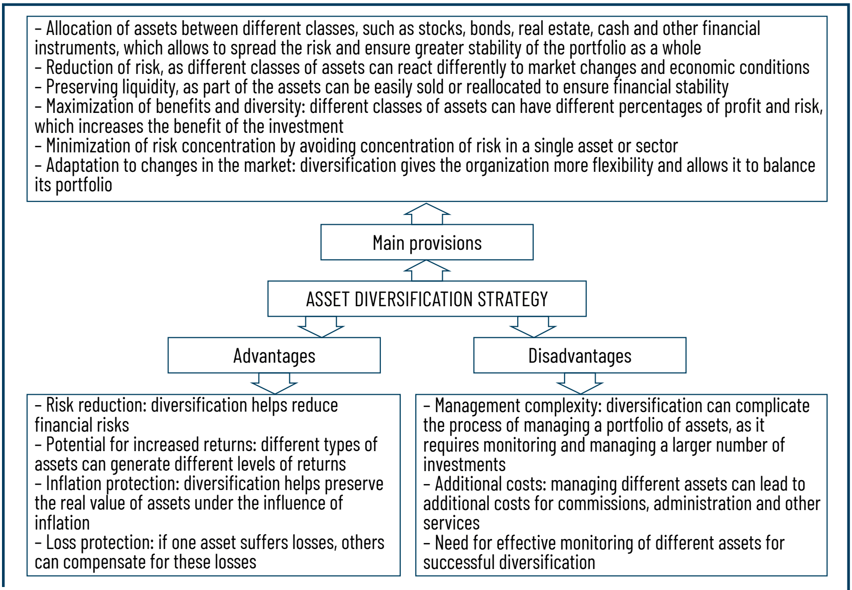

Fig. 1.3 The essence of the asset diversification strategy

Source: compiled by the authors

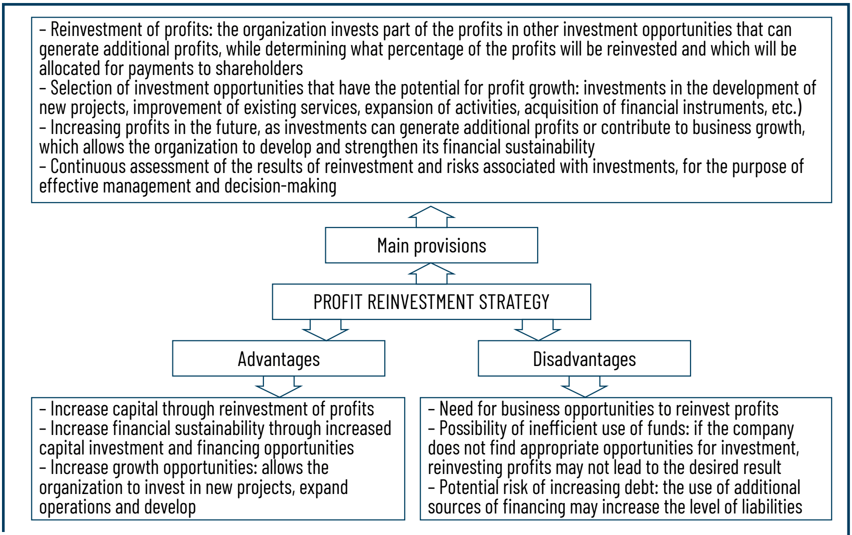

Fig. 1.4 The essence of the profit reinvestment strategy

Source: compiled by the authors

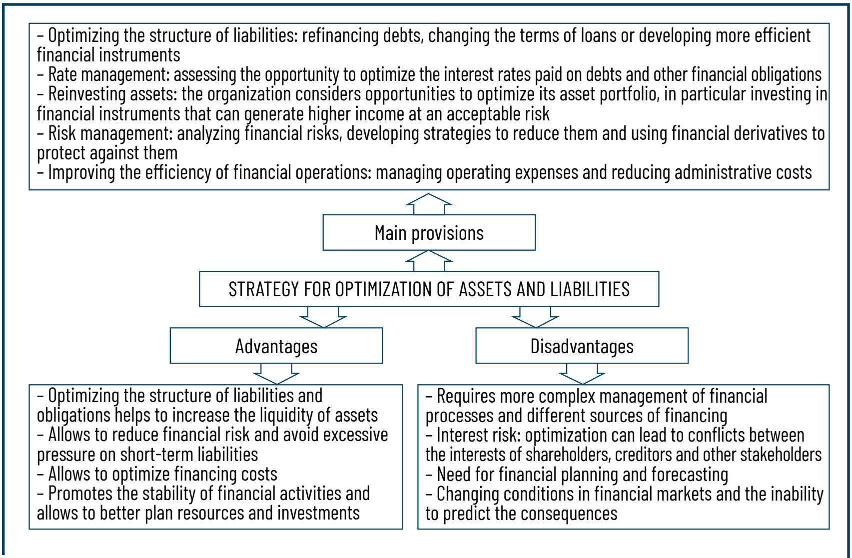

Fig. 1.5 The essence of the strategy for optimizing liabilities and obligations

Source: compiled by the authors

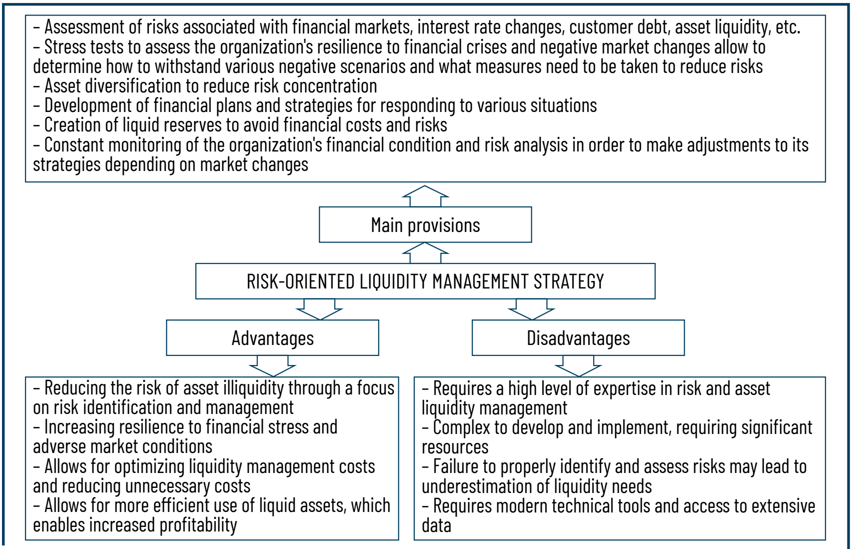

Fig. 1.6 The essence of the risk-based liquidity management strategy

Source: compiled by the authors

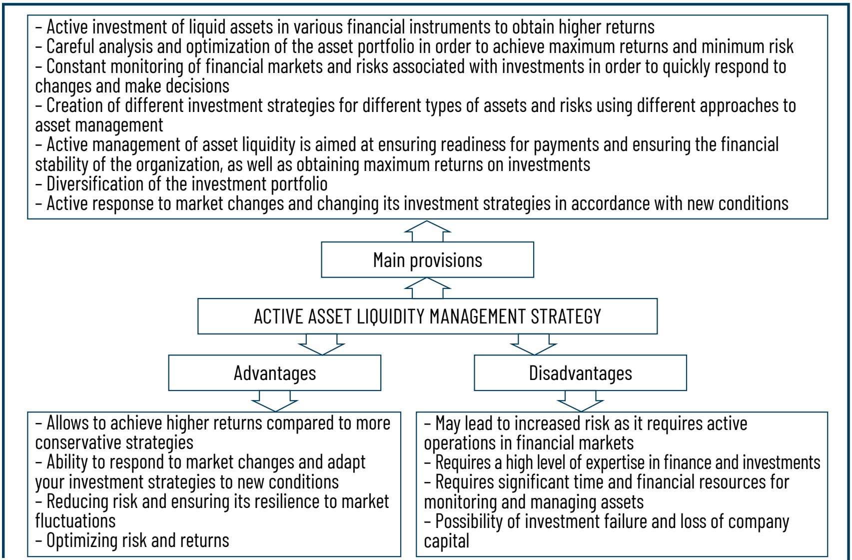

Fig. 1.7 The essence of the active asset liquidity management strategy

Source: compiled by the authors

The study determined that the implementation of combined strategies can be a key factor in achieving financial stability and ensuring the development of organizations. The need for further improvement of resource management strategies, careful monitoring and risk management, as well as the development of the ability to adapt different strategies to the unique conditions and needs of their activities is important.

To further strengthen financial stability and maintain competitiveness, it is worth considering opportunities for the implementation and improvement of innovative strategies. The emphasis on the implementation of advanced technologies can not only provide an advantage in the market, but also help solve possible challenges and make any organization less vulnerable to fluctuations in the external environment. The key drivers of success and sustainable development in the future may be the expansion of markets and the ability to implement innovations.

As a result of the study, a two-component methodological approach was developed, which makes it possible to optimize the assessment of the readiness of enterprises for development based on the calculation of the integral indicator of investment adequacy and the level of material cost. The integral indicator of investment adequacy was calculated based on the comparison of depreciation charges, equity, long-term loan capital, non-current assets with the size of capital investments. The level of material cost was determined based on the comparison of material and other operating costs with the income of the enterprise.

The proposed methodological approach was tested, which showed the low resource capacity of enterprises. The dynamics of the integral indicator of investment adequacy showed that in general for enterprises engaged in road freight transportation, its level is significantly lower than the normative value. This indicates the dominance of survival strategies, not development, among motor transport enterprises, and weak state policy, which does not stimulate investment activity in the legal environment. The advantage of the developed methodological approach is the possibility of using different components for each component, setting different weights in the integral assessment, and the possibility of adjusting target ranges.

Strategies for managing the development of the organization have been developed: a reserve management strategy, an asset diversification strategy, a profit reinvestment strategy, a strategy for optimizing liabilities and obligations, a risk-oriented liquidity management strategy, and an active liquidity management strategy. The implementation of combined strategies can be a key factor in achieving financial stability, optimal risk management, and the possibility of further development of organizations.

The destabilization of the geopolitical, socio-economic and security situation in the world has exacerbated the issue of sustainable development of regional economies and deepening their interaction. Ensuring the growth of the national economy as a whole and individual regions in particular makes the search for mechanisms aimed specifically at internal sources relevant. Spatial development is gaining particular importance due to the increasing role of transport infrastructure in ensuring the economic growth of regions.

The socio-economic heterogeneity of regional systems plays a decisive role in the formation of mechanisms for ensuring economic growth, which determines the diversity and contradictions of the effects of transport infrastructure on them. This is expressed in the fact that similar infrastructure facilities in different regions can have different organizational and economic effects. Thus, the appearance of a road can lead to the acceleration of material flows, thereby contributing to the development of the region's economy, and on the other hand, can stimulate an accelerated outflow of population. At the same time, the principles of managing social development and economic growth of regions obtained in practice do not allow to take into account the functional diversity and inconsistency of the effects of transport infrastructure and thereby complicate the search for effective mechanisms for ensuring regional development. growth based on the development of transport infrastructure.

Therefore, the study focuses on the actualization of the need to introduce innovative mechanisms into the economy of regions by determining the conditions necessary and sufficient for the implementation of the role of transport infrastructure as one of the sources of sustainable economic growth. In this regard, the knowledge of the essence and patterns of the mutual influence of transport and regional economic development is of great theoretical and practical interest.

1.8 CONDITIONS AND FEATURES OF ENSURING ECONOMIC GROWTH OF TRANSPORT INFRASTRUCTURE

At the beginning of our study, the task is to understand the conditions that allow transport infrastructure to be interconnected with regional economic systems, and to formulate a general concept of improving mechanisms for ensuring economic growth of regions based on the development of transport infrastructure.

It should be noted that one of the conditions, in particular, is the need to take into account the stability of the inflationary or recessionary gap in which various regional territorial entities are located. The state when prices in some regions exceed the equilibrium, and aggregate demand consistently lags behind supply, is accompanied in other regions by a state when prices are lower than the equilibrium, and demand is constantly not satisfied.

The difference in conditions also requires different mechanisms for activating economic growth. The main mechanism for stimulating growth in regions with insufficient supply is the stimulation of aggregate demand. It is characteristic of such regions that infrastructure development is carried out by private agents.

As an example, it is possible to cite the process of formation in the transport infrastructure of the function of ensuring the movement and distribution of goods (associated with the development of logistics and trade). Successful resolution of issues of stimulating growth on the basis of this mechanism in individual regions has initiated interest in it as a basis for regional development [1]. However, this mechanism, as a national practice of managing regional development, cannot always ensure the growth and development of the entire complex of regional economic systems.

The main feature of regions in the inflationary gap is that stimulating demand negatively affects their economic system, since demand already exceeds supply. Such regions need targeted state investments, including for the development of transport infrastructure. The main mechanisms here should be aimed at expanding the capabilities of regional industrial production, taking into account the established industry specifics and stimulating interregional industrial cooperation.

In addition to the above-mentioned features of infrastructure development in different regions, one should not lose sight of the implementation of state interests in general. An important factor in the formation of an economically integrated space is the transport infrastructure, which provides living conditions and economic activity in the regions, contributes to the creation of a favorable investment environment and is a condition for the expansion of industrial and social structures. The formation of economic integrity and the establishment of regular interactions mean the strengthening of interdependence and the development of interregional production interactions.

Thus, it can be noted that the dynamics of the development of transport infrastructure in some regions and the parameters of the economic situation in other regions are mutually determining (the situation in each region depends on decisions and events in other regions). At the same time, it is not possible to forget about the internal property of regional economic systems, namely the possibility of mutually beneficial exchange. And here the development of transport infrastructure expands the possibilities of beneficial interaction for all regions through the formation of a single economic space and the deepening of interregional cooperation.

In addition to the tasks of the global and national division of labor and the state task of connecting the country's territory, there are tasks of lower territorial levels. In this context, the development of transport infrastructure should be linked to the economic level of the regional system, the goals set for it, the scale of the existing and prospective production potential. During periods of crisis and post-crisis stages of development, the need for state participation in economic regulation increases sharply, since the state is the only agent capable of focusing on systemic goals under any circumstances. By implementing infrastructure projects and ensuring the integrity of the territory, the state contributes to reducing uncertainty and lays the basic foundation for overcoming crisis phenomena.

Next, it is possible to highlight the following essential condition that must be taken into account when forming mechanisms for activating regional growth. It consists in the mutual influence of economic systems of different levels and different regions, which can manifest itself in the interregional movement of population, resources, and investments. Thus, when implementing some regulatory influences in the field of transport infrastructure, it is necessary to take into account both internal and interregional flows of population and investment. In particular, the construction of highways in remote and depressed areas of the country is often accompanied by an outflow of population. That is, measures to develop transport infrastructure to achieve the goal of its attraction and consolidation should be accompanied by additional solutions that could stimulate such effects.

In addition to taking into account the conditions of regional economic systems and the specifics of interregional cooperation, another necessary condition for activating regional growth through the development of transport infrastructure is the inclusion of the regional aspect in the system of public administration. Studies show that the effectiveness of the same measure can be assessed differently by different agents. That is, the effectiveness of measures cannot be assessed according to conditional principles. For example, the construction of a relevant infrastructure facility may have a negative commercial effect, but a positive budgetary effect, for example, in the case when the city (regional) authorities decide to introduce a fee for the passage of commercial transport. Otherwise, the construction of a highway may require the demolition of some industrial building, but it can increase the transport accessibility and attractiveness of the territory for the population, stimulate the organization of new service enterprises along the route (public catering, car workshops), which can lead to an increase in the standard of living, income, population, land value and an increase in tax revenues. Thus, with negative effects for one entity, there are positive effects for others, including for local (regional) authorities. This indicates the importance of harmonizing different opinions and interests in planning and organizing the development of transport infrastructure. Therefore, it is advisable to involve regional and local administrations, as well as the local community, in assessing the effectiveness of measures and developing mechanisms for their implementation.

Thus, for the effective organization of transport infrastructure and improving the mechanisms for managing its impact on the economic development of regions, it is necessary to take into account all the above conditions, they are reflected in **Fig. 1.8**.

Thus, solving the above tasks allows ensuring the effectiveness of management mechanisms and the applicability of this toolkit for any regional territorial entities. A natural consequence of the existence of various connections and the complexity of the subject of research is the diversity of approaches to assessing the role of transport infrastructure and to the formation of mechanisms for ensuring economic growth of regions based on the development of transport infrastructure.

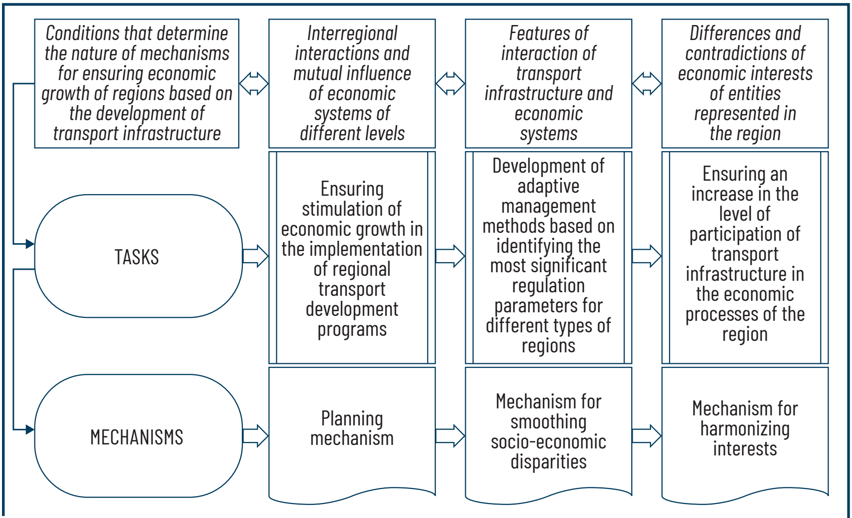

Fig. 1.8 General concept of improving mechanisms for ensuring economic growth of regions based on the development of transport infrastructure

Source: [2–4]

At the next stage of the study, it should be noted that the complexity of the transport infrastructure system, the multidirectional impact on both the economic and social systems determined a wide range of tools for forming mechanisms for ensuring regional growth based on the development of transport infrastructure. Having studied and generalized international experience, a systematization of methodological approaches and methods for forming mechanisms for the development of transport infrastructure was obtained (**Table 1.5**).

Table 1.5 Systematization of methodological approaches and methods for forming mechanisms for the development of transport infrastructure

Main aspects of the methodology	Development of management mechanisms	Advantages of approaches	Disadvantages of approaches
Descriptive approach – Technocratic method			
Analysis of the state and technical parameters of transport networks	Organization of interaction between modes of transport, harmonization of network operation	Systematization of transport activities	Complexity of comparison and quantification
Descriptive approach – Economic and geographical method			
Description, assessment of quantitative indicators proceed from economic sense	Regulation of the provision of infrastructure facilities in various territories	Comparison possibilities (ranking, assessment of dynamics)	Lack of consideration of spatial characteristics
Economic and analytical approach – Balance method			
Transport is considered as one of the branches of the economy through cost indicators	Improving the planning of the distribution of costs for the development of transport infrastructure	Depth of assessments and ideas about the parameters of the interconnections of industries	Laboriousness; the balanced scenario does not seem realistic enough
Economic and analytical approach – Capital method			
Cost and quantitative assessments of transport infrastructure as a capital resource	Regulation of interregional interactions on the use of transport infrastructure	Assessment of the role of transport in comparison with other resources (labor and capital)	Complexity of modeling spatial aspects
Economic and analytical approach – Investment method			
Cost assessments of transport infrastructure as an investment, providing for the return of invested funds	Organization of principles of joint financing of transport infrastructure development	Possibility of assessing the time horizon of the implementation of the Transport Infrastructure Development Project; the effectiveness of transport infrastructure development for individual companies	Contradictions between the guidelines for increasing the efficiency (return) of investments and stimulating regional development processes

Source: [5–7]

Therefore, it is possible to conclude that there are theoretical premises that are the basis for further research and analysis. Initially, it is assumed that the territorial location and economic significance of transport infrastructure are extremely heterogeneous, the level of its development differs significantly between regions. This necessitates the structuring of regions according to the ratio of economic characteristics and transport infrastructure indicators.

Therefore, for an adequate analysis and assessment of the impact of transport infrastructure on economic growth and, ultimately, for the formation of adaptive management methods, it is necessary to take into account the spatial structure in order to correctly understand the scale, nature of the inclusion of transport infrastructure in the regional economic system, the level of interregional connections. that it provides. On the other hand, it is important to take into account the main characteristics of the economic system within which the analysis of transport infrastructure takes place.

The essence of the analysis in this approach is not limited to the study of individual aspects of transport infrastructure or the economic environment. Spatial prerequisites for the formation and support of economic interactions have been identified, which, together with the assessment of the main parameters of the economic system, allows to put forward adequate hypotheses regarding the determination of the main factors and conditions of the economic development of the region and further determine the mechanisms by which this development can be carried out. Thus, the conditions considered above that allow transport infrastructure to be interconnected with regional economic systems and methodological approaches and methods for forming mechanisms for the development of transport infrastructure make it relevant to improve the mechanisms for implementing management functions presented in **Fig. 1.9**. Let's consider it an important scientific and managerial task to determine the parameters and conditions for the functioning of transport infrastructure necessary to stimulate the growth and development of a specific regional economic system. Thus, a fundamental basis is formed for the implementation of these mechanisms in practice, since the required state of transport infrastructure significantly depends on the current structure of the economy.

1.9 TRANSPORT INFRASTRUCTURE DEVELOPMENT PLANNING MECHANISM

To increase management efficiency, it is necessary to create and develop an information and analytical system for managing the implementation of programs at different levels [8]. The main tasks of such a system are: registration of analytical information in various forms (in terms of basic indicators; planned indicators, territories, etc.); design of transport development programs both in territorial and temporal terms with a breakdown into objects, nodes, directions and corridors with their current and prospective characteristics.

Such a large-scale and intensive process of forming programs in the system of public administration and local self-government was designed to solve problems related to determining the goals of regional and local authorities in terms of stimulating the economy and ensuring the focus of the territorial development process. However, it is worth saying that this mechanism is not completely perfect, since the formally approved requirements for ensuring territorial development were not properly supported by an understanding of the nature of the impact of transport infrastructure on the economic growth of individual territories, ways to enhance growth through transport infrastructure. One way to overcome such planning difficulties is to transfer planning goals from higher-level programs. In general, this approach corresponds to the established practice of setting management tasks from top to bottom.

It should be noted that the transformation of the principles of public administration will allow to increase awareness of significant interrelationships and develop mechanisms that will have a tangible impact on the development of territories. This will make it possible to increase the degree of compliance of the planned process of state and local administration with the goal of regional growth. It should be expected that the priority of the principle of territorial development will contribute to the most complete achievement of the goal of activating regional growth. At the same time, the system of indicators that will reflect the stages and levels of achieving the goal needs to be improved. The relevance of such improvement is dictated by the need to monitor the process of stimulating growth through the development of transport infrastructure, as well as the need for an objective assessment of the existing reality and options for territorial development.

The principle of purposefulness in application to planning activities for the development of territories provides that for territories with different characteristics a set of special actions or measures will be developed that will increase the efficiency of transport infrastructure as a source of growth. Efficiency here should be understood as the most close to the goal of economic growth of the territory through the use of material, labor and energy resources of the transport industry.

No less important is the group of principles related to an adequate description of existing socio-economic systems and the study of the features and patterns of their development, which provides for the strengthening of the regional vector and the systematization of knowledge about the genesis of socio-economic systems of various types. A substantial and meaningful understanding of the trends in the development of socio-economic systems, obtaining reliable ideas about their reactions to external influences is the most important condition for the implementation of the scientific principle in the process of territorial development planning. Based on reliable data, it is possible to develop measures that will be effective in different conditions for different regions. This ensures the implementation of the principle of reality. In the absence of scientific research of systemic reactions, it is impossible to develop effective mechanisms for improving socio-economic systems, it is impossible to determine the level of resource provision that can lead to solving problems. The choice of methods according to any other principle, such as the introduction of best practices, does not remove the question of understanding and assessing the consequences of implementing certain decisions. At the same time, the implementation of the principle of connection with the socio-economic life of the territory is not achieved, as indicated in the source [9]. Only under the condition of a meaningful analysis of the conditions for the development of regional economic systems and their connections with the transport infrastructure is it possible to select and develop such managerial influences that can significantly affect the system in a certain direction [10], which makes it possible to successfully implement the planned function of managing the development of transport infrastructure.

Another group can be those principles that contribute to the formation of the sustainability of the planning process for the development of organizational and economic relations of transport infrastructure. These include the principles of continuity and flexibility. Continuity should be understood as the ability of the management system at any time to determine the development process with varying degrees of success. It is obvious that in conditions of crisis, with changes in national and/or international macroeconomic trends, with changes in priorities and key principles of national policy, manageability and predictability may decrease, which requires a new scientific understanding and coordination with reality. Reproducing this stage in new, changed conditions and developing actions corresponding to the prevailing circumstances will be an expression of the principle of continuity. The flexibility of the public administration planning process is expressed in the ability to perceive and take into account such transformations in the current and subsequent planning cycles.

Therefore, it is possible to conclude that when implementing the priority of territorial development, it is necessary to deepen the established programs for the development of transport infrastructure through objective assessments of connections with socio-economic systems of different levels [11].

1.10 MECHANISM FOR SMOOTHING SOCIO-ECONOMIC DISPARITIES IN THE DEVELOPMENT

Earlier in our study, the need to perceive regional economic systems as complex and heterogeneous elements of the national system, in which multidirectional trends can operate, was substantiated. The features of economies in conditions of inflationary and recessionary gaps were highlighted. The essence of this division is that different properties of economic systems imply different mechanisms for activating economic growth. Since the territories of the recessionary gap are characterized by a state of overproduction, the main vector of approaching the equilibrium state is determined by economic theory to stimulate demand. Unlike recessionary territories, territories in the inflationary gap have a price level below the equilibrium, which hinders production processes, which ultimately leads to a significant excess of demand over supply. Therefore, the use of mechanisms for stimulating demand turns out to be detrimental for such territories due to the intensification of negative trends and an increase in deviations from the equilibrium state. It was also proven that this property of economies is systemic and affects not only the sphere of transport infrastructure.

For this reason, the formation of mechanisms for stimulating economic growth through the development of transport infrastructure should be adapted to the current situation in the regions. Such unevenness of the national economy makes it necessary to develop mechanisms that would improve the proportions of regional development and reduce gaps.

Based on the study of the conditions of economic growth in regions of the inflationary gap, it is possible to conclude that it is necessary to take into account important organizational conditions to ensure economic growth. Based on this, let's highlight the main groups of measures and areas of improvement for stimulating the economic growth of regional territorial entities in the inflationary gap through the development of transport infrastructure, in particular:

1. Stimulating the organization of primary processing of the flow of raw materials with coordination between private and regional business entities at the highest level of management; state support for industrial and infrastructure development. Mechanisms for harmonizing industry interests and interests of regional and local development in the formation of transport infrastructure:

— legislative registration of incentives for the creation of industrial transport networks taking into account the potential for regional growth; financial support for transport infrastructure development projects; control over targeted spending of funds; coordination of national-level interests in industrial development and regional-level interests in economic growth;

— development of transport infrastructure projects to ensure regional growth; financing; control over the technological and technical level of transport infrastructure project implementation; implementation of measures invested in stimulating industrial development;

— development of transport infrastructure projects at the regional level to ensure regional growth; interregional cooperation in the formation of transport infrastructure development projects; organization and implementation of a transport infrastructure development project; development of measures to stimulate the development of industry on the basis of the created infrastructure.

2. Stimulation of the production of final demand products, organizational work by local and regional administrations, production associations. Mechanism for the development of public transport infrastructure networks based on state funding:

— legislative provision of opportunities for interregional cooperation on infrastructure and industry development; financial support for transport infrastructure development projects; control over targeted spending of funds;

— development of transport infrastructure projects to ensure regional growth; organization and implementation of a transport infrastructure development project; development of measures to stimulate economic growth on the basis of the created infrastructure.

3. Purposeful formation of territorial and economic relations for the organization of production. Creation of conditions for attracting flows of technological transfers from highly developed regions. Mechanisms for preserving transport infrastructure and increasing its level of improvement and quality. At the initial stage, the construction of better roads and the organization of roadside service. Involvement of the most convenient places in economic turnover:

— financial support for projects to improve the existing transport infrastructure system; control over targeted spending;

— development of the regional level and financial support for projects to improve the existing transport infrastructure system; organization and implementation of projects to improve transport infrastructure; development of measures to stimulate economic growth based on the infrastructure being created.

Thus, it is possible to conclude that most regions have significant potential for significant economic growth. However, its implementation is associated with the implementation of a set of measures, and specialized for different groups of regions. Therefore, the next step is to develop mechanisms that ensure the most complete consideration of the interests of local communities in the growth of the local economy. The importance of developing a coordination mechanism is due to the fact that it is also necessary to ensure that national interests and the interests of individual manufacturing companies and industries are taken into account.

MECHANISM FOR HARMONIZING INTERESTS IN THE TRANSPORT INFRASTRUCTURE DEVELOPMENT SYSTEM

Transport infrastructure projects, oriented towards end-use, implement social functions and ensure the expansion of consumer demand. Thus, the involvement of local private entities in investment activities in the transport construction sector will contribute to the mitigation of the recessionary gap. The functioning of the mechanism for harmonizing the interests of stakeholders should be aimed at harmonizing two blocks of issues:

BLOCK I. This block is related to the conditions of investment activities, in particular, specific measures for the construction of transport infrastructure facilities should be determined (quantitative measurement of the expected length of roads of a certain class, special structures, etc.). On the other hand, these measures should be reflected in the financing part. Determine the terms and stages of direct implementation of infrastructure construction measures. Implementation of the project by a private agent with the involvement of its investment potential can contribute to increased savings due to more economical use of materials and increased labor productivity. During the implementation and upon completion of construction, the state's efforts should be aimed at monitoring the planned passage of construction stages and achieving the required level of quality of infrastructure formation. This is necessary because the private investor will focus on the fastest and most economical solution, which, in turn, may lead to disruption of a number of technological operations and a general decrease in the quality of facilities, and this is designed to make state control impossible at this stage.

BLOCK II. Determining the conditions for the return of investment to private agents. Here, the state as a stakeholder formalizes its interests in creating the prerequisites for socio-economic development. And, accordingly, the more significant the external positive effects of creating a transport infrastructure project, the higher the concession payments can be. To implement such impulses, taking into account the specifics of the territories, transport construction should be accompanied by measures to improve the urban environment, expand development and increase the accessibility and availability of transport infrastructure. To this end, organizations implementing an infrastructure project should interact with local authorities on issues of increasing the significance of the transport facility in social terms.

At the end of our study, it is possible to determine the positive effects of the practical implementation of improved mechanisms for ensuring economic growth of regions based on the development of transport infrastructure:

— change in the ratio of the number of enterprises in the regional center and in the rest of the region (reduction of concentration in the capital);

— increase in the number of companies localized in a certain industrial zone on the "periphery" of the region;

— decrease in the specific costs of each enterprise located on the periphery;

— reduction of negative consequences in areas of overconcentration of production while simultaneously reducing it;

— development of production cooperation due to an increase in the number of regional suppliers and contractors;

— increase in the share of meeting the needs of transport construction at the expense of local goods, resources, components;

— increase in industrial production in terms of volume;

— expansion of the range of own products, components, parts, etc., as an element of the country's national security in the field of goods;

— reduction in the physical volume of imports of certain categories of industrial goods;

— increase in the labor intensity and depth of raw material processing;

— growth in private investments (public finances) attracted to the production sector;

— increase in the introduction of innovative equipment and technologies.

CONCLUSIONS

Currently, an active scientific search is underway for tools and mechanisms for ensuring economic growth of regions at the expense of the country's internal forces. Transport infrastructure is considered one of the most important engines. The study:

— theoretical provisions were generalized and practical recommendations were developed for ensuring economic growth of regions based on the development of transport infrastructure;

— the main theoretical concepts of the role of transport infrastructure as a source of regional growth and development were considered and the conditions that must be taken into account for the formation of effective mechanisms for ensuring economic growth of regions based on the development of transport infrastructure were identified and described: the need to take into account the mutual influence of economic systems at different levels; the need to analyze the interrelationships of transport infrastructure and the regional economic system; the need to coordinate the interests of various agents (stakeholders) represented in the region;

— an analysis and generalization of existing approaches to the formation of mechanisms for ensuring growth based on the development of the transport infrastructure of the system was carried out and it was established that they mainly take into account to a small extent the participation and nature of the prevailing organizational and economic relations of the transport infrastructure and the local economic system.

The above-described conditions, in combination with the tasks set and their solution, allowed to improve and form a number of mechanisms that took shape in the concept of improving the mechanisms of economic growth of regions based on the development of transport infrastructure.

The proposed mechanisms can serve as the basis for the development of management decisions that will be different in content (attraction of private or public investments in infrastructure projects;

development of industrial transport or transport infrastructure of final demand; development of the distribution functions of transport infrastructure or transport). interactions that provide integration and cooperative interregional production links) for each individual regional or local economic system, but are united by the goal of ensuring economic growth of regions based on the development of transport infrastructure.

CONFLICT OF INTEREST

There is no conflict of interest. The authors declare that they have no financial, academic, personal or other conflicts of interest that could influence the content, results or interpretation of this study.

USE OF ARTIFICIAL INTELLIGENCE

The authors confirm that they did not use artificial intelligence technologies in creating the submitted work.

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2 INTEGRATION OF INCLUSIVE ENGINEERING PRINCIPLES AND CRAFT TECHNOLOGIES IN THE DESIGN OF FOOD SERVICE FACILITIES IN THE CONTEXT OF POST-WAR RECONSTRUCTION OF UKRAINE: BUILDING MATERIALS, ARCHITECTURAL SOLUTIONS, QUALITY, SAFETY

ABSTRACT

The study is devoted to the integration of inclusive engineering principles and craft technologies in the design of food service facilities within the context of Ukraine's post-war reconstruction. The primary focus is on the environmentally responsible selection of building materials (wood, clay, straw, hemp fiber, arbolite concrete) and architectural solutions that address the needs of vulnerable population groups, including veterans, persons with disabilities, and internally displaced persons. Emphasis is placed on ensuring quality standards, safety (notably HACCP), and hygiene, which are critically important in the food service sector.

In the context of the war in Ukraine, which has caused extensive infrastructure destruction, there is a need to create a new architectural and construction culture oriented toward sustainable development, social inclusivity, and the preservation of local identity. The proposed approach combines circular economy principles (material reuse), craft technologies (hand labor, local resources), and inclusive design (barrier-free access, adaptive furniture, sensory comfort). This contributes to the economic recovery of communities, reduces environmental impact, and creates culturally significant spaces.

The objective is to develop a methodology for integrating inclusive engineering and craft technologies to create accessible, safe, and authentic food service facilities.

The study includes an analysis of the thermophysical characteristics of building materials such as density, heat capacity, thermal conductivity, and vapor permeability, along with a comparison of their technological complexity, environmental friendliness, and economic feasibility. Results demonstrate the advantages of materials with high heat capacity (reed panels, arbolite) for energy efficiency and low thermal conductivity (cellulose insulation, foam glass) for thermal insulation. Architectural solutions encompass ramps, wide corridors, zoning, anti-slip surfaces, and hygienic materials compliant with HACCP standards.

This approach ensures the creation of sustainable, safe, and socially inclusive spaces that support the local economy, reduce ecological footprint, and contribute to the preservation of Ukrainian identity. It is recommended to adapt regulatory frameworks and educational programs to promote these principles.

KEYWORDS

Inclusive engineering, craft technologies, design, architectural solutions, building materials, sustainable development, post-war reconstruction of Ukraine, food service facilities, quality, safety, HACCP.

The war in Ukraine has caused extensive destruction [1] to the housing stock and social infrastructure facilities, demolishing millions of square meters of residential buildings, schools, hospitals, public structures, and cultural heritage sites. In the face of such losses, the task arises not only of physical reconstruction but also of forming a new architectural and construction culture focused on the principles of sustainable development, environmental responsibility, and social sensitivity. Considering resource limitations, rising costs of building materials, and the urgent need for fast and efficient solutions, the reuse of building materials obtained from the demolition of destroyed structures becomes especially important [2–4].

In this context, the restoration of social infrastructure requires the implementation of new approaches to the design of public facilities – primarily food service establishments – that take into account the needs of vulnerable population groups, as well as quality requirements [5–7] and the safety of the food environment [7, 8]. This approach should be based on four strategic directions:

– social inclusivity, which implies the creation of a barrier-free environment accessible to all population categories, including persons with disabilities, elderly people, veterans, and internally displaced persons [9–12];

– environmental responsibility, realized through the use of renewable natural resources, reuse of building materials [2–4], and minimization of the carbon footprint at all stages of construction;

– local identity, expressed in the preservation of cultural characteristics, architectural traditions, and the material heritage [13] of a specific community;

– sanitary and hygienic safety [7, 8, 14], ensured through the implementation of quality management systems [6, 7, 15] and HACCP [7, 8, 15], which regulate spatial, engineering-technological, and operational solutions in food service establishments in accordance with food safety principles and hygiene standards.

2.1 NEW CONSTRUCTION GUIDELINES IN THE PROCESS OF UKRAINE'S RECONSTRUCTION

In the post-war period [16], when resources are limited and the need for prompt, effective, and economically viable solutions is critical, approaches based on the circular economy gain special importance. The reuse of building materials recovered from demolished structures allows not only to reduce the demand for new resources and lower transportation and disposal costs but also significantly decreases environmental impact [2, 3, 17–19]. This becomes particularly relevant in designing social infrastructure facilities, especially food service establishments, which require fast, high-quality, and accessible reconstruction [10–12].

At the same time, physical reconstruction must be accompanied by a paradigm shift: from "technocratic restoration" [2, 4, 13] to "human-centered reconstruction", which takes into account social sensitivity and the needs of vulnerable groups – including persons with limited mobility, veterans, elderly people, children, and internally displaced persons [11, 12, 14, 20, 21]. In this context, inclusive engineering design is regarded as a necessary prerequisite for creating environments that are not only accessible but also adapted to diverse physical, sensory, and cognitive needs [9–12, 14, 20, 21].

Craft technologies [14], based on manual labor, local knowledge, and the use of natural materials, play a special role in this approach. Their advantage lies in high adaptability to local contexts: from small communities and rural areas to temporary facilities, including field kitchens, mobile canteens, and modular cafés. Combined with inclusive engineering, they enable the creation of spatial solutions that are environmentally balanced, technically simple to implement, and socially acceptable. Moreover, this approach encourages community involvement in reconstruction processes, fostering economic recovery at the local level [11, 12, 14].

Another critically important aspect is the preservation and restoration of local identity, which for decades has suffered destruction and homogenization. Local identity includes architectural styles, materials, color schemes, decorative motifs, landscape features, linguistic and cultural codes, and social rituals that form the unique character of each territory, creating a distinct "national style" [22]. In the design of food service establishments, this is expressed, for example, through the use of traditional forms (such as clay facades, wooden elements, ceramic inserts), the introduction of ethnodesign elements in interiors, and the use of local products in menus.

Combined with inclusive and ecological approaches, local identity creates the foundation for culturally significant, socially cohesive, and sustainable gastronomic spaces that reflect the uniqueness of the community while meeting modern technical, ergonomic, and sanitary-hygienic standards. This allows avoiding the stereotypical "standardized design" characteristic of "soviet architecture" and instead promotes a conscious transformation of space through the lens of authenticity, safety, and quality. It imparts a unique character to the community, supports its historical memory, roots social bonds, and contributes to sustainable development.

2.1.1 THE ROLE OF CRAFT APPROACHES IN THE CONTEXT OF THE CIRCULAR ECONOMY

In the process of Ukraine's post-war reconstruction, craft approaches [14] are gradually gaining status as one of the key vectors for implementing the principles of the circular economy [4, 23, 24], especially in the context of architectural and engineering design of social facilities — particularly food service establishments. These approaches imply a shift away from the linear model of "production — consumption — disposal" toward a cyclical model, where materials receive a second life and architectural solutions focus on restoration, reuse, recycling, and prolonged service life [23].

Craft technologies involve the manual or semi-manual production of building materials with maximal use of local resources — natural, renewable, and low-toxicity. This not only reduces dependence on industrial supply chains but also allows flexible adaptation of designs to local conditions and community needs. In the design of food service facilities, this approach offers several advantages:

— enables the creation of aesthetically expressive, individualized interiors featuring elements of regional style (clay, wood, straw, ceramics, linen textiles);

— allows for the reuse of materials (e.g., bricks, wood, stone) for facades, bar areas, furniture, or decorative elements;

— contributes to reducing the carbon footprint and the volume of construction waste, aligning with the ecological goals of reconstruction [4, 23].

At the same time, the material life cycle — from the original source to reintegration into a new structure — becomes a central category in engineering design [9]. Within this approach, not only the primary parameters of the material (strength, thermal insulation, moisture resistance) are planned, but also its potential for further utilization, reclamation, or reassembly.

The application of craft technologies is particularly effective when combined with modular constructions and adaptive architecture, enabling the creation of both permanent and temporary food service facilities – mobile canteens, summer kitchens, social cafés – that account for seasonality, population migration, or fluctuating demand.

Engaging the community – local artisans, small entrepreneurs, and craftsmen – in this process not only supports the local economy but also fosters social responsibility in projects, enhances their cultural rootedness, and stimulates the development of craft food productions closely linked to the food service establishment.

Thus, craft technologies in the architecture of food service facilities in post-war Ukraine represent not only aesthetics and tradition but also a strategic resource for sustainable reconstruction, integrated into the principles of ecological feasibility, economic efficiency, and social inclusion.

2.1.2 THE ROLE OF INCLUSIVITY IN DESIGN

Inclusive engineering in Ukraine's post-war reconstruction acquires particular importance as an interdisciplinary approach that combines technical, architectural, social, and humanitarian dimensions in the design, construction, and operation of the physical environment [9, 11, 12]. Its key goal is to create spaces that are physically, sensorially, and psychologically accessible, functional, safe, and comfortable for all user categories – regardless of age, gender, physical or cognitive characteristics [10, 14, 25].

Inclusivity becomes especially relevant in the design of food service establishments [5, 11, 14], which perform not only service functions but also social, rehabilitative, and integrative roles. In the context of the return to peaceful life of a significant number of veterans [26], persons with disabilities, and internally displaced persons, food service facilities become spaces for meeting, socializing, employment, and support, requiring a particularly sensitive architectural approach.

This approach goes beyond mere formal compliance with technical accessibility standards and includes a profound rethinking of architectural-spatial models [27], engineering systems [9, 27], and technological processes, taking into account the real-life experiences of users. The principle "the environment must adapt to the person, not vice versa" demands the involvement of specialists in ergonomics, psychology, interior design, and medical rehabilitation.

In establishments that combine food service functions with craft production (such as bakeries, mini-workshops, or family cafés), inclusivity acquires an additional dimension – production accessibility. This concerns not only the physical adaptation of work areas (surface heights, safe equipment placement, presence of tactile or visual markers) but also an inclusive work culture that supports the participation of people with functional limitations in production and service processes. This promotes not only economic integration but also reduces labor market discrimination, increases autonomy, and fosters local entrepreneurship.

Thus, inclusive engineering in the design of food service establishments is not only a tool for spatial accessibility [14, 28] but also a powerful mechanism for creating a just, "humane", and sustainable environment where technical solutions meet real user needs and architecture becomes an instrument of social cohesion and dignity.

2.1.3 RELEVANCE OF THE RESEARCH DIRECTION

The full-scale war in Ukraine has caused a profound transformation of the social, engineering, and architectural environment, posing new demands on the spatial design, construction, and operation of public facilities. Today, the task is not only the physical reconstruction of damaged housing and social infrastructure but also the rethinking of approaches to architectural and structural modeling, taking into account the principles of sustainable development, environmental responsibility, social justice, and cultural rootedness.

In conditions of resource scarcity, rapid urbanization, and the need for quick solutions, inclusive engineering practices oriented toward the needs of a wide range of users — especially persons with disabilities, combat veterans, elderly people, children, and internally displaced persons — gain special relevance. The growing share of the population with functional limitations requires fundamentally new approaches to shaping the physical environment, where accessibility, comfort, safety, and adaptability are considered the basic characteristics of spatial quality.

At the same time, the role of craft technologies is increasing — as an alternative to mass industrial construction — that ensures the use of local resources, consideration of the local context, community involvement in reconstruction, and the restoration of local identity. The combination of manual production methods, artisanal practices, and modern materials science approaches creates conditions for forming a more flexible, ecological, and socially sensitive architectural environment.

At the intersection of inclusive engineering and craft technologies, a promising research direction is emerging that allows the design of food service establishments not only as functional objects but also as centers of social integration, cultural renewal, and spatial justice. These facilities must meet criteria of environmental sustainability, technological adaptability, economic feasibility, and regulatory safety, taking into account quality standards and HACCP principles.

In this context, the aim of the research is the integration of inclusive engineering principles and craft technologies into the design process of food service establishments with an emphasis on the selection of building materials, architectural solutions, and spatial organization in the context of Ukraine's post-war reconstruction. Special attention is paid to safety, quality, social sensitivity, environmental responsibility, and cultural appropriateness.

Research objectives:

— to analyze current challenges and trends in the field of inclusive engineering, particularly considering the needs of persons with disabilities, veterans, and internally displaced persons;

— to investigate the potential of craft technologies for implementing circular economy principles and preserving local identity in construction;

— to develop methodological approaches for combining inclusive engineering and craft practices in the production of building materials and the implementation of architectural solutions involving local resources;

– to assess the impact of the proposed approach on the level of social integration, environmental sustainability, and economic efficiency within food service projects;

– to formulate recommendations for adapting regulatory frameworks and educational programs to disseminate principles of inclusive and craft approaches in architectural design and construction practice.

2.2 MATERIALS AND METHODS

2.2.1 MATERIALS

The study analyzed building materials that comply with the principles of the circular economy, inclusive engineering, and craft technologies, taking into account the requirements of DSTU 9191:2022 [29]. Building products were characterized by origin (organic and inorganic) and type (concretes, arbolites, fibrous, bituminous, etc.), as well as suitability for designing food service establishments in the context of Ukraine's post-war reconstruction. The thermophysical properties of the building materials were evaluated:

– density (ρ_0) – from 35 to 1000 kg/m^3;

– specific heat capacity (C) – from 0.84 to 2.3 kJ/(kg·K);

– declared thermal conductivity (λ_0) – from 0.039 to 0.16 W/(m·K);

– calculated moisture content by mass (w), for operating condition A – from 0.1 to 16%; for operating condition B – from 0.2 to 24%;

– calculated thermal conductivity (λ_d) for operating condition A – from 0.045 to 0.24 W/(m·K); for operating condition B – from 0.048 to 0.3 W/(m·K);

– calculated heat absorption coefficient (s) for operating condition A – from 0.41 to 6.75 W/(m^2·K); for operating condition B – from 0.45 to 7.7 W/(m^2·K);

– calculated vapor permeability (δ) for operating conditions A and B – from 0.002 to 0.49 mg/(m·h·Pa).

The selection of materials was based on their environmental friendliness (low carbon footprint, biodegradability), local availability, hygienic compliance (adherence to HACCP principles), as well as suitability for craft production, which promotes community involvement.

2.2.2 METHODS

The research methodology involved a comprehensive approach to assessing materials and architectural solutions for the creation of inclusive, environmentally sustainable, and safe food service establishments. A comparative analysis of the thermophysical characteristics of materials according to DSTU 9191:2022 [29] was applied to determine their effectiveness in energy-efficient structures.

The evaluation criteria included:

1) technological accessibility (ease of production, use of local resources);

2) environmental sustainability (possibility of reuse, low environmental impact);

3) social inclusivity (adaptability to the needs of vulnerable groups, including persons with disabilities and veterans);

4) economic feasibility (optimization of construction costs).

Additionally, the compliance of materials and solutions with safety and hygiene standards (HACCP) was analyzed, as well as their potential to implement local identity through ethno-design. Both quantitative methods (analysis of thermophysical parameters) and qualitative methods (comparison of architectural solutions such as zoning, barrier-free access, non-slip coatings) were used for evaluation.

2.3 RESULTS

2.3.1 PRINCIPLES OF INCLUSIVE ENGINEERING IN THE FIELD OF BUILDING MATERIALS

In the modern competitive environment, craft productions, like food service establishments, face the need to increase business efficiency to maintain their viability and adapt to social changes. Considering factors such as employee health, motivation, inclusivity, and professional skill development becomes not only socially necessary but also economically viable.

Inclusive engineering in the field of building materials involves a systematic integration that combines technical, social, and economic aspects [20] aimed at ensuring a barrier-free environment and improving the quality of working conditions.

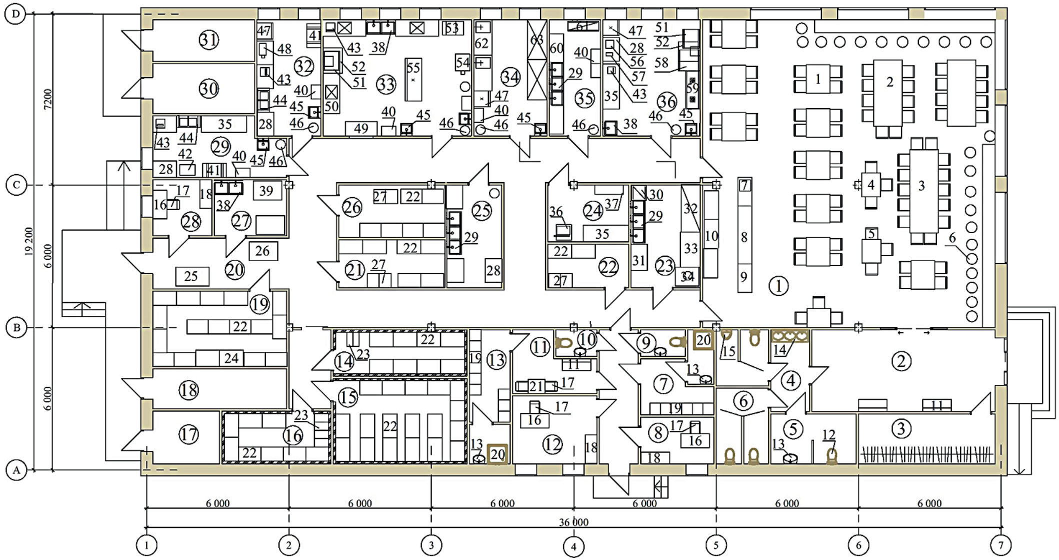
Technical aspects of implementing inclusive solutions in food establishments include architectural and planning measures (ramps with a slope of up to 8%, handrails, non-slip coverings, designated parking spaces), engineering and technical solutions (standardized ventilation and air conditioning systems, energy-efficient heating, alternative energy sources), ergonomic equipment (adjustable furniture, lifts), information tools (Braille, sound systems), and specialized premises (accessible lobbies, restrooms, cloakrooms) [20] (**Fig. 2.1**).

Social aspects include rehabilitation practices, staff motivation, ensuring inclusivity, and developing employee competencies, which together form a comprehensive model of sustainable production [20, 30–32].

Rehabilitation – one of the key aspects of the engineering approach to work organization – involves not only adapting work areas for people with disabilities but also creating conditions for the social reintegration of groups such as war veterans [32]. This includes the accessibility of the architectural environment, specialized equipment, compliance with microclimate parameters [14], and staff training to work in an inclusive environment.

Employee motivation in craft productions is closely related to corporate culture, which takes into account the social significance of work, its contribution to the community, and the personal value of the employee. This is implemented through clearly defined goals, training programs, and opportunities for professional growth [33].

Inclusivity as a strategy covers not only physical accessibility but also the creation of cultural diversity. This requires staff training in cultural and gender sensitivity, which is the basis for forming a safe and supportive environment [33]. Employee competence – another key element of the engineering approach – concerns not only technical skills but also the development of communication, organizational, and adaptive abilities necessary for work in the modern production environment [31, 33].



1 – restaurant hall; 2 – vestibule; 3 – cloakroom; 4 – restroom; 5 – restroom for persons with reduced mobility; 6 – guest restrooms; 7 – male staff cloakroom; 8 – office; 9 – male staff restrooms; 10 – female staff restrooms; 11 – staff room; 12 – director's office; 13 – female staff cloakroom; 14 – refrigerated room for meat and fish; 15 – refrigerated room for vegetables, fruits, and greens; 16 – refrigerated room for dairy, gastronomy, and eggs; 17 – exhaust ventilation room; 18 – heat station; 19 – dry goods storeroom; 20 – loading area; 21 – vegetable and root vegetable storeroom; 22 – janitorial inventory and equipment room; 23 – dishwashing area; 24 – bread slicing room; 25 – egg processing room; 26 – dry products storeroom; 27 – ware and inventory washing and storage area; 28 – storekeeper's office; 29 – vegetable processing room; 30 – electrical room; 31 – supply ventilation room; 32 – meat and fish processing room; 33 – pastry room; 34 – cold kitchen; 35 – kitchenware washing area; 36 – hot kitchen

Fig. 2.1 Floor plan at elevation 0.000 of a foodservice enterprise
Source: [20]

Finally, ensuring team stability, reducing staff turnover, and improving brand image require the implementation of long-term strategies that combine social responsibility and economic efficiency [30, 33].

The economic aspects of inclusive solutions in food service establishments involve reducing staff turnover and lowering recruitment and training costs by creating a comfortable working environment. The requirement to provide at least 5% of seats in dining areas for wheelchair users expands the customer base and increases profitability, while the possibility of receiving state support encourages the implementation of accessible solutions [20].

Thus, the principles of inclusive engineering in the field of building materials are not limited to technical aspects but also cover social, psychological, cultural, and economic parameters that form the foundation of a sustainable, safe, and "human-centered" production environment.

2.3.2 PRINCIPLES OF CRAFT TECHNOLOGIES IN THE FIELD OF BUILDING MATERIALS

In the post-war period of Ukraine's reconstruction, there is an increasing interest in the use of local natural building materials — wood, straw, clay, hemp fiber, and others. Importantly, these materials harmoniously combine environmental friendliness, locality, and the possibility of manual production — key characteristics of the craft approach that align with the ideas of the circular economy. Traditional Ukrainian structures, such as adobe and rammed clay blocks, demonstrate high adaptability and durability. Their potential for reuse, recycling, or complete biodegradation makes them ideal for sustainable construction, especially in socially oriented and rehabilitation projects of post-war recovery.

Modern scientific research highlights the relevance of bio-based composites, in particular hempcrete, which is characterized by a low carbon footprint, high thermal insulation, hygroscopicity, and biodegradability [34].

Another promising direction is wood-concrete (arbolite) — lightweight concrete based on wood chips and plant fibers with gypsum binder [35], which provides excellent thermal insulation properties. Local production based on wood waste makes this technology accessible to small communities and enterprises.

Rammed clay and adobe technologies, deeply rooted in Ukrainian architecture, are being revived today as environmentally friendly and affordable construction methods [36]. Modern developments combine traditional methods with innovative solutions, such as the use of straw blocks, "super-adobe" technology, and other natural materials. There are already modern eco-houses in Ukraine made of adobe, confirming the viability of these approaches.

A distinctive feature of using these materials is their craft nature — local raw materials, small production volumes, involvement of local communities, and the possibility of rapid implementation of innovations [35]. This not only supports the development of crafts and the local economy but also aligns with the principles of inclusive engineering. In particular, the simplicity and accessibility of producing clay or arbolite blocks make it possible to involve different social groups in construction, including people with disabilities.

In the context of post-war reconstruction, this integration of craft technologies and the principles of inclusive design is especially relevant for creating food service establishments that should be not only energy-efficient and environmentally friendly but also maximally accessible. The use of natural materials contributes to a healthy microclimate, reduces the impact of chemicals and temperature fluctuations, which is important for vulnerable population groups.

Fig. 2.2–2.10 present the calculated thermophysical characteristics of building materials – products made from natural organic and inorganic raw materials in accordance with the requirements of DSTU 9191:2022 [29]. The comparative characteristics of the thermal insulation material take into account its density (ρ); heat capacity (C); thermal conductivity (λ); moisture content by mass (w); heat absorption coefficient (s); and vapor permeability (δ) under operating conditions (A, B). According to DBN V.2.6-31:2021 [37], operating conditions A are applied to internal walls and enclosing structures in dry rooms, while B – to external walls and structures operating in normal, humid, or wet environments.

According to thermophysical properties, building products can be classified into three categories:

1) high heat capacity ($C \geq 2.0$ kJ/(kg·K));

2) medium heat capacity ($C \approx 1.0$–2.0 kJ/(kg·K));

3) low heat capacity ($C \leq 1.0$ kJ/(kg·K)).

Products with high heat capacity ($C \geq 2.0$ kJ/(kg·K)):

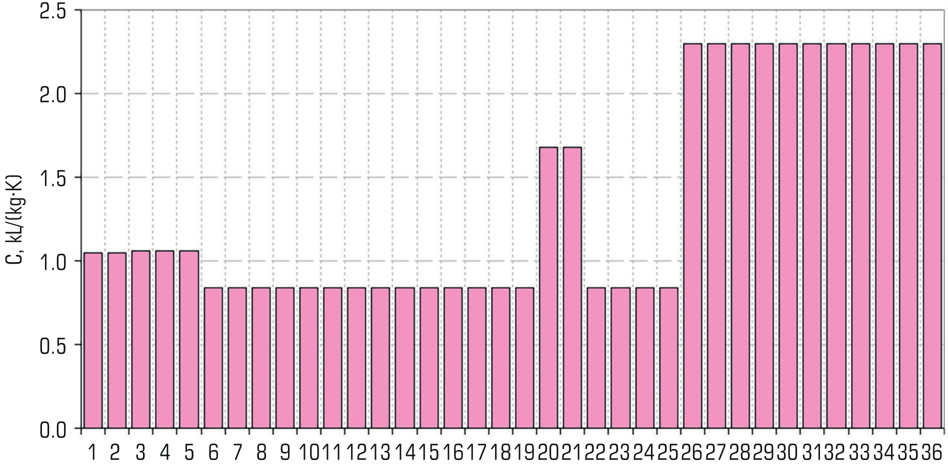
– reed thermal insulation boards – 2.3 kJ/(kg·K), characterized by high heat capacity, which ensures high heat retention ability. They are used as natural thermal insulation materials in walls, floors, and roofs, especially in environmentally oriented construction. Due to their natural composition, they have good vapor permeability, help regulate indoor humidity, and create comfortable microclimatic conditions. In addition to thermal insulation, these boards provide environmental friendliness and biodegradability, although they may require additional protection against moisture and pests. The use of reed boards is advisable in projects focused on sustainable development and natural materials;

– fiberboard and particleboard – 2.3 kJ/(kg·K), characterized by high heat capacity, suitable for interiors and internal partitions where temperature regulation without sharp fluctuations is needed. These materials have high vapor permeability, which helps maintain optimal humidity levels. Thanks to their natural composition, the boards are environmentally friendly, have good sound insulation properties, but require protection from moisture and pests. Ideal for projects emphasizing a healthy environment and energy efficiency;

– wood concrete (arbolite) products on Portland cement – 2.3 kJ/(kg·K), used for load-bearing and self-supporting walls of low-rise buildings; enclosing structures where a combination of thermal insulation and strength is important; ecological facilities (housing, public buildings, inclusive spaces) – due to natural fillers and vapor permeability; structures where smooth leveling of temperature fluctuations is needed – arbolite accumulates heat during the day and releases it at night. Arbolite works well in external walls, especially in regions with sharp daily temperature fluctuations, and in passive heating systems.

Products with high heat capacity ($C \geq 2.0$ kJ/(kg·K)) effectively accumulate and release heat, ensuring a stable microclimate and comfort indoors even under significant daily temperature fluctuations, making them optimal for energy-efficient and environmentally friendly constructions.

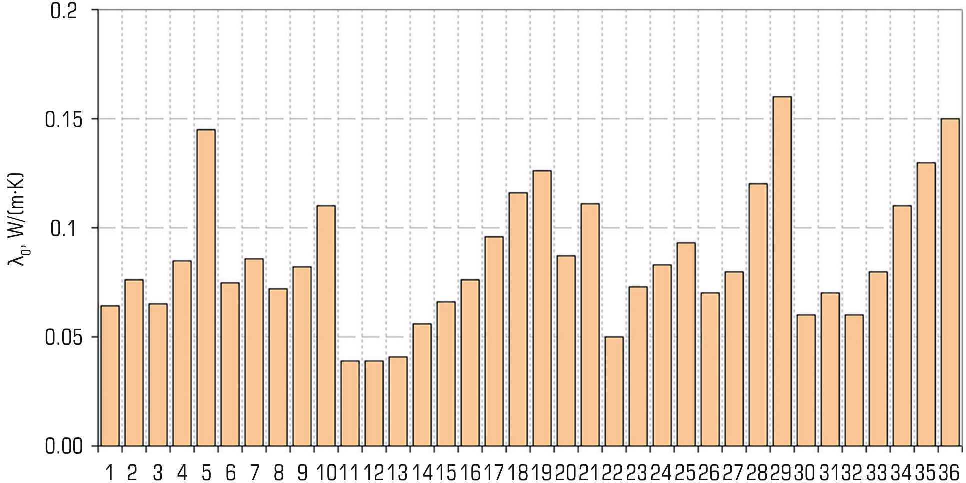
Materials with high heat capacity are especially effective in passive heating systems and in regions with a continental climate.



1 – perlite-phosphogel products (200)*; 2 – perlite-phosphogel products (300); 3 – wall polystyrene concrete blocks (200); 4 – wall polystyrene concrete blocks (300); 5 – wall polystyrene concrete blocks (600); 6 – perlite-cement and perlite-gypsum thermal insulation products (300); 7 – perlite-cement and perlite-gypsum thermal insulation products (450); 8 – perlite-bentonite thermal insulation products (250); 9 – perlite-bentonite thermal insulation products (300); 10 – perlite-bentonite thermal insulation products (400); 11 – cellulose insulation (35); 12 – cellulose insulation (50); 13 – cellulose insulation (65); 14 – cellulose insulation (100); 15 – cement-polystyrene products (250); 16 – cement-polystyrene products (300); 17 – cement-polystyrene products (400); 18 – cement-polystyrene products (500); 19 – cement-polystyrene products (550); 20 – perlite-bitumen thermal insulation products (300); 21 – perlite-bitumen thermal insulation products (400); 22 – foam glass products (120); 23 – silicate-cement blocks (300); 24 – silicate-cement blocks (400); 25 – silicate-cement blocks (500); 26 – wood concrete (arbolite) products on Portland cement (300); 27 – wood concrete (arbolite) products on Portland cement (400); 28 – wood concrete (arbolite) products on Portland cement (600); 29 – wood concrete (arbolite) products on Portland cement (800); 30 – reed thermal insulation boards (200); 31 – reed thermal insulation boards (300); 32 – fiberboard and particleboard (200); 33 – fiberboard and particleboard (400); 34 – fiberboard and particleboard (600); 35 – fiberboard and particleboard (800); 36 – fiberboard and particleboard (1000)

(material density, ρ_0, kg/m^3)

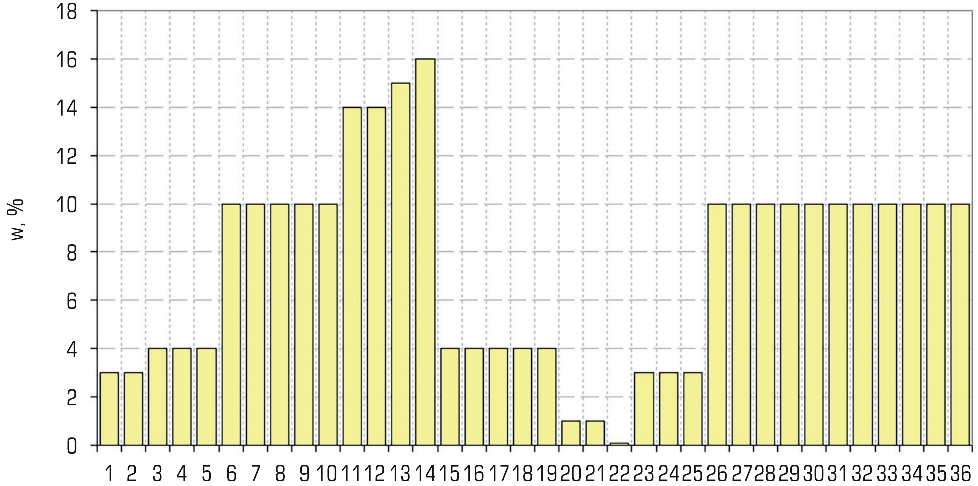
Fig. 2.2 Comparison of the heat capacity of products made from natural organic and inorganic raw materials (C, kJ/(kg•K)) depending on the density of materials (ρ_0, kg/m^3) in the dry state



1 – perlite-phosphogel products (200)*; 2 – perlite-phosphogel products (300); 3 – wall polystyrene concrete blocks (200); 4 – wall polystyrene concrete blocks (300); 5 – wall polystyrene concrete blocks (600); 6 – perlite-cement and perlite-gypsum thermal insulation products (300); 7 – perlite-cement and perlite-gypsum thermal insulation products (450); 8 – perlite-bentonite thermal insulation products (250); 9 – perlite-bentonite thermal insulation products (300); 10 – perlite-bentonite thermal insulation products (400); 11 – cellulose insulation (35); 12 – cellulose insulation (50); 13 – cellulose insulation (65); 14 – cellulose insulation (100); 15 – cement-polystyrene products (250); 16 – cement-polystyrene products (300); 17 – cement-polystyrene products (400); 18 – cement-polystyrene products (500); 19 – cement-polystyrene products (550); 20 – perlite-bitumen thermal insulation products (300); 21 – perlite-bitumen thermal insulation products (400); 22 – foam glass products (120); 23 – silicate-cement blocks (300); 24 – silicate-cement blocks (400); 25 – silicate-cement blocks (500); 26 – wood concrete (arbolite) products on Portland cement (300); 27 – wood concrete (arbolite) products on Portland cement (400); 28 – wood concrete (arbolite) products on Portland cement (600); 29 – wood concrete (arbolite) products on Portland cement (800); 30 – reed thermal insulation boards (200); 31 – reed thermal insulation boards (300); 32 – fiberboard and particleboard (200); 33 – fiberboard and particleboard (400); 34 – fiberboard and particleboard (600); 35 – fiberboard and particleboard (800); 36 – fiberboard and particleboard (1000)

(material density, ρ_0, kg/m^3)

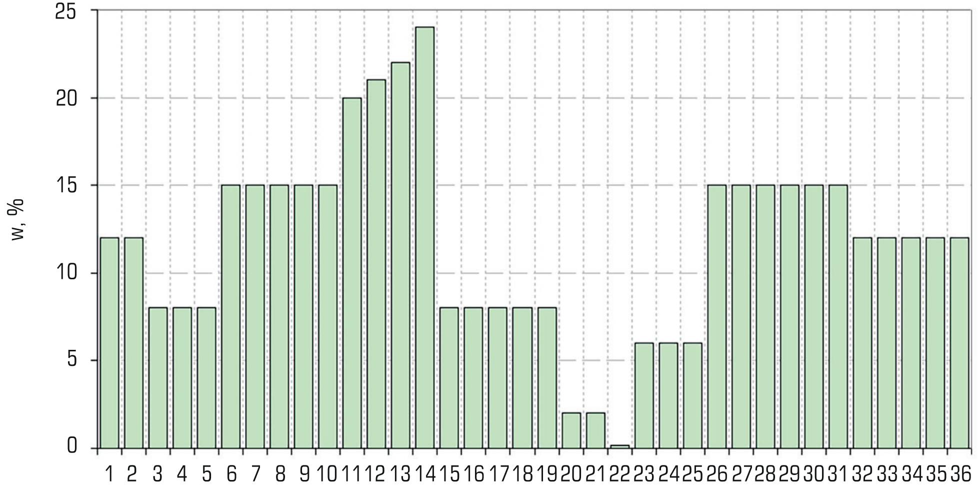
Fig. 2.3 Comparison of the declared thermal conductivity of products made from natural organic and inorganic raw materials (λ_0, W/(m•K)) depending on the density of materials (ρ_0, kg/m^3) in the dry state



1 – perlite-phosphogel products (200)*; 2 – perlite-phosphogel products (300); 3 – wall polystyrene concrete blocks (200); 4 – wall polystyrene concrete blocks (300); 5 – wall polystyrene concrete blocks (600); 6 – perlite-cement and perlite-gypsum thermal insulation products (300); 7 – perlite-cement and perlite-gypsum thermal insulation products (450); 8 – perlite-bentonite thermal insulation products (250); 9 – perlite-bentonite thermal insulation products (300); 10 – perlite-bentonite thermal insulation products (400); 11 – cellulose insulation (35); 12 – cellulose insulation (50); 13 – cellulose insulation (65); 14 – cellulose insulation (100); 15 – cement-polystyrene products (250); 16 – cement-polystyrene products (300); 17 – cement-polystyrene products (400); 18 – cement-polystyrene products (500); 19 – cement-polystyrene products (550); 20 – perlite-bitumen thermal insulation products (300); 21 – perlite-bitumen thermal insulation products (400); 22 – foam glass products (120); 23 – silicate-cement blocks (300); 24 – silicate-cement blocks (400); 25 – silicate-cement blocks (500); 26 – wood concrete (arbolite) products on Portland cement (300); 27 – wood concrete (arbolite) products on Portland cement (400); 28 – wood concrete (arbolite) products on Portland cement (600); 29 – wood concrete (arbolite) products on Portland cement (800); 30 – reed thermal insulation boards (200); 31 – reed thermal insulation boards (300); 32 – fiberboard and particleboard (200); 33 – fiberboard and particleboard (400); 34 – fiberboard and particleboard (600); 35 – fiberboard and particleboard (800); 36 – fiberboard and particleboard (1000)

*(*material density*, ρ_0, *kg/m*^{3})

Fig. 2.4 Comparison of the calculated mass moisture content of products made from natural organic and inorganic raw materials (w, %) under service conditions (A), depending on the density of materials (ρ_0, kg/m^3)



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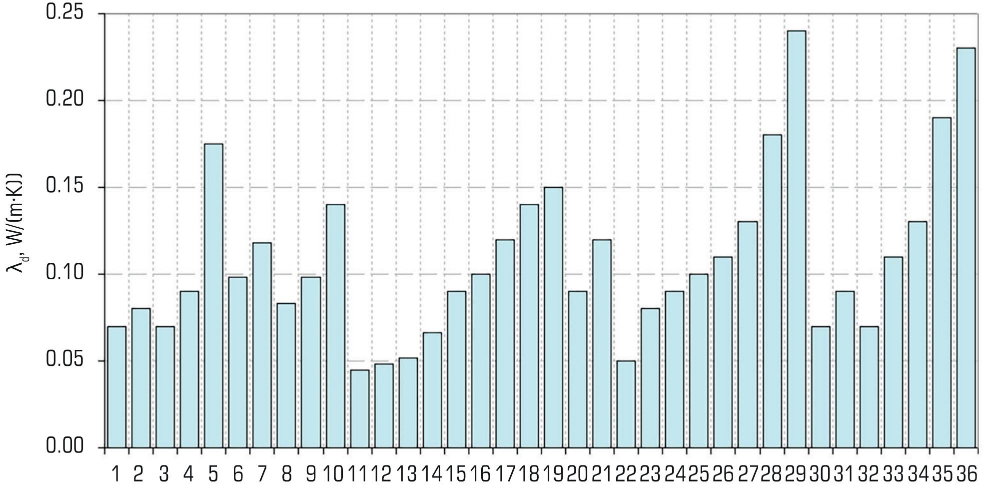
*(*material density*, ρ_0, *kg/m*^{3})

Fig. 2.5 Comparison of the calculated mass moisture content of products made from natural organic and inorganic raw materials (w, %) under service conditions (B), depending on the density of materials (ρ_0, kg/m^3)



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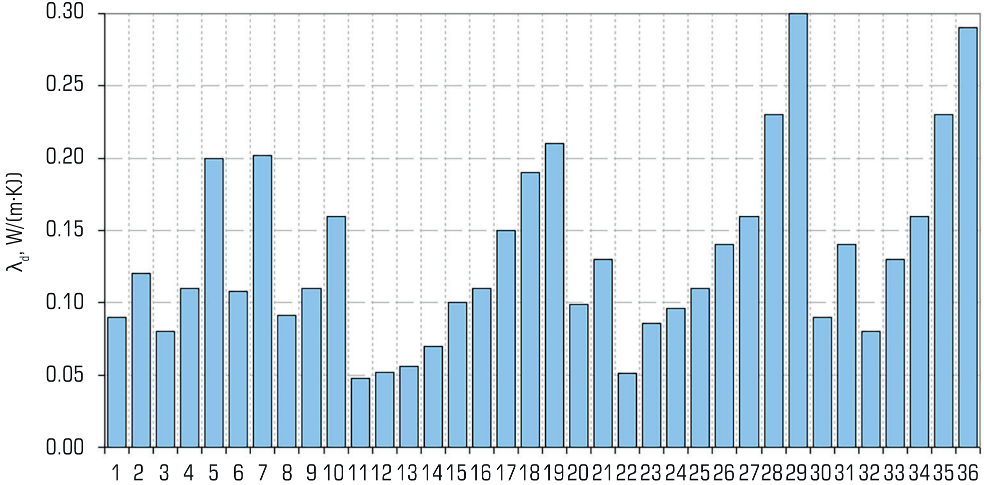
(material density, ρ_0, kg/m^3)

Fig. 2.6 Comparison of the calculated thermal conductivity characteristics of products made from natural organic and inorganic raw materials (λ_d, W/(m•K)) under service conditions (*A*), depending on the density of materials (ρ_0, kg/m^3)



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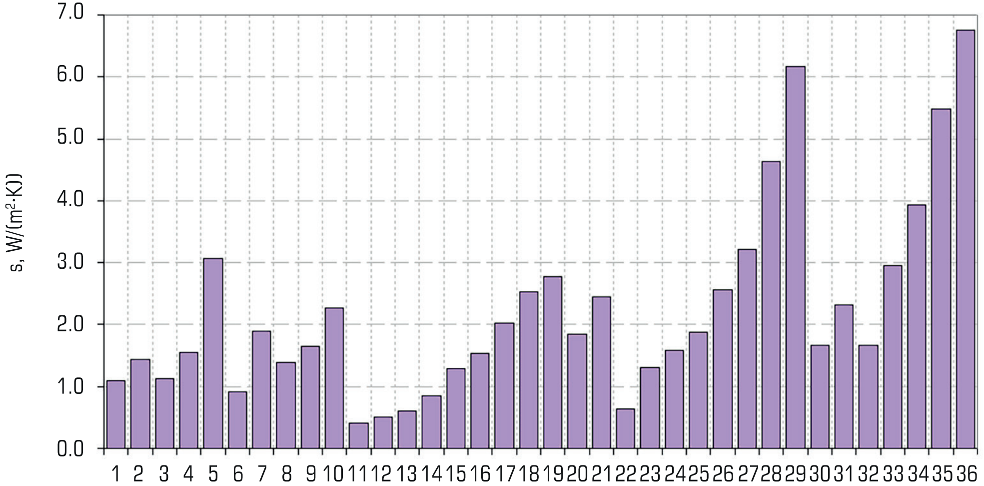
*(material density, ρ_0, kg/m^3)

Fig. 2.7 Comparison of the calculated thermal conductivity characteristics of products made from natural organic and inorganic raw materials (λ_d, W/(m•K)) under service conditions (*B*), depending on the density of materials (ρ_0, kg/m^3)



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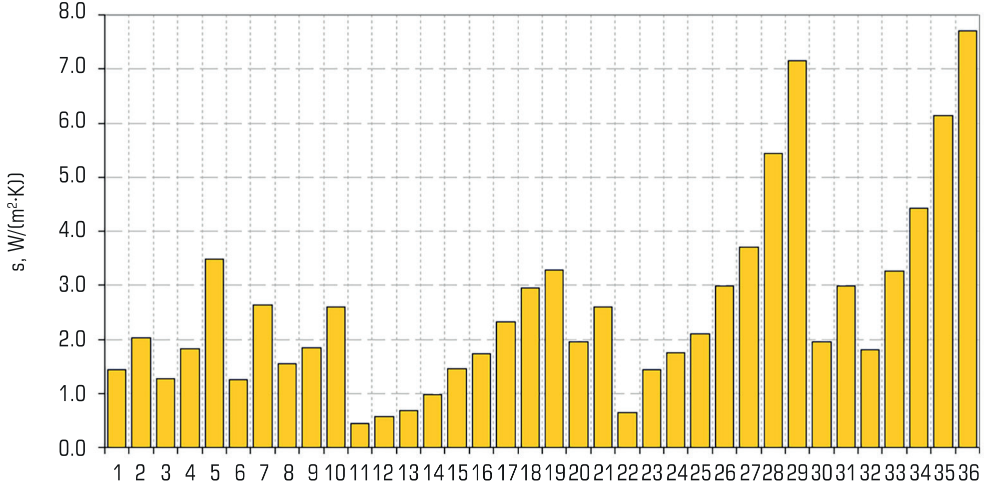
(material density, ρ_0, kg/m^3)

Fig. 2.8 Comparison of the calculated heat absorption coefficient characteristics of products made from natural organic and inorganic raw materials (s, W/(m^2•K)) under service conditions (A), depending on the density of materials (ρ_0, kg/m^3)



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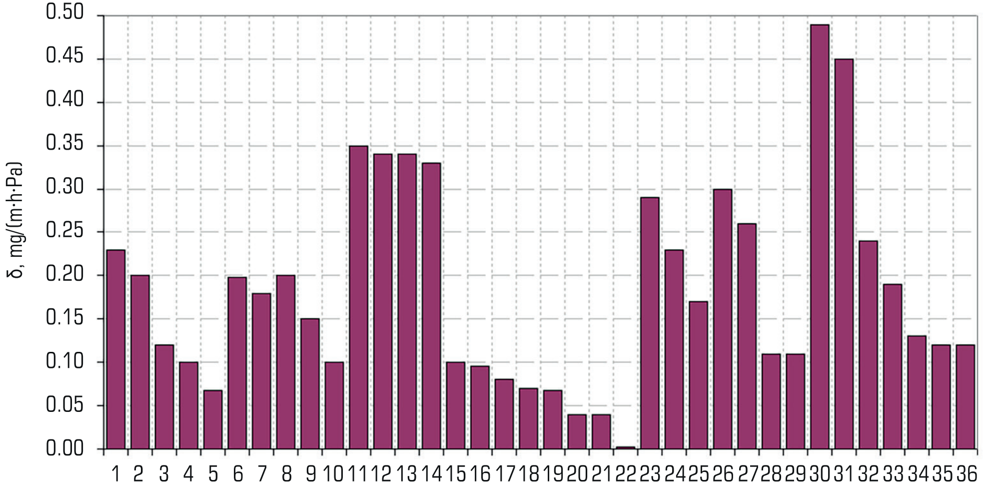
*(material density, ρ_0, kg/m³)

Fig. 2.9 Comparison of the calculated heat absorption coefficient characteristics of products made from natural organic and inorganic raw materials (s, W/(m²•K)) under service conditions (B), depending on the density of materials (ρ_0, kg/m³)



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(material density, ρ_0, kg/m^3)

Fig. 2.10 Comparison of the calculated vapor permeability characteristics of products made from natural organic and inorganic raw materials (δ, mg/(m•h•Pa)) under service conditions (*A*, *B*), depending on the density of materials (ρ_0, kg/m^3)

Products with medium heat capacity ($C \approx 1.0$–2.0 kJ/(kg·K)):

– perlite-bitumen insulation products – 1.68 kJ/(kg·K), characterized by medium thermal inertia. They are used as lightweight insulation layers in roofs, floors, and walls; in constructions where minimal weight with sufficient insulation is required; in systems that do not demand significant heat accumulation, such as for rapid heating and cooling of rooms; and in combination with more massive materials to balance insulation and inertia. They are moisture-resistant and biologically durable, but due to bitumen content, they are less eco-friendly and vapor-impermeable, which limits their use in inclusive spaces with higher microclimate demands;

– polystyrene concrete wall blocks – 1.06 kJ/(kg·K), have moderate heat accumulation ability. Thanks to this combined with low density and thermal conductivity, they effectively reduce heat loss but respond quickly to temperature changes. Such blocks are applied in quick-assembly and lightweight wall constructions, especially in post-war recovery conditions, combined with materials of higher thermal inertia to ensure stable indoor microclimate;

– perlite-phosphogel products – 1.05 kJ/(kg·K), possess moderate heat storage capacity. This, combined with low density and thermal conductivity, makes them effective insulation materials that significantly reduce heat loss in enclosing structures. They are typically used for insulating walls, roofs, and floors, particularly in buildings where structural lightness and good energy-saving properties are important.

Products with medium heat capacity ($C \approx 1.0$–2.0 kJ/(kg·K)) provide a balance between insulation properties and rapid response to temperature changes, making them suitable for lightweight and fast-assembly constructions, but requiring combination with more massive layers for stable microclimate.

Products with low heat capacity ($C \leq 1.0$ kJ/(kg·K)):

– perlite-cement and perlite-gypsum insulation products (0.84 kJ/(kg·K)) – have low heat capacity, indicating a limited ability to accumulate heat. They are used as effective lightweight thermal insulation materials in walls, floors, and roofs of buildings. They combine well with other more massive structural elements, reducing heat loss. They are characterized by vapor permeability, which contributes to humidity regulation and maintaining microclimatic conditions indoors. They are more environmentally friendly due to their natural components;

– perlite-bentonite thermal insulation products (0.84 kJ/(kg·K)) – characterized by low heat capacity and increased strength due to the inclusion of bentonite. They are used as lightweight thermal insulation layers in wall and roof structures where thermal insulation and shape stability are important. They provide adequate vapor permeability and moisture resistance. They contribute to creating a comfortable microclimate by regulating humidity;

– cellulose insulation (0.84 kJ/(kg·K)) – an eco-friendly insulation material made from recycled cellulose with low heat capacity, providing minimal heat accumulation and rapid temperature changes. They are widely used for insulating walls, roofs, and floors. They have high vapor permeability and "breathability", making it optimal for inclusive and ecological projects and requires additional treatment for moisture and pest protection;

– cement-polystyrene products (0.84 kJ/(kg·K)) – lightweight thermal insulation materials combining the insulating properties of expanded polystyrene with the strength of cement binder. Low heat capacity causes rapid temperature changes in the material, suitable for constructions with minimal thermal inertia.

They are used in external walls, floors, and facades. They have relatively low vapor permeability, which may require additional measures to maintain microclimate;

— foam glass products (0.84 kJ/(kg·K)) — thermal insulation materials based on foamed glass with low heat capacity, providing lightness and low thermal inertia. They are used in roofs, foundation insulation, and external walls and characterized by high moisture resistance and chemical inertness, making them durable. Relatively high cost and brittleness limit their widespread use;

— silica-cement blocks (0.84 kJ/(kg·K)) — building materials with reduced heat capacity, providing low thermal inertia. They are used in load-bearing and self-supporting wall structures with additional insulation. They maintain shape well and resist moisture exposure. Vapor permeability is moderate, allowing use in various climatic conditions.

Materials with heat capacity ≤ 1.0 kJ/(kg·K) are typically characterized by low thermal storage capacity, making them effective lightweight thermal insulators for rapid temperature regulation of indoor spaces. They are widely used in external enclosing structures, roofs, and floors, providing reduction of heat losses. At the same time, they vary in vapor permeability, strength, and environmental properties, which influences the choice of material depending on the specific project requirements, especially in the context of inclusive and sustainable construction.

Craft technologies allow the production of materials from natural, local components, ensuring not only ecological compatibility but also optimal thermophysical properties. Materials with high heat capacity, produced using craft methods, are used in heavy external structures for heat accumulation and stabilization of indoor microclimate. Medium heat capacity products serve as intermediate layers where a balance between heat storage and rapid heat release is required, contributing to a comfortable temperature regime. Lightweight materials with low heat capacity, made from natural components by craft technologies, are used in internal insulation layers for quick response to temperature changes, providing dynamic thermal regulation.

Thus, the integration of craft production principles with consideration of materials' heat capacity enables the creation of adaptive, ecological, and energy-efficient building structures that meet the requirements of inclusivity and sustainable development in the post-war reconstruction of Ukraine.

The lowest declared thermal conductivity values (λ_0) are observed for: cellulose insulation (ρ_0 35–100 kg/m^3) — λ_0 = 0.039–0.056 W/(m·K); foam glass products (ρ_0 120 kg/m^3) — λ_0 = 0.05 W/(m·K); reed insulation boards (ρ_0 200 kg/m^3) and wood fiber and wood chip boards (ρ_0 200 kg/m^3) – λ_0 = 0.060 W/(m·K). These materials best retain heat, making them effective thermal insulators at relatively small thicknesses.

The highest vapor permeability is found in reed insulation boards (ρ_0 200 kg/m^3) – δ = 0.49 mg/(m·h·Pa). In contrast, foam glass products (ρ_0 120 kg/m^3) have extremely low vapor permeability (δ = 0.002 mg/(m·h·Pa)), acting as a vapor barrier. Materials with a low heat absorption coefficient, such as cellulose insulation (ρ_0 35–100 kg/m^3) — s = 0.41–0.97 W/(m^2·K) — are suitable for interior partitions. A high heat absorption coefficient is characteristic of wood fiber and wood chip boards (ρ_0 1000 kg/m^3) — s = 7.7 W/(m^2·K) (under service condition B) — used for external or massive structures.

Craft thermal insulation materials based on arbolite, reed, cellulose, and wood are suitable for ecological construction and have: low thermal conductivity, good vapor permeability, moderate density, and comply with sustainable building principles:

– provide natural thermoregulation, reducing the need for heating and air conditioning;

– possess hygienic properties if properly treated (vacuum impregnation, natural antiseptics based on essential oils);

– have a low carbon footprint and promote biodegradation after the end of their life cycle;

– allow significant construction cost reduction due to local availability and ease of use.

The Ukrainian experience closely aligns with international trends in sustainable construction and is widely applied in Europe and North America in accordance with ecological standards and other decarbonization programs [34]. Although Ukrainian developments are still at early stages of commercialization, they have high potential and can significantly influence the formation of a new building culture that combines ecology, social justice, and local identity.

2.3.3 COMPREHENSIVE ASSESSMENT OF BUILDING MATERIALS QUALITY

The comprehensive assessment of building materials quality (K_0, points) was determined according to four key criteria (**Table 2.1**):

– thermal protection – based on the calculated thermal conductivity of materials λ_d (W/m·K);

– inclusiveness – evaluated through the vapor permeability of materials δ (mg/m·h·Pa);

– environmental performance – assessed by the natural origin, biodegradability, and chemical safety of materials;

– local availability – defined by the possibility of producing the material locally without the need for import.

Thermal protection of materials was assessed using a five-point scale according to the following values of thermal conductivity λ_d (W/m·K):

5 points – $\lambda_d < 0.08$, very good (excellent) thermal protection;

4 points – λ_d 0.08–0.15, good thermal protection;

3 points – λ_d 0.15–0.20, moderate thermal protection;

2 points – λ_d 0.20–0.25, poor thermal protection;

1 point – $\lambda_d > 0.25$, very poor thermal protection.

Thermal protection of materials makes it possible to evaluate their ability to retain heat and reduce energy consumption for building heating.

Inclusiveness of materials was assessed using a five-point scale according to the following values of vapor permeability δ (mg/m·h·Pa):

5 points – $\delta \geq 0.20$, very good (excellent) inclusiveness;

4 points – δ 0.15–0.20, good inclusiveness;

3 points – δ 0.10–0.15, moderate inclusiveness;

2 points – δ 0.05–0.10, poor inclusiveness;

1 point – $\delta < 0.05$, very poor inclusiveness.

The inclusiveness of materials directly influences indoor comfort and safety by regulating the microclimate and preventing condensation.

Table 2.1 Comprehensive assessment of the quality of building materials based on the criteria of thermal protection, inclusivity, environmental sustainability, and local availability

No.	Material name	Thermal protection, points	Inclusivity, points	Environmental sustainability, points	Local availability, points	Comprehensive quality assessment of building materials, points	Comprehensive ranking
1	2	3	4	5	6	7	8
1	Perlite – phosphogel products (200)	5	5	3	3	4.00	12
2	Perlite – phosphogel products (300)	4	4	3	3	3.50	18
3	Polystyrene concrete wall blocks (200)	5	3	2	2	3.00	25
4	Polystyrene concrete wall blocks (300)	4	3	2	2	2.75	27
5	Polystyrene concrete wall blocks (600)	3	2	2	2	2.25	36
6	Perlite – cement and perlite – gypsum thermal insulation products (300)	4	4	3	3	3.50	19
7	Perlite – cement and perlite – gypsum thermal insulation products (450)	4	4	3	3	3.50	20
8	Perlite – bentonite thermal insulation products (250)	4	4	3	3	3.50	21
9	Perlite – bentonite thermal insulation products (300)	4	3	3	3	3.25	24
10	Perlite-bentonite thermal insulation products (400)	4	2	3	3	3.00	26
11	Cellulose insulation (35)	5	5	5	5	5.00	1
12	Cellulose insulation (50)	5	5	5	5	5.00	2
13	Cellulose insulation (65)	5	5	5	5	5.00	3
14	Cellulose insulation (100)	5	5	5	5	5.00	4
15	Cement – polystyrene products (250)	4	2	2	2	2.50	32
16	Cement – polystyrene products (300)	4	3	2	2	2.75	28
17	Cement – polystyrene products (400)	4	2	2	2	2.50	33
18	Cement – polystyrene products (500)	4	2	2	2	2.50	34
19	Cement – polystyrene products (550)	4	2	2	2	2.50	35
20	Perlite – bitumen thermal insulation products (300)	4	1	3	3	2.75	29
21	Perlite – bitumen thermal insulation products (400)	4	1	3	3	2.75	30

Continuation of Table 1

1	2	3	4	5	6	7	8
22	Foam glass products (120)	5	1	3	2	2.75	31
23	Silicate – cement blocks (300)	4	5	3	3	3.75	14
24	Silicate – cement blocks (400)	4	5	3	3	3.75	15
25	Silicate – cement blocks (500)	4	4	3	3	3.50	22
26	Wood concrete (arbolite) products on Portland cement (300)	4	5	4	5	4.50	8
27	Wood concrete (arbolite) products on Portland cement (400)	4	5	4	5	4.50	9
28	Wood concrete (arbolite) products on Portland cement (600)	3	3	4	5	3.75	16
29	Wood concrete (arbolite) products on Portland cement (800)	2	3	4	5	3.50	23
30	Reed thermal insulation boards (200)	5	5	5	5	5.00	5
31	Reed thermal insulation boards (300)	4	5	5	5	4.75	7
32	Wood fiber and particle boards (200)	5	5	5	5	5.00	6
33	Wood fiber and particle boards (400)	4	4	5	5	4.50	10
34	Wood fiber and particle boards (600)	4	3	5	5	4.25	11
35	Wood fiber and particle boards (800)	3	3	5	5	4.00	13
36	Wood fiber and particle boards (1000)	2	3	5	5	3.75	17

Environmental friendliness of materials was assessed using a five-point scale according to the following criteria:

5 points – natural, biodegradable materials (wood, reed, cellulose);

4 points – natural materials with cement additives or minimally processed (arbolite);

3 points – mineral, conditionally ecological materials (perlite, mineral boards, foam glass);

2 points – synthetic materials with limited recyclability (polystyrene concrete, cement – polystyrene composites);

1 point – chemically treated materials.

Local availability of materials was assessed using a five-point scale according to the following criteria:

5 points – easily manufactured in a craft-based manner from local raw materials;

4 points – local raw materials but requiring factory production;

3 points – requiring industrial-scale production;

2 points — demanding specialized industry;

1 point — imported materials.

For each material, the arithmetic mean score across all four criteria was calculated, providing a comprehensive rating of the material's suitability for use in inclusive and energy-efficient building structures.

The summarized results of the comprehensive material quality assessment (**Fig. 2.11**) demonstrated that the highest scores across all criteria were achieved by cellulose insulation, reed-based thermal insulation boards, and wood-fiber materials. Their overall scores (5.00 and 4.75–5.00) indicate excellent thermal insulation properties, high environmental friendliness and inclusivity, as well as the availability of local raw materials. Such materials exemplify a balanced approach to creating modern building structures that not only reduce energy consumption but also contribute to the formation of barrier-free environments through ecological safety and adaptability to the needs of diverse users. The high ranking of arbolite products based on Portland cement further confirms the potential of combining traditional and natural components to ensure comprehensive sustainability.

At the same time, a number of materials, such as high-density polystyrene concrete blocks, cement-polystyrene products, and foam glass, received significantly lower scores (2.25–2.75). This indicates limited inclusivity and environmental friendliness, despite satisfactory thermal insulation properties.

Perlite-bitumen and perlite-bentonite materials demonstrated average results, highlighting the need for further modernization and adaptation to contemporary requirements. Thus, the analysis confirmed that priority in designing inclusive and sustainable environments should be given to materials derived from natural and renewable resources, whereas traditional synthetic or high-tech solutions require additional improvements to meet the criteria of accessibility and ecological safety.

2.3.4 INCLUSIVE ENGINEERING AND ACCESSIBILITY ARCHITECTURE IN FOOD SERVICE SPACES

Creating accessible, safe, and inclusive environments in food service establishments must consider the diverse needs of consumers, including people with disabilities, veterans, elderly individuals, parents with young children, as well as those with sensory or cognitive differences.

Principles of inclusive engineering involve designing spaces that do not require users to adapt but rather adapt to diverse functional needs. Key solutions include:

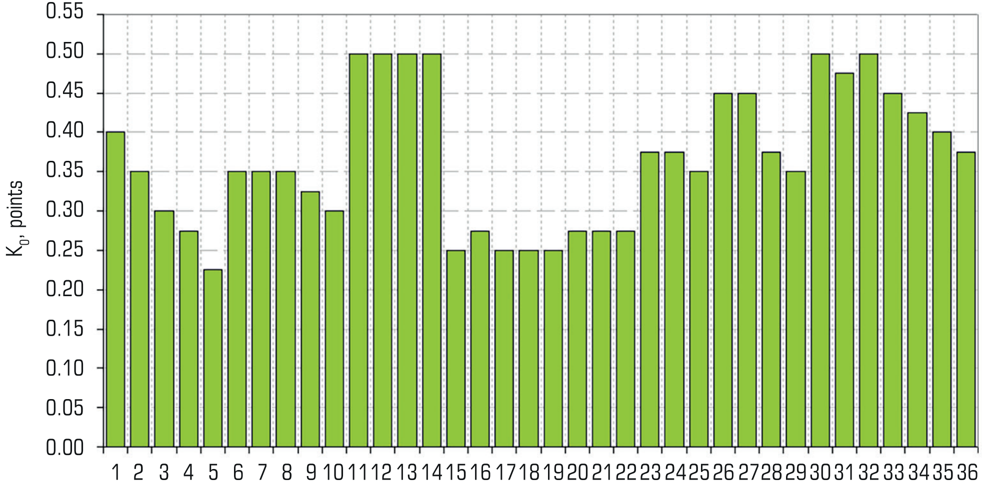
— barrier-free access to the building: ramps with non-slip surfaces, automatic doors, sufficiently wide entrances and corridors;

— navigational orientation within the interior: use of tactile, visual, and auditory landmarks, contrasting zone markings;

— ergonomic functional zones: height-adjustable tables, adapted restrooms, accessible bar counters and reception areas;

— reduction of sensory overload: subdued lighting, natural colors, low-contrast textures, sound insulation, softened acoustic background — essential for people with post-traumatic stress disorder or hypersensitivity.

An important component of inclusive spaces is architectural zoning: avoiding "blind spots", clearly



1 – perlite-phosphogel products (200)*; 2 – perlite-phosphogel products (300); 3 – wall polystyrene concrete blocks (200); 4 – wall polystyrene concrete blocks (300); 5 – wall polystyrene concrete blocks (600); 6 – perlite-cement and perlite-gypsum thermal insulation products (300); 7 – perlite-cement and perlite-gypsum thermal insulation products (450); 8 – perlite-bentonite thermal insulation products (250); 9 – perlite-bentonite thermal insulation products (300); 10 – perlite-bentonite thermal insulation products (400); 11 – cellulose insulation (35); 12 – cellulose insulation (50); 13 – cellulose insulation (65); 14 – cellulose insulation (100); 15 – cement-polystyrene products (250); 16 – cement-polystyrene products (300); 17 – cement-polystyrene products (400); 18 – cement-polystyrene products (500); 19 – cement-polystyrene products (550); 20 – perlite-bitumen thermal insulation products (300); 21 – perlite-bitumen thermal insulation products (400); 22 – foam glass products (120); 23 – silicate-cement blocks (300); 24 – silicate-cement blocks (400); 25 – silicate-cement blocks (500); 26 – wood concrete (arbolite) products on Portland cement (300); 27 – wood concrete (arbolite) products on Portland cement (400); 28 – wood concrete (arbolite) products on Portland cement (600); 29 – wood concrete (arbolite) products on Portland cement (800); 30 – reed thermal insulation boards (200); 31 – reed thermal insulation boards (300); 32 – fiberboard and particleboard (200); 33 – fiberboard and particleboard (400); 34 – fiberboard and particleboard (600); 35 – fiberboard and particleboard (800); 36 – fiberboard and particleboard (1000)

(material density, ρ_0, kg/m^3)

Fig. 2.11 Comprehensive quality assessment of products made from natural organic and inorganic raw materials (K_0, points) under operating conditions (A, B) depending on material density (ρ_0, kg/m^3)

separating staff and visitor flows, and providing quiet areas that allow for emotional comfort restoration.

Inclusivity must be integrated at all stages of design — from urban planning to interior design.

The interior can serve not only decorative but also navigational functions. Natural finishing materials — wood, textiles, ceramics — can include tactile markers or be visually contrasting to facilitate navigation. For example, embossed wooden panels or patterned clay tiles serve not only as aesthetic but also functional accessibility elements. This also emphasizes the establishment's local identity, combining inclusivity with cultural heritage.

Restrooms, kitchens, and other technical rooms must be hygienically safe and adapted to the needs of all staff and visitors. Surfaces should be non-slip, antibacterial, fire-resistant, and easy to clean. The use of non-toxic paints, varnishes, and sealants ensures compliance with food safety standards and HACCP requirements.

The inclusive approach to designing food service establishments fulfills not only a technical role but also a social integrative function. Facilities that consider the needs of people with limited mobility become spaces for rehabilitation, autonomy, and social interaction. This is especially relevant for veterans, individuals with musculoskeletal disorders, sensory impairments, or psycho-emotional traumas.

Craft technologies are gaining particular importance as a tool for integrating local knowledge, resources, and cultural practices. In the sphere of public catering establishments, they perform a dual function: on one hand — an aesthetic and identificational role (through reflecting regional style), and on the other — an ecological and functional role (thanks to the use of natural materials with a low environmental footprint).

Craft approaches allow architectural and construction solutions to be adapted to the local climate, cultural context, and the needs of specific communities. Such technologies contribute to reducing energy consumption, supporting local production, and restoring the authentic character of the environment.

Craft technologies fit within the logic of the circular economy, where key roles are played by resource renewability, material durability, and closed-loop models. Building materials produced by craft methods possess high reparability and the ability to be reused or recycled with minimal environmental impact.

The use of materials based on arbolite, reed, cellulose, and wood ensures natural regulation of humidity and temperature indoors, which is critically important in food service spaces. These solutions also promote energy saving by reducing the need for technical climate control systems. Wood, handmade clay tiles, reed panels, or textiles made of natural fibers not only serve decorative purposes but also emphasize the ethnocultural uniqueness of the region.

The practice of restoring facades and interiors of cafes and restaurants using natural materials is actively developing in Ukraine. In particular, the use of locally sourced wood species, clay (saman), and straw insulation demonstrates a successful synergy of traditions and modern engineering solutions. These approaches not only reduce construction costs but also support local employment and create opportunities for social entrepreneurship based on artisanal work.

Thus, craft technologies in the architecture of food service establishments act as a tool for socio-ecological transformation, combining sustainability, authenticity, functionality, and community involvement in the restoration process.

2.3.5 QUALITY AND SAFETY: SPATIAL AND TECHNOLOGICAL SOLUTIONS

Ensuring quality and safety are fundamental requirements for the operation of public catering establishments, especially in the context of post-war reconstruction. Increased sanitary and hygienic risks [7, 8, 14], resource shortages, and the need for rapid adaptation of the built environment demand a comprehensive approach to designing engineering and architectural solutions. In this context, the integration of HACCP principles [7, 8, 38–40], quality management systems [6, 7, 15], and inclusive engineering [9–12] forms the foundation for creating a reliable, safe, and sustainable food environment.

The quality of a facility's physical environment is determined not only by comfort and aesthetics but primarily by the conformity of functional zoning and technological processes to safety standards. The main criteria for spatial quality include:

– rational functional zoning, involving clear separation of "clean" and "dirty" zones, sequential arrangement of technological process stages: raw material reception, storage, preparation, thermal processing, serving of finished products, dishwashing, etc.;

– adherence to HACCP principles, particularly avoiding cross-flow of raw materials, finished products, waste, and personnel, reducing the risk of microbiological contamination;

– microclimate control – temperature, humidity, ventilation, and lighting levels according to hygienic norms and food safety standards;

– use of hygienic finishing materials – moisture-resistant, heat-resistant, non-toxic, smooth-textured, easy to clean and disinfect.

Thus, a quality environment in a food service facility is shaped at the intersection of spatial logic, engineering design, and sanitary-hygienic control standards.

Within an inclusive approach, it is important to adapt the food space not only to technological requirements but also to the needs of vulnerable users – persons with disabilities, veterans, elderly people, and workers with limited mobility.

Engineering adaptation not only reduces risks of injury and overload but also creates a space of social support that promotes rehabilitation and employment of vulnerable groups.

In the context of safety regarding building structures and finishes, the choice of materials plays a crucial role, directly affecting hygiene and sanitary safety of premises. Key requirements for materials include:

– biological safety – resistance to mold formation, fungi, and parasite colonization;

– chemical neutrality – absence of volatile toxic substances, formaldehydes, phthalates, hazardous dyes, and sealants;

– heat and moisture resistance – the ability to maintain physico-chemical properties under exposure to high temperatures and moisture, especially critical for kitchens and sanitary facilities;

– compliance with food safety standards set forth in normative legal documents and other industry regulations.

The use of tested, environmentally safe, and certified materials is a prerequisite for forming a sustainable, safe environment that meets HACCP requirements and quality management system principles.

CONCLUSIONS

The conducted analysis demonstrates that post-war reconstruction in Ukraine requires the creation of accessible environments for persons with disabilities, veterans, and internally displaced persons. Inclusive engineering involves adapting public catering spaces through barrier-free access (ramps, wide aisles), ergonomic furniture, contrast lighting, and reducing sensory overload for individuals with post-traumatic stress disorder or sensory impairments. These solutions promote social integration and rehabilitation of vulnerable groups.

Craft technologies based on local materials are effective tools for implementing circular economy principles. They ensure resource reuse, reduce carbon footprint, and support local communities. The use of traditional materials (such as adobe and reed panels) emphasizes local identity, fostering the creation of authentic spaces with ethnodesign elements.

A proposed integration methodology includes the use of eco-friendly materials with high heat capacity (e.g., arbolite, reed panels) for stable microclimate and low thermal conductivity materials (cellulose insulation, foam glass) for thermal insulation. Architectural solutions involve zoning, hygienic coatings, and adaptive elements that comply with HACCP standards and meet the needs of vulnerable groups.

The combination of inclusive engineering and craft technologies enhances social integration through accessible spaces, ecological sustainability by reducing resource consumption, and economic efficiency through local production. This creates a comfortable and safe environment that supports rehabilitation and social cohesion.

To promote the principles of inclusive and craft approaches, it is necessary to consider accessibility and environmental requirements and develop new academic disciplines within bachelor's, master's, and PhD educational programs that address circular economy, craft technologies, and inclusive design.

These conclusions confirm that integrating inclusive engineering and craft technologies shapes sustainable, safe, and culturally significant spaces in public catering establishments, contributing to Ukraine's recovery.

CONFLICT OF INTEREST

There is no conflict of interest. The authors declare that they have no financial, academic, personal or other conflicts of interest that could influence the content, results or interpretation of this study.

USE OF ARTIFICIAL INTELLIGENCE

The authors of this study state that AI tools were not used as a replacement for critical thinking, expertise, and human evaluation.

During the preparation of this work, the authors used Chat GPT (Chat GPT 5.1) for purely mechanical work, editorial assistance: stylistic improvement, grammar, spelling, and translation of sources/references.

The authors carried out a full check of all materials obtained with the participation of AI by: comparing each fragment with primary sources and current scientific literature; manually clarifying terms, definitions, and content in accordance with the research methodology; verifying statistical data, facts, international examples, and regulatory references; ensuring compliance with academic standards, research logic, and the requirements of the target publication. The use of AI tools did not affect the scientific results, empirical conclusions, statistical models, and research position of the authors. All key findings, conceptual models, methodological positions and recommendations of the study are formulated solely by the authors and reflect their own scientific position. After using this tool/service, the authors reviewed and edited the content of the work and bear full responsibility for the content of the published article.

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3 PROSPECTIVE COMPOSITIONS OF HEAT-RESISTANT HIGH-ENTROPY ALLOYS FOR FOUNDRY PRODUCTION

ABSTRACT

The work investigates promising compositions of high-entropy alloys (HEAs) based on the FeNiCrCuAl and FeNiCrCuMn systems, which have the potential for use as heat-resistant materials in foundry production. It is shown that the use of a specially designed vacuum medium-frequency induction furnace allows obtaining high-quality ingots with active mixing of the melt and temperatures up to 1800°C. The thermodynamic parameters (entropy and enthalpy of mixing, atomic radii, electronegativities, VEC, Ω parameter) were calculated, on the basis of which the phase composition was predicted. X-ray phase analysis confirmed the formation of solid solutions with FCC and BCC lattices, an ordered B2 phase (of the NiAl type). In addition to phase analysis and structural study, the thermophysical properties (melting and crystallization heats, liquidus-solidus temperatures) of alloys, and elastic properties by the dynamic mechanical analysis (DMA) method, were investigated in a wide temperature range. The dependences of the elastic modulus and the loss factor on temperature were established. The heat resistance of alloys (at 900°C and 1000°C) was assessed, which showed high stability of the structure of high-entropy alloys in an oxidizing environment. The casting properties of the experimental alloys – fluidity and linear shrinkage – were studied using spiral and U-shaped test molds, which allowed comparing them with the indicators of cast irons and steels. The fluidity of high-entropy alloys of the FeNiCrCuMn system is lower, and that of alloys of the FeNiCrCuAl system is higher compared to standard steels (G25, GX10CrNiMn18-9-1). Thus, the results of the study confirm the feasibility of using alloys of the FeNiCrCuMn and FeNiCrCuAl systems as heat-resistant casting materials of a new generation.

KEYWORDS

High-entropy alloys, heat resistance, phase composition, elastic properties, thermophysical parameters, B2-phase, fluidity, induction melting.

In the early 2000s, a new type of materials was discovered – high-entropy alloys (HEAs) [1–3]. Traditional alloys have one or two main chemical elements, to which other elements are added in relatively low concentrations to achieve the desired properties. Whereas HEAs have at least five main elements, which are in an equiatomic or close to equiatomic composition. Due to the high concentration of components, such alloys have a high entropy of mixing, and it is entropy to a much greater extent than enthalpy that ensures the thermodynamic stability of HEAs. High-entropy alloys, due to the different diameters of the atoms that make up their composition, have a deformed crystal lattice of the face-centered cubic (FCC) or body-centered cubic (BCC) types. Such alloys are characterized by unique properties: high values of the yield strength at room temperature, fracture toughness at low temperatures, resistance to softening at elevated temperatures, and wear resistance. High-entropy alloys with a BCC lattice are usually characterized by high hardness, while those with FCC lattice are characterized by high plasticity.

But conventional single-phase high-entropy alloys also have a number of disadvantages. Hard high-entropy alloys are brittle, while plastic ones have too low a yield strength. Conventional high-entropy alloys have poor casting properties: high volumetric and linear shrinkage and low fluidity. Also, individual components and the technology for producing high-entropy alloys are quite expensive. Usually, the method of arc remelting in a vacuum is used. These disadvantages limit the areas of practical use of high-entropy alloys.

One of the methods for improving the operational properties of HEAs is the manufacture of alloys with several high-entropy phases. This work is devoted to the development of cheap multiphase high-entropy alloys from available components with the prospects for mass casting production.

If the entropy of mixing ΔS_{mix} of the solution takes on large positive values, this leads to a significant negative contribution to the Gibbs free energy of mixing and stabilization of the corresponding solid phase. In the approximation of an ideal solution, the entropy of mixing ΔS_{mix} can be calculated as

$$\Delta S_{mix} = -R\sum_{i=1}^{N} c_i \ln(c_i), \quad (3.1)$$

where c_i – the mole fraction of component i in the melt, R – the universal gas constant.

In the case of equal molar concentrations c_i of each element, equation (3.1) takes the form

$$\Delta S_{mix} = R\ln n, \quad (3.2)$$

where n – the number of components in the alloy.

Alloys with an entropy of mixing greater than 12.5 J/mol K are considered high-entropy alloys [4].

The second thermodynamic function characterizing the stability of the phase is the alloy's enthalpy of mixing ΔH_{mix}, and its effect on the phase composition of the alloy is ambiguous. According to [5], the values of this function should be in the range –15 kJ/mol < ΔH_{mix} < 5 kJ/mol. At ΔH_{mix} > 5 kJ/mol, there is a lower degree of mixing of the components, which leads to segregation of elements in the alloy, and at high positive values of the enthalpy of mixing, stratification is possible. At high negative enthalpy of mixing ΔH_{mix} < –15 kJ/mol, the formation of intermetallics and ordered phases during melt crystallization is possible [6]. Only zero or small values of the enthalpy of mixing contribute to the random distribution of atoms in the crystal lattice sites and the formation of a disordered solid solution [7]. The enthalpy of mixing of a disordered multicomponent single-phase alloy is calculated by the equation [8, 9]

$$\Delta H_{mix} = \sum_{i=1;\, j\neq i}^{N} 4\Delta H_{ij}^{mix} c_i c_j, \quad (3.3)$$

where ΔH_{ij}^{mix} – enthalpy of mixing of a binary equiatomic alloy of components i and j; c_i, c_j – molar fractions of components in the corresponding multicomponent alloy.

The values ΔH_{ij}^{mix} calculated by the Miedema model for atomic pairs between elements with atomic numbers from 1 to 94 are presented in works [10–12].

The entropy of mixing is not always the dominant factor that ensures the formation of a single-phase structure and affects the microstructure. In work [13], the structures of HEAs were analyzed and three principles of the formation of solid solutions were formulated:

1) to obtain a high entropy of mixing, it is necessary that the number of main constituent elements be at least five;

2) the maximum difference in the atomic radii of the elements should not exceed 12%;

3) the enthalpy of mixing should vary in the range -40 kJ/mol $< \Delta H_{mix} <$ 10 kJ/mol.

In [5, 14], more precise parameters have been established, namely the coefficients Ω and δ_r, which can be used to predict phase formation in high-entropy alloys. The thermodynamic parameter Ω considers the influence of entropy and enthalpy of mixing, as well as the melting point on the formation of a solid solution [15]:

$$\Omega = \frac{T_m \Delta S_{mix}}{\left|\Delta H_{mix}\right|}, \tag{3.4}$$

$$T_m = \sum\nolimits_{i=1}^{n} c_i \left(T_m\right)_i, \tag{3.5}$$

where T_m – the average melting point of an n-element alloy, K; $(T_m)_i$ – the melting point of the i-th element.

To describe the influence of differences in the atomic radii of the constituent elements, the empirical parameter δ_r can be expressed as follows:

$$\delta_r = \sqrt{\sum_{i=1}^{n} c_i \left(1 - \frac{r_i}{\bar{r}}\right)^2}, \tag{3.6}$$

$$\bar{r} = \sum\nolimits_{i=1}^{n} c_i r_i, \tag{3.7}$$

where r_i – the atomic radius of the i-th component, $\bar{r}$ – the average atomic radius (taking into account atomic fractions).

A large difference in the atomic radii of the elements significantly affects the formation of a solid solution. Strong lattice distortions lead to an increase in the strain energy, and therefore to an increase in the free energy, which is accompanied by a decrease in the probability of solid solution formation, so the difference in the atomic radii of the elements should not exceed 6.6%.

Thus, the parameters Ω and δ_r can be a fairly reliable tool for separating between the formation of solid solutions and intermetallic phases in multicomponent systems. At a high value of the parameter Ω > 1.1 and a small value of the parameter $\delta_r \leq 4.6\%$ according to [5] or $\delta_r \leq 6.6\%$ according to [14], a solid solution based on phases with FCC or BCC lattice will form in the structure of the high-entropy alloy.

Based on the analysis of the structures of high-entropy systems, it can be stated that the formation of a solid solution is likely at the following values of the parameters mentioned above: Ω > 1.1 and $\delta_r \leq 6.6\%$.

To describe the collective behavior of components in high-entropy alloys, the authors of [16, 17] proposed two additional parameters: the electronegativity difference ($\Delta\chi$) and the valence electron concentration (VEC). The value of $\Delta\chi$ is determined according to the classical Hume-Rothery rule:

$$\Delta\chi = \sqrt{\sum_{i=1}^{n} c_i \left(\chi_i - \overline{\chi}\right)^2}, \tag{3.8}$$

where χ_i — the Pauling electronegativity for the *i*-th element:

$$\overline{\chi} = \sum_{i=1}^{n} c_i \chi_i. \tag{3.9}$$

The current literature does not provide ranges of $\Delta\chi$ values that would indicate the formation of solid solutions in the HEAs structure, however, the study [18] showed that with a large value of $\Delta\chi$, the formation of intermetallic compounds or an amorphous phase is more likely. Judging from the tabular data [16, 18] and the relationship between the enthalpy of mixing and electronegativity [17], it can be concluded that for the existence of disordered solid solutions in the structure of high-entropy alloys, the difference in electronegativity ($\Delta\chi$) should not exceed 0.12 (or $\Delta\chi \leq 12\%$).

According to the Hume-Rothery rule [19], the valence electron concentration (VEC) predicts the type of crystal lattice. The valence electron concentration can also be used to predict the formation of intermetallics [20]. VEC is determined from the following equation:

$$VEC = \sum_{i=1}^{n} c_i \left(VEC\right)_i, \tag{3.10}$$

where $(VEC)_i$ — VEC for the *i*-th element.

VEC is a key physical parameter that governs the tendency for the formation of FCC and BCC solid solutions, a high VEC value (> 8), the FCC phase is formed, in the interval 6.87 < VEC < 8, a mixed BCC + FCC structure is formed, and at a lower VEC value (< 6.87) — the BCC phase [17].

In [21], a simple and practical pseudo-binary method was proposed for the design of eutectic HEA using the VEC and ΔH_{mix} parameters. Using this strategy, a series of nanostructured eutectic HEAs consisting of an ordered body-centered cubic (B2) phase and a phase with FCC lattice were successfully developed. By adding aluminum to high-entropy basic systems ($CoCrFeNi_2$, $Co_2CrFeNi$, $CoCrFe_2Ni$) with a FCC lattice, eutectic high-entropy alloys were obtained. Their eutectic structure consists of a mixture of a solid solution with FCC structure and intermetallic compounds (FCC/IMC). All developed alloys demonstrated unique mechanical properties with a tensile strength above 1000 MPa and a total elongation of more than 10%. When developing eutectic HEAs with FCC/IMC structure, the FCC solid solution is selected according to the following criteria: -5 kJ/mol < ΔH_{mix} < 0 kJ/mol and VEC ≥ 8.

High-entropy alloys constitute a new class of structural materials that demonstrate a unique combination of high strength, heat resistance, corrosion resistance and wear resistance even under extreme operating conditions. Due to their stable microstructure and stability at high temperatures, HEAs are promising for use in the aerospace and energy industries (in particular, in elements of gas turbine engines and nuclear reactors), in military equipment, cryogenic systems, the chemical industry, as well as in the production of tools and bioinert implants and wear-resistant coatings [22, 23]. On their basis, unique new generation composite materials with controllable properties for critical engineering applications can be created [24, 25]. Another promising direction is the new HEAs based on lightweight elements that combine high thermal stability of the structure and resistance to local overheating during the joining processes involving high-energy sources [26].

3.1 PREPARATION OF HIGH-ENTROPY ALLOYS

To smelt high-entropy alloys in an argon atmosphere, a specialized induction vacuum furnace was developed and fabricated. It was based on a shaft-type vacuum resistance furnace, and its schematic diagram is shown in **Fig. 3.1** [27]. The tungsten heater was replaced by an inductor powered by a thyristor converter with a power of 6 kW and a frequency of 20–22 kHz. Melting was performed in an alundum crucible placed inside a graphite cup. The wall thickness of the graphite cup was optimized to minimize electromagnetic shielding of the charge, thereby ensuring active stirring of the melt during the process. The furnace manufactured in this way provided intensive mixing of the melt and overheated the alloy to a temperature up to 1800°C. The following were used as charge materials: carbonyl iron of special purity TU 6-09-3000-78 (Fe ≥ 99.99% wt.); cathode nickel (Ni ≥ 99.99% wt.); flakes of electrolytic chromium, grade ERX1 and chromium grade X99 in the form of small pieces; metallic manganese grade Mn997 (99.7 wt.%); copper grade M1 (99.9 wt.%) (the foreign equivalent Cu-ETP (99.9 wt.%)), aluminum ingot grade A85 (99.85 wt.%) (the foreign equivalent ENAW-1085 (99.85 wt.%)); electrolytic cobalt grade K0 (Co ≥ 99.98% wt.). Also, as a source of iron, nickel and chromium, stainless steel of the grade 10H18N9L (the foreign equivalents GX10CrNiMn18-9-1, EN 10213) was used. The technology for obtaining samples was as follows: after loading components into a crucible with a total mass of no more than 1500 grams, the working chamber was evacuated (P = 2.10-2 Pa), then flushed 2 times with high-grade argon (99.993%) and the furnace was filled with it to an excess pressure of 15–20 kPa. When heated to 1000°C, the heating rate did not exceed 25°C/min, so as not to crack the alundum crucible. During melting, the excess pressure of argon in the chamber rose to 30–40 kPa. After melting and dissolving all elements, the alloy was overheated to a temperature of 1550–1600°C and held in a liquid state for at least 30 min. The total duration of melting, including heating and holding the alloy in its liquid state, was at least 90 minutes. After holding the alloy in a liquid state in a high-purity argon environment, it was cooled together with the furnace to room temperature. The high-entropy alloys obtained in this way were remelted once more in an argon environment, and after the melting was completed, the furnace lid was opened, and the melt was poured into molds using traditional sand-clay casting. The chemical composition of the experimental HEA samples was determined using an X-ray fluorescence express analyzer (XRF) "EXPERT 3L".

The chemical composition of the obtained alloys is shown in **Table 3.1**.

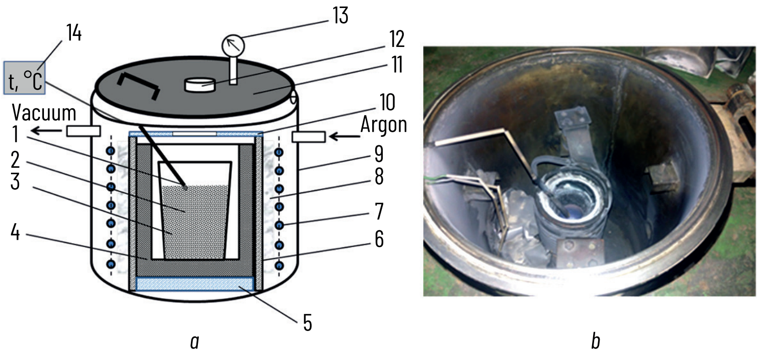


Fig. 3.1 Schematic diagram of vacuum induction furnace for smelting samples of high-entropy alloys: *a* – schematic diagram; *b* – photograph ; 1 – thermocouple; 2 – charge material; 3 – alundum crucible; 4 – graphite cup; 5 – alundum stand; 6 – alundum tube; 7 – inductor; 8 – kaolin wool; 9 – vacuum chamber; 10 – alundum cover with a viewing window; 11 – chamber cover; 12 – viewing window; 13 – vacuum gauge; 14 – temperature recording device

Table 3.1 Chemical composition of HEA samples, expressed in atomic percent

No.	Fe	Ni	Cr	Co	Mn	Cu	Al	C	Si	P+S
1	23.88	20.42	14.54	–	18.49	21.92	–	0.430	0.300	0.036
2	23.99	20.66	12.65	–	0.11	20.66	21.32	0.430	0.170	0.018
3	21.77	20.58	14.02	–	0.354	23.22	19.50	0.302	0.233	0.020
4	17.10	22.17	18.58	–	–	23.51	18.56	–	0.076	0.012
5	18.96	19.97	20.10	–	20.30	20.42	–	–	0.213	0.042
6	19.30	20.13	18.60	–	–	20.85	21.03	–	0.077	0.013
7	20.48	21.63	18.54	21.38	17.97	–	–	–	–	–
8	24.09	20.43	14.14	–	19.27	21.27	–	0.380	0.368	0.040
9	24.72	20.80	12.41	–	19.64	21.63	–	0.381	0.388	0.038
10	19.10	21.52	17.79	–	–	21.87	19.65	–	0.065	0.015

3.2 X-RAY PHASE ANALYSIS, MICROSTRUCTURE AND THERMODYNAMIC PARAMETERS OF HIGH-ENTROPY ALLOYS

X-ray phase analysis of the alloys was performed by X-ray diffraction on DRON-3, and Bruker D8 Advance diffractometer (Germany) using Mo-Kα (λ = 0.07093187 nm), Co-Kα (λ = 0.178897 nm) radiations, respectively, and with focusing of X-rays according to the Bragg-Brentano geometry. Depending on the type of radiation, measurements were carried out in the angular ranges of 10°–55° and 15°–135° with a step of 0.02° or 0.05°, respectively, with a pulse accumulation time of 2 s. For accurate determination of the lattice parameters in the region of far diffraction peaks at large angles, a step of 0.01° and an accumulation time of 12–16 s was used, depending on the type of sample. To study the microstructure and chemical phase composition of the HEA samples, a REM106I scanning electron microscope with an energy-dispersive microanalyzer (manufactured by OJSC "SELMI") was used. **Fig. 3.2** shows the diffraction patterns obtained on Samples No. 4 and No. 5 of the FeNiCrCuAl and FeNiCrCuMn systems, respectively. High-entropy alloys of the FeNiCrCuAl system demonstrate two phases with different crystal lattices, in particular BCC (the space group Pm3m) and FCC (the space group Fm3m). A solid solution based on the BCC phase has an ordered structure of type B2, which is characterized by a uniform distribution of all elements within the phase and exists in equiatomic NiAl alloys. The structure of type B2 is similar to a disordered solid solution based on a phase with a BCC structure of type A2 and differs in that the position in the center of the unit cell is occupied by one specific type of atoms, while another type occupies the corner positions. This is confirmed by the presence of a diffraction maximum (100) at $2\theta \approx 36°$ for Co-Kα radiation (**Fig. 3.2, *a***, Sample No. 4). The alloys of the FeNiCrCuMn system have a multiphase structure, but with different FCC lattices (FCC1, FCC2) with different periods and a BCC lattice (A2) (the space group Im3m) (**Fig. 3.2, *b***, Sample No. 5). The lattice periods were calculated for each reflection (*hkl*) in the X-ray diffraction pattern, and then the average value of the lattice parameters was determined. For certain X-ray diffraction patterns, Miller indices corresponding to large diffraction angles were selected to determine the lattice parameters. Specifically, the (321) peak from Sample No. 6 was observed at angles of 54.81° and 55.18°, using molybdenum radiation with wavelengths MoKα_1 = 0.7093187 Å and MoKα_2 = 0.710806 Å, respectively. The calculation of lattice parameters was also carried out on the basis of diffractograms using cobalt radiation (CoKα1 = 1.78897 Å). Lattice parameters depend on the chemical composition and for alloys of the FeNiCrCuAl system (Samples No. 3, 4, 6) the parameter of the BCC lattice varies from 2.8788 Å to 2.8900 Å, and the FCC lattice from 3.6358 Å to 3.6500 Å (**Table 3.2**). For alloys of the FeNiCrCuMn system (Samples No. 1, 5), the parameter of the FCC1 lattice changes from 3.6700 Å to 3.6800 Å, and the FCC2 lattice does not change at 3.6200 Å (**Table 3.2**). For alloys of the FeNiCrCuMn system, the diffraction pattern of one of the phases is similar to austenite or an iron-manganese alloy Fe_3Mn_7 with FCC1 lattice periods of 3.6700 Å, 3.6800 Å, respectively, and the second phase is similar to solid solutions in copper-iron alloys, but with slightly smaller parameters of the face-centered cubic FCC2 lattice (3.6200 Å). According to Vegard's law, the theoretical parameters of crystal lattices of alloys with the nominal charge composition $Fe_{20}Ni_{20}Cr_{20}Cu_{20}Al_{20}$ and $Fe_{20}Ni_{20}Cr_{20}Cu_{20}Mn_{20}$ were calculated. It turned out that they differ from the experimental ones, and the theoretical parameter of the BCC lattice has a larger value (2.9125 Å), and the parameters of the FCC lattice have smaller values (3.5039 Å, 3.6152 Å) compared to the experimental periods.

The discrepancy in the values of the experimentally determined and theoretically calculated parameters can be due to both the inaccuracy of the calculation and the change in the electronic structure, chemical composition, local order, magnetic and many other properties of solid solutions. In addition, the calculations did not take into account the influence of impurities of silicon, carbon, phosphorus and sulfur.

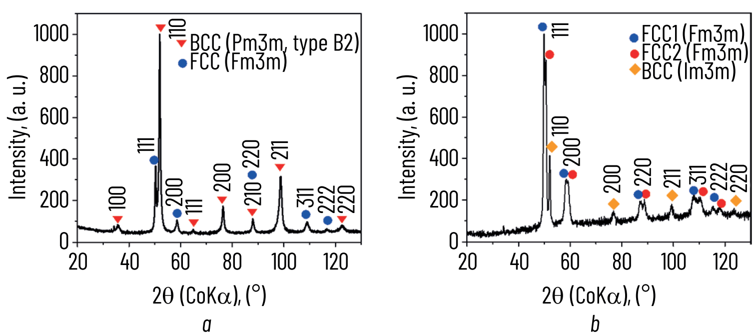


Fig. 3.2 X-ray diffraction patterns of high-entropy alloys: *a* — FeNiCrCuAl system (Sample No. 4); *b* — FeNiCrCuMn system (Sample No. 5)

Table 3.2 Results of phase analysis and lattice parameters of alloys of the FeNiCrCuAl, FeNiCrCuMn, FeCoNiCr systems

Sample	Lattice (space group)	Radiation	Lattice parameter, Å
1	**2**	**3**	**4**
Fe20Ni20Cr20Cu20Al20	BCC (Im3m) FCC (Fm3m)	calculation	2.9125 3.6152
Fe20Ni20Cr20Cu20Mn20	FCC (Fm3m)	calculation	3.5039
1	FCC 1 (Fm3m) FCC 2 (Fm3m)	CoKα	3.6800 3.6200
3	BCC (Pm3m) FCC (Fm3m)	CoKα	2.8800 3.6400
4	BCC (Pm3m) FCC (Fm3m)	CoKα	2.8900 3.6500
5	FCC 1 (Fm3m) FCC 2 (Fm3m) BCC (Im3m)	CoKα	3.6700 3.6200 2.8800

Continuation of Table 3.2

1	2	3	4
6	BCC (Im3m) BCC (Fm3m)	CoKα MoKα MoKα CoKα MoKα	2.8788±0.00460 2.8894±0.00536 2.8830* 3.6358±0.00517 3.6480±0.00510
FeNiCoCr	BCC (Fm3m)	CoKα MoKα	3.5702±0.00239 3.5768±0.0015**

*Note: The lattice parameters were calculated from peaks with Miller indices *(321), **(331) and (420).*

Typical microstructures of the cast high-entropy alloy samples of the FeNiCrCuAl and FeNiCrCuMn systems after crystallization are shown in **Fig. 3.3**. The cast samples exhibit a heterogeneous structure consisting of several phases, including dendrites, an interdendritic region, and a third phase enriched in copper. The branches of the dendrites have a rounded shape for both alloy systems. The chemical composition of the individual phases was determined using local chemical analysis (EDX analysis). In **Fig. 3.3, *a*, *b***, the structural components are indicated by numbers (1—7), and their corresponding chemical composition is presented in **Table 3.3**.

More refractory elements, such as iron and chromium, are concentrated in the branches of the dendrites, while the interdendritic regions are enriched in elements with lower melting points, such as copper, aluminum, manganese, and nickel. Unlike other alloy components, copper shows a tendency to segregation, forming a separate phase (**Fig. 3.3, *a***, point 4, **Fig. 3.3, *b***, point 7). This is due to its limited solubility in the FeNiCrAl-based solid solution and thermodynamic tendency to form copper-enriched regions, therefore, copper-enriched regions have a lower mixing entropy (**Table 3.3**). The calculated valence electron concentrations of individual phases indicate the potential formation of solid solutions with FCC or BCC lattices. In alloys of the FeNiCrCuAl system, the white elongated regions in the interdendritic space of alloy No. 4, enriched in copper (**Fig. 3.3, *a***, point 4), are characterized by the VEC equal to 9.566 el/at. This indicates the probable formation of a phase with FCC lattice. At the same time, the dendrites and the interdendritic space, where the VEC varies from 7 to 8 el/at (**Table 3.3**), probably contain a mixture of solid solutions with FCC and BCC lattices. This range of VEC corresponds to the transition zone between the stability of BCC and FCC phases, which indicates the possible coexistence of both types of crystal structures in the microstructure of the alloy. In alloys of the FeNiCrCuMn system, the dendrites have an elongated oval shape with uneven edges (**Fig. 3.3, *b***). The concentration of valence electrons suggests a high probability of forming two solid solutions in the interdendritic space of alloy No. 5, based on phases with a face-centered cubic lattice (**Table 3.3**, items 6 and 7). This is further supported by the results of X-ray phase analysis. The dendrites` branches of the alloy No. 5 of the FeNiCrCuMn system are enriched in chromium, therefore these regions are characterized by a lower mixing entropy compared to the interdendritic space (**Table 3.3**, point 5).

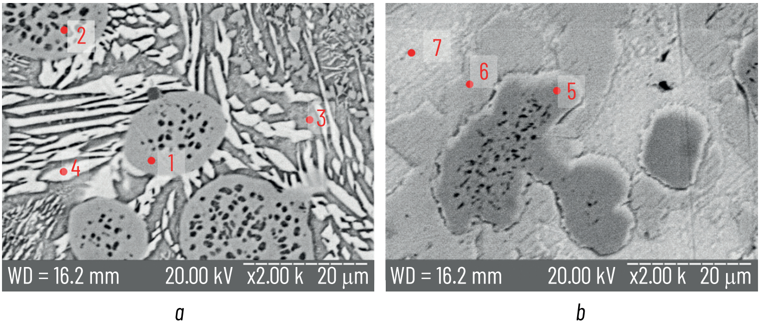


Fig. 3.3 Microstructures of cast high-entropy alloys: a – No. 4 and b – No. 5 of the FeNiCrCuAl and FeNiCrCuMn systems. Individual phases are indicated by numbers, and their chemical composition is given in **Table 3.3**

Table 3.3 Chemical composition of individual phases in high-entropy alloys of the FeNiCrCuAl and FeNiCrCuMn systems

Alloy No.	Point	Chemical composition (at.%)						VEC (el/at)	ΔSmix (J/mol·K)	Lattice
		Fe	Ni	Cr	Cu	Al	Mn			
4	1	37.78	5.61	46.78	4.15	5.68	–	7.017	9.809	BCC FCC
	2	26.75	12.36	34.53	13.09	13.27	–	7.286	12.576	BCC FCC
	3	8.18	34.25	4.31	23.47	29.80	–	7.814	11.709	BCC FCC
	4	3.73	13.36	1.47	67.51	13.92	–	9.566	8.259	FCC
5	5	28.36	6.21	52.33	2.00	–	11.1	6.250	9.903	BCC
	6	25.31	25.39	19.99	10.01	–	19.3	8.215	13.016	FCC
	7	5.46	19.51	2.88	44.80	–	27.4	9.404	10.760	FCC

As shown in **Table 3.4**, the increased content of chromium and iron in the dendrites of alloys of both systems caused an increase in the microhardness of the dendritic branches, which turned out to be 1.1–2 times higher compared to the microhardness of the interdendritic regions. At the same time, in alloy No. 3, the opposite trend is observed – the interdendritic region demonstrates a slightly higher hardness.

Table 3.4 The microhardness of the structural constituents in FeNiCrCuAl and FeNiCrCuMn high-entropy alloy samples

Alloy No.	Microhardness, Hμ (kgf/mm²)		
	Interdendritic space	Dendrites	Shell around dendrites
1	233±39	233±32	–
2	198±20	296±58	–
3	328±51	290±52	–
4	245±24 263±57	322±41	–
5	194±25	288±41	330±44
6	343±42	375±60	–
8	172±13	192±37	–
10	195±17 252±28	381±42	–

To further evaluate phase formation and the development of solid solutions in the studied FeNiCrCuAl and FeNiCrCuMn alloys, key thermodynamic parameters were calculated, as summarized in **Table 3.5**. The concentration of valence electrons in the alloys of the FeNiCrCuMn system (Samples No. 1, 5, 8, 9) varied from 8.397 to 8.589 el/at, and for the alloys of the FeNiCrCuAl system (Samples No. 2–4, 6, 10) – from 7.601 to 7.846 el/at. These values indicate the formation of solid solutions with FCC lattice in the alloys of the FeNiCrCuMn system, and in the alloys of the FeNiCrCuAl system – a mixture of two phases with BCC and FCC lattices, which was previously confirmed by X-ray phase analysis. For the studied systems, the value of the thermodynamic parameter Ω exceeds 1.1. The alloys have relatively small negative values of the enthalpy of mixing ΔH_{mix} from –4.867 to –3.23 kJ/mol for the FeNiCrCuAl system and small positive values of ΔH_{mix} from 1.798 to 2.427 kJ/mol for the FeNiCrCuMn alloy system. All values of ΔH_{mix} are in the range -15 kJ/mol < ΔH_{mix} < 10 kJ/mol [5, 17, 28]. In addition, the configurational entropy coefficient $\Delta S_{mix}/R \geq 1.61$ also indicates the probability of solid solution formation (**Table 3.5**). A literature review of high-entropy systems shows that solid solution formation is likely when $\delta_r \leq 6.6\%$. The FeNiCrCuAl system exhibits an average atomic radius difference of ≤ 6.4%, influenced by the presence of aluminum (143 pm), while in the FeNiCrCuMn system it is about 4%. In the FeNiCrCuMn system, all elements have similar radii (from 124 to 130 pm), which contributes to a smaller δ_r and, accordingly, a higher probability of forming stable solid solutions. For reference, the atomic radii of elements in the studied systems are: Fe – 126 pm, Ni – 124 pm, Cr – 130 pm, Cu – 128 pm, Mn – 127 pm. The difference in electronegativity ($\Delta\chi$) has a minimal effect on the formation of a solid solution. Studies [16–18] show that at $\Delta\chi$ values exceeding 0.117, the formation of intermetallics is likely.

Table 3.5 Thermodynamic parameters of high-entropy alloys

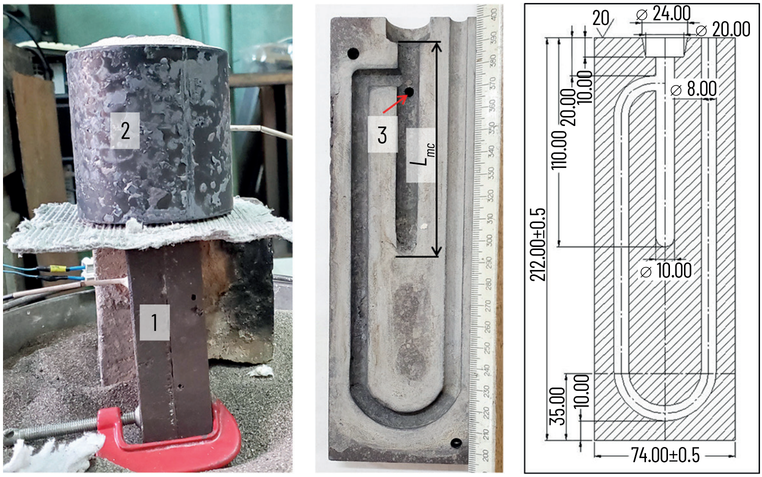
Alloy No.	ΔSmix/R*	ΔSmix (J/mol·K)	ΔHmix (kJ/mol)	Ω	δr (%)	$\Delta\chi$	VEC	Lattice
1	1.635	13.597	1.992	11.50	4.091	0.147	8.56	FCC
2	1.628	13.538	–4.867	4.315	6.349	0.132	7.69	BCC+ FCC
3	1.644	13.669	–3.863	5.527	6.011	0.129	7.823	BCC+FCC
4	1.608	13.371	–3.230	6.587	5.461	0.125	7.846	BCC+FCC
5	1.624	13.504	2.427	9.549	3.256	0.143	8.397	FCC
6	1.615	13.424	–4.231	5.025	5.721	0.125	7.601	BCC+FCC
7	1.609	13.374	–4.153	5.814	3.171	0.136	8.033	FCC
8	1.636	13.601	1.799	12.74	4.046	0.148	8.540	FCC
9	1.628	13.535	1.798	12.62	4.066	0.148	8.589	FCC
10	1.612	13.404	–3.772	5.639	5.588	0.124	7.745	BCC+FCC

*Note: *R – universal gas constant (8.314463 J/mol·K).*

3.3 CASTING PROPERTIES OF HIGH-ENTROPY ALLOYS

To evaluate alloys as casting materials, their technological characteristics, which are commonly called casting properties, are studied. To date, the casting properties of high-entropy alloys remain insufficiently studied, which determines the relevance of the presented work. The main casting properties include fluidity, linear and volumetric shrinkage, crack resistance. In addition, this these characteristics include macro- and microstructure, the tendency of the alloy to gas saturation, contamination with oxide films during melting, as well as the manifestation of liquation heterogeneity of the composition. In this work, fluidity (λ) (the ability of the alloy to fill the cavity of the casting mold and accurately reproduce its configuration) and linear shrinkage (ε_l) were studied. To determine them, special test molds were developed that allow obtaining quantitative data: U-shaped cast iron test mold with a vertical channel, which is an improved modification of the Nehendzi–Samarin mold, and a sand-clay test mold with an annular channel [29]. For the manufacture of sand-clay test molds, quartz sand was used as a filler. Liquid glass (4–5% by mass), technical lignosulfonates and kaolin (2–3% by mass), as well as the special surfactant (mixture of sodium salts of alkylbenzenesulfonic acids), fuel oil (1–1.5% by mass) and technical urea were used as binders. To prevent the formation of burn-in on the surface of the castings during pouring, the inner surface of the sand-clay sample was covered with antipenetration paste, which included: marshalite (ground powdered quartz), polyvinyl butyral, technical alcohol, acetone and nitro enamel.

To ensure the feeding of the mold with liquid metal until complete solidification in the U-shaped channel, a sand-clay pouring cup (funnel) was used, which provided effective thermal insulation of the melt (**Fig. 3.4**). The dimensions of the pouring cup: external dimensions – diameter 90 mm, height 90 mm; cavity dimensions – diameter 50 mm, height 65 mm. The metal flowed from the cup into the cast-iron U-shaped sample through a transition channel 30–35 mm long and 13 mm in diameter, which ensured uniform metal flow from the funnel. This contributed to the initial stabilization of the filling rate of the cast iron mold, while the final stabilization was provided by the central downgate of the U-shaped mold itself. The temperature of the metal in the cast iron U-shaped test mold was controlled using a tungsten-rhenium thermocouple installed in the central riser near its junction with the U-shaped channel (**Fig. 3.4**, designation 3). Based on these measurements, the key thermal parameters of the experiment were determined: liquidus temperature, solidus temperature, cooling rate.



a *b* *c*

⬡ **Fig. 3.4** Cast iron U-shaped test mold for determining fluidity and linear shrinkage of alloys according to the Nehendzi–Kuptsov method: *a* – photograph of the collected test mold; *b* – manufactured cast iron test mold; *c* – test mold`s drawing ; 1 – cast iron U-shaped test mold; 2 – sand-clay pouring cup (funnel); 3 – thermocouple installation location in the central downgate of the U-shaped test mold

The inner surface of the cast iron test mold was painted with a special water-based refractory paint (disthene-sillimanite – 70% by weight, perlite – 25%, bentonite – 2.5%, dextrin – 2.5%). Both halves of the mold after assembly were fixed with guide rods and a clamp. The temperature of the U-shaped mold was 16°C (room temperature). The pouring cup and the sand-clay mold with an annular channel, which was used as a test mold for fluidity, were dried at a temperature of 600°C for 3–4 hours.

After drying, the pouring cup was installed on the upper part of the U-shaped cast iron test mold, and the sand-clay test mold with an annular channel — on a special ceramic stand. One portion of molten metal weighing about 600 g was poured into the funnel of a U-shaped cast iron test mold, and the second portion of the same mass was poured into a sand-clay mold for fluidity test. The temperature of the melt before pouring was controlled in the furnace, then in the pouring cup and in both test molds (**Table 3.6**). The pouring time was 3–4 seconds.

Table 3.6 Pouring temperatures for fluidity and linear shrinkage of various alloys

Alloy	$t_{furnace}$, °C	$t_{pouring\ cup}$, °C	$t_{U\text{-}mold}$, °C	λ, mm	ε_l, %
FeNiCrCuMn	1450–1500	1400–1406	1180–1206	142–147 {65–105}	2.22–2.63
FeNiCrCuAl	1550–1600	–	–	320	2.50
G25 (AISI 1025)	1570	1514	1446	277{114}	1.95±0.15
GX10CrNiMn18-9-1 (AISI 304L)	1550	1459	1398	262{179}	2.66±0.058

*Note: In curly brackets is the length of the cost annular channel of the sand-clay mold (**Fig. 3.6**). $t_{furnace}$ – metal temperature in the crucible of the induction furnace before casting; $t_{pouring\ cup}$ – metal temperature in the pouring cup above the U-shaped test mold; t_{U-mold} – metal temperature at the entrance to the U-shaped channel*

A control series of experiments were conducted to study the fluidity and linear shrinkage of high-entropy alloys of the FeNiCrCuMn and FeNiCrCuAl systems. For comparison, the casting properties of steel grades G25L (AISI 1025) and GX10CrNiMn18-9-1 (AISI 304L) were also determined.

As shown in **Fig. 3.5, 3.6** and **Table 3.6**, the fluidity of the FeNiCrCuMn high-entropy alloy is lower than that of standard steels, whereas the FeNiCrCuAl alloy exhibits higher fluidity. It is known that the fluidity of alloys is significantly affected by the chemical composition and other technological properties [30]. The increased fluidity of the FeNiCrCuAl system alloy can be explained by a shorter crystallization interval compared to the FeNiCrCuMn system alloy. In order to finally draw a conclusion about the fluidity of high-entropy alloys, it is necessary to conduct additional experiments: stabilize the metal pressure in the test mold, its geometric dimensions and configuration; control the temperature of the melt overheating above the liquidus temperature; and also control the temperature in the pouring cup.

It should also be taken into account that when using a massive metal U-shaped test mold, the influence of the thermophysical properties of the alloy under study on the result can be very significant. This influence increases with increasing heat transfer intensity from the metal to the mold. In this case, the thermophysical parameters of the alloy may become the predominant factor governing fluidity, diminishing the influence of other melt properties. No tendency to the formation of hot cracks was detected in the studied high-entropy alloys.

The linear shrinkage in this work was determined as the difference between the linear dimensions of the foundry mold cavity (L_{mc}) filled with molten metal and the dimensions of the resulting casting (L_c) after cooling, according to the formula [29]

$$\varepsilon_l = \frac{L_{mc} - L_c}{L_c} \cdot 100\%. \tag{3.11}$$

Prior to pouring the metal into the fluidity test mold, the linear dimension of the mold cavity (L_{mc}) was measured (**Fig. 3.4, *b***). After solidification, the length of the casting (L_c) formed in the central downgate of the U-shaped test mold was recorded (**Fig. 3.5**), and the linear shrinkage was subsequently calculated. The linear shrinkage of castings from high-entropy alloys of the FeNiCrCuMn and FeNiCrCuAl systems approaches the shrinkage of high-alloy steels and ranges from 2.22% to 2.63% (**Table 3.6**). The value of the linear shrinkage depends on the chemical composition of the alloy, the temperature and rate of filling the mold, as well as the cooling rate of the casting itself. It is known that the linear shrinkage of castings of gray cast iron is on average 1%, of steel – 2%, and for most other alloys – about 1.5%.

a *b* *c* *d*

Fig. 3.5 Filled U-shaped channels in the Nehendzi–Kuptsov test mold with overfills for determining the fluidity of various alloys: *a* – casting from stainless steel GX10CrNiMn18-9-1 (λ = 262 mm); *b* – steel casting G25 (λ = 277 mm); *c* – high-entropy alloy casting of the FeNiCrCuMn system (λ = 142 mm); *d* – high-entropy alloy casting of the FeNiCrCuAl system (λ = 320 mm)

Fig. 3.6 Assembled complex sand-clay test mold and castings from various alloys for determining fluidity and mechanical properties: *a* – complex ring test mold; *b* – high-entropy alloy casting of the FeNiCrCuMn system (λ = 105 mm); *c* – stainless steel casting GX10CrNiMn18-9-1 (λ = 179 mm); *d* – gray cast iron (λ = 265 mm)

3.4 STUDY OF THE PHYSICAL AND MECHANICAL PROPERTIES OF HIGH-ENTROPY ALLOYS

Uniaxial tensile testing is relatively straightforward to analyze and enables the determination of several key mechanical properties of a material in a single test. These properties serve as quality indicators and are essential for engineering design calculations. Testing of samples with a diameter of 6 mm and a length of 30 mm was carried out on a tensile machine model P5.

Samples with a diameter of 3 mm and a length of 35 mm were stretched on a 1246P-2/2300 NIKIMP installation in accordance with the requirements of DSTU EN 10002-1:2006. The stretching rate was constant and was 1 mm/min, which corresponded to a deformation rate of $\acute{\varepsilon} = 10^{-3}$ s^{-1}. The load and elongation of the samples were measured using force and displacement sensors (extensometers) with adapters. During the tests, the yield strength ($\sigma_{0.2}$), the ultimate tensile strength (σ_u), relative elongation (δ), reduction of area (ψ) and the elastic modulus (E) were determined.

Brinell hardness was determined by applying a load of 750 kgf for 15 seconds using a hardened steel ball with a diameter of 5 mm pressed into the material. To determine the hardness by the Vickers method, a tetrahedral diamond pyramid with an angle at the apex of 136° was pressed into the samples. During the tests, loads of 10, 20 and 30 kgf were used; the holding time did not exceed 15 s.

The samples` hardness of alloys of the FeNiCrCuAl system (Samples No. 2–4, 6, 10) (**Table 3.7**) is more than one and a half times higher than the hardness of samples of the FeNiCrCuMn system (Samples No. 1, 5, 8, 9). The formation of a B2-ordered body-centered cubic (BCC) phase at higher aluminum contents is the main factor responsible for the hardness increase. In addition, a significant difference in the atomic radii of aluminum compared to other alloy elements causes local distortions of the crystal lattice, which additionally contributes to increasing hardness and temporary resistance to fracture. The results obtained are consistent with the data of other studies. In particular, in [31], experimental values of microhardness and reduced Young's modulus for the studied alloys in the entire range of aluminum concentrations are given. The dependence of microhardness is monotonic and reaches a maximum when the alloy consists entirely of a solid solution based on the BCC phase. Samples of the FeNiCrCuAl system with a mixed structure (with BCC and FCC lattices) in the cast state are characterized by brittle fracture in the elastic region: $\delta < 0.1\%$, $\psi < 0.1\%$, without a clearly defined conditional yield point (**Fig. 3.7**). In contrast, alloys of the FeNiCrCuMn system with FCC structure demonstrate high plasticity: $\delta = 40\%$, $\psi = 64\%$ (**Table 3.7**).

The ultimate strength or temporary fracture resistance (σ_u) was used in the formula [32]:

$$HB(HV) = k\sigma_u, \tag{3.12}$$

where the coefficient k is 2.54 for alloys of the FeNiCrCuMn system and 3.04 for alloys of the FeNiCrCuAl system were calculated.

Thus, high-entropy alloys with aluminum content are brittle, but are characterized by the highest hardness. In contrast, samples of the FeNiCrCuMn system with FCC structure have significant plasticity and relatively low hardness, while their ultimate tensile strength and yield strength are not inferior to those of high-alloy standard steels.

The tensile strength of alloys of the FeNiCrCuAl system exceeds the strength of high-strength cast iron of the EN-GJS-600-3 grade. Therefore, the mechanical properties of high-entropy alloys are determined by their crystal structure and elemental composition: alloys with a BCC lattice are characterized by high strength and low plasticity, while materials with FCC lattice, on the contrary, are characterized by lower strength but high plasticity.

Table 3.7 Hardness and mechanical properties of high-entropy alloys

Alloy No.	Hardness (kgf/mm²)		σ_u, MPa	$\sigma_{0.2}$, MPa	δ, %	ψ, %	Elastic modulus, GPa
	HB	HV					
1	156±13.5	–	603	335	40	64	122
2	309±6.4	–	997	–	–	–	–
3	228±36	246.4±10.5	735	–	–	–	136
4	304±25	–	981	–	–	–	–
5	218±18.5	–	842	–	–	–	–
6	291±8		939				
7	–	152±5.5	587	–	–	–	–
8	125±12	–	483	–	–	–	–
9	157±3.64	–	606	–	–	–	–
10	275±17.3	–	887	–	–	–	–

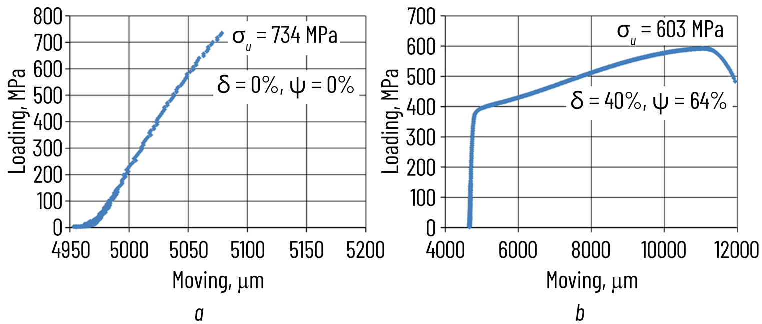


Fig. 3.7 Load-strain curves obtained during tensile testing of cast alloy samples belonging to the following systems: *a* – FeNiCrCuAl; *b* – FeNiCrCuMn

3.5 STUDY OF THE THERMOPHYSICAL CHARACTERISTICS OF THE OBTAINED ALLOYS

The thermophysical characteristics of the alloys were studied using a synchronous thermal analyzer (STA) of the STA 449F1 brand, manufactured by NETZSCH, Germany. STA is a combination of two research methods that are implemented simultaneously on one sample – thermogravimetry (TG) and differential scanning calorimetry (DSC). The main advantage of synchronous thermal analysis is that the mass change and thermal effects are measured on one sample simultaneously.

This approach provides a comparison of the results obtained by eliminating the influence of such factors as material heterogeneity, experimental conditions, sample preparation, etc. In addition, the combination of TG and DSC provides a more accurate determination of enthalpy values, since at any moment of the experiment the actual mass of the sample is known. In addition, the STA method saves time and sample material, which is especially important if the amount of the studied substance is limited, as well as when working with expensive or scarce materials.

The study of the thermophysical characteristics of the HEAs were carried out in crucibles made of alumina, in a dynamic environment of high-purity argon (20 ml/min). The heating and cooling rate was 20 K/min. The accuracy of temperature measurement was ±1°C. The sensitivity of the DSC signal registration was less than 1 μW. At the same time, the accuracy of determining enthalpy and heat capacity is ensured at the level of 3%. Thermal balances allow, during the experiment, to determine the current mass of the sample with an accuracy of 1×10^{-7} grams. The high sensitivity of the DSC allows to detect even insignificant thermal effects that arise in the material when heated or cooled, on the other hand, to record changes in the thermophysical properties of the sample under study. The ability of thermal balances to record the slightest change in the mass of the sample during the experiment allows to record the processes that occur in alloys during heating. Therefore, by the increase in the mass of the sample, it is possible to detect and control the oxidation of alloys. The loss of mass of the sample can be used to track the process of evaporation and decomposition. Therefore, synchronous thermal analysis is widely used in the study of high-entropy and amorphous alloys [33].

When studying the obtained high-entropy alloys, the melting point of the alloy (t_s – solidus temperature) was determined, and during cooling, the crystallization point (t_l – liquidus temperature) and the crystallization interval of the alloy were determined as the difference $\Delta t = t_s - t_l$. The alloy samples were heated to a temperature of 1450°C at a rate of 20 K/min, then cooled below 200°C and heated again to 1450°C (**Fig. 3.8**).

It is possible to distinguish the difference between the alloys of two different systems FeNiCuCrMn and FeNiCuCrAl during their melting (**Fig. 3.9**). The thermogram of the alloy containing manganese clearly shows two separate melting peaks from two different phases, while in alloys of the FeNiCuCrAl system containing aluminum, one broad asymmetric peak was usually recorded.

The results of the studies are given in **Table 3.8**.

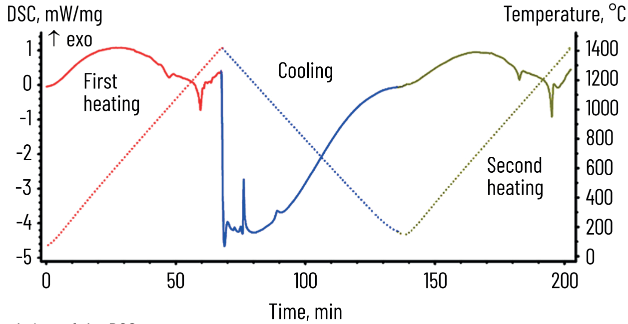
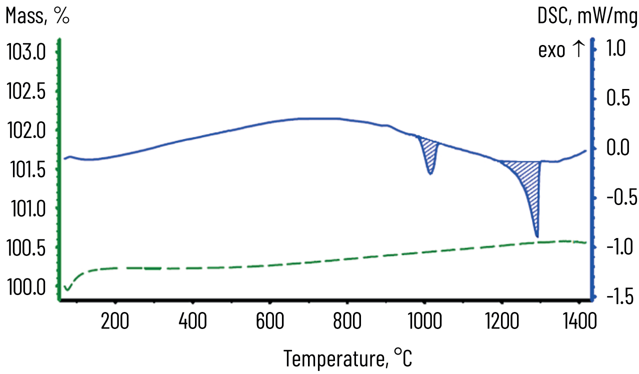
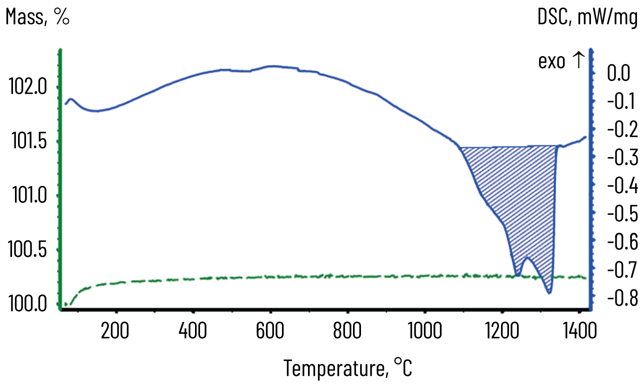


Fig. 3.8 General view of the DSC curve



a



b

Fig. 3.9 STA curves: *a* — FeNiCrCuMn system; *b* — FeNiCrCuAl system

Table 3.8 Solidus, liquidus temperatures and crystallization intervals of high-entropy alloy samples

Sample No.	Solidus temperature, °C	Liquidus temperature, °C	Crystallization interval, °C	Melting heat, J/g	
				Solidus	Liquidus
1	2	3	4	5	6
1	988.6	1284.4	295.8	29	80
2	1200	1310.8	110.8	223*	–
3	1090	1320.8	230.8	226*	–

Continuation of Table 3.8

1	2	3	4	5	6
4	1123	1350	227	241*	–
5	996.9	1306.2	309.3	24	76
6	1098.5	1342.3	243.8	3,6	119
8	984.6	1281.2	296.6	30	131
9	990.8	1285.2	294.4	26	120
10	1100	1345.5	245.5	279*	

*Note: *Double peaks that cannot be separated.*

3.6 STUDY OF ELASTIC PROPERTIES OF HIGH-ENTROPY ALLOYS BY DMA METHOD

In this work, dynamic mechanical analysis (DMA) was first used to study the elastic properties and internal friction of high-entropy alloys depending on temperature. The basics of the DMA method were developed by K. Menard in 1998 [34]. DMA provides an opportunity to investigate the change in elastic properties of materials under the action of small periodic, usually sinusoidal dynamic loads depending on temperature, time and frequency. One of the leading companies in the world that produce DMA analyzers is the NETZSCH company (Germany). The DMA 242C analyzer of this company was used for the research.

Main technical characteristics of the DMA 242C analyzer of the NETZSCH company:

– temperature range: –170…600°C;
– frequency range: 0.01…100 Hz;
– range of adjustable loads: Max. ± 8 N static and Max. ± 8 N dynamic;
– range of deformation amplitudes: Max. ± 240 μm;
– sensitivity to the magnitude of deformation: 0.5 nm.

The appearance and schematic diagram of the DMA 242C analyzer are shown in **Fig. 3.10**.

As can be seen from the above characteristics, in this case very small loads are applied to the sample (total 1.6 kg), therefore this method is rarely used for metals and alloys. This method is widely used to study the mechanical characteristics of rubber, polymer films, polymers and fibers.

Based on the fact that the mechanical properties of alloys are structurally sensitive, that is, a change in the phase composition or structure of the material necessarily affects its mechanical characteristics, the DMA method was used not for its direct purpose – determining the absolute values of mechanical characteristics, but to study the features of structure formation in HEAs during their heat treatment and loading.

The principle of DMA operation is based on the registration of the reaction of the material (elongation, stress, phase shift, amplitude) to the action of small periodic dynamic loads depending on temperature, time and frequency. If a mechanical force (F) is applied to the sample under study, it will cause the corresponding reaction of the material – deformation, stress, amplitude and phase shift. Registration of changes in parameters and appropriate mathematical processing make it possible to assess the influence of factors on the elastic properties of the material.

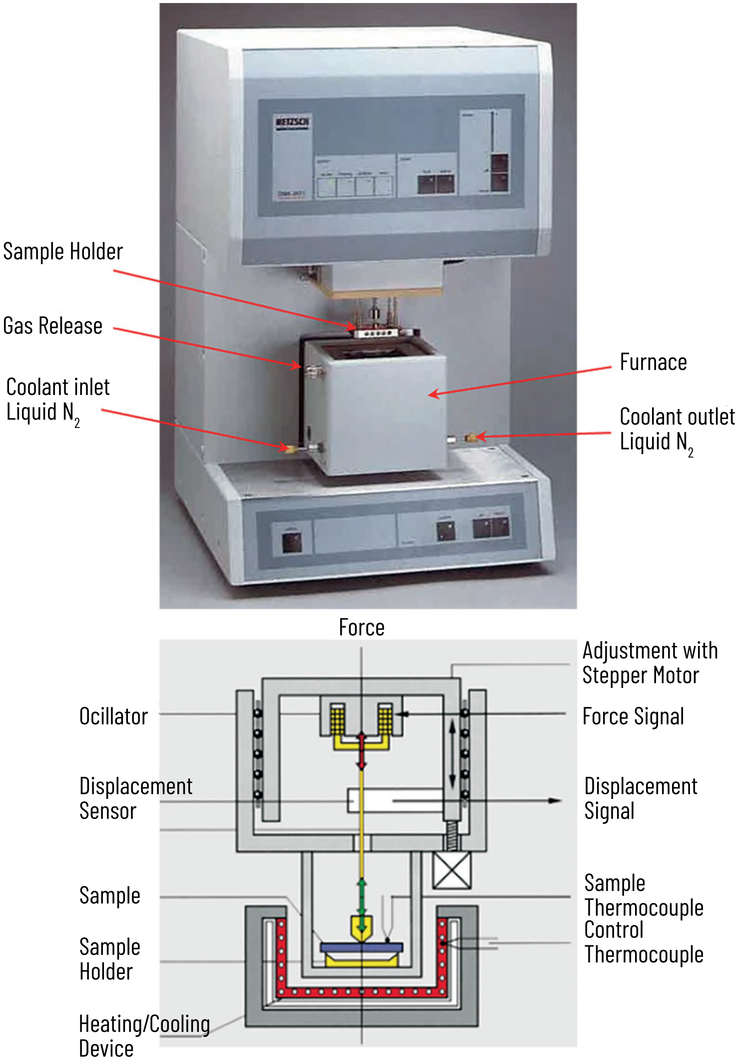


Fig. 3.10 Appearance and schematic diagram of the DMA 242C analyzer

As is known, the complex modulus of elasticity of a viscoelastic material can be written as:

$$|E| = \frac{\sigma}{\varepsilon}, \quad (3.13)$$

where E — the complex modulus, MPa; σ - the load, N; ε — the strain, μm; or

$$|E| = \sqrt{\left[E^{I}(\varepsilon)\right]^2 + \left[E^{II}(\varepsilon)\right]^2}, \quad (3.14)$$

where E_I — the modulus of elasticity, characterizing the elastic properties of the material; E_{II} — the loss modulus, characterizing the conversion of mechanical energy into other types of energy, for example, into heat, and is a measure of the unreturned, lost energy of oscillations; ω — the frequency of oscillations.

Moduli of elasticity are vector quantities, the relationship between them is shown by the equations:

$$E^{I} = |E|\cos\delta, \quad (3.15)$$

$$E^{II} = |E|\sin\delta. \quad (3.16)$$

For an elastic material: α = 0, cos 0 = 1, sin 0 = 0

$$E = E^{I}. \quad (3.17)$$

For a viscous material: α = 90°, cos90° = 0, sin90° = 1

$$E = E^{II}. \quad (3.18)$$

Often, to assess the elastic properties of materials, a quantity called the loss coefficient, or the tangent of the loss angle, or the internal friction of the viscoelastic system is used, it is defined as

$$\tan\alpha = \frac{E^{II}(\omega)}{E^{I}(\omega)}. \quad (3.19)$$

DMA analysis makes it possible to determine all the above parameters depending on time, temperature, load value and frequency. Additionally, it is possible to determine the coefficients of thermal expansion of the material.

DMA studies were carried out by the three-point bending method on samples measuring 2×1×45 mm at a static load of 8 N and a dynamic load of 7 N, a maximum amplitude of 100 μm and frequencies of 1, 5, 10 Hz.

Since there are no values of the elastic characteristics of high-entropy alloys in the literature, to assess the reliability of our results, a theoretical calculation of the elastic modulus was performed according to the additivity law:

$$E_{theor} = \sum_{i=1}^{n} c_i E_i, \quad (3.20)$$

where E_i — the Young's modulus of the *i*-th element; $c_i \leq 1$ — the concentration of the *i*-th element in atomic ratio; *n* - the number of elements in the alloy. The values of Young's modulus of pure metal elements are given in **Table 3.9**. The results of the studies are given in **Table 3.10** and **Fig. 3.11, 3.12**.

Table 3.9 Values of Young's modulus of pure metals

Metal	Al	Fe	Cr	Co	Ni	Mn	V	Ti	Zr	Nb	Hf	Ta
Young's modulus, GPa	70	210	250	200	200	194	135	120	97	105	137	186

Table 3.10 Elastic properties of the studied alloys

Alloy	Etheor, GPa	Eexp, GPa	Eexp/Etheor
$Ti_2ZrHfNbTa$	130.9	91	0.7
$TiZr_2HfNbTa$	134.2	119	0.88
$CrMnFeCo_2Ni_3$	210.7	194	0.92
$Al_5Cr_{15}Mn_{11}Fe_{18}Co_{17}Ni_{31}V_3$	202.9	147	0.72
$Al_{27}Cr_{16}Fe_{20}Co_{18}Ni_{19}$	174.9	131.2	0.75

Young's modulus and internal friction of the alloy are structurally sensitive parameters, therefore, using dynamic mechanical analysis, it is possible to establish those structural changes that are not recorded by DSC analysis, since they occur without thermal effects, or these effects are strongly stretched in time, therefore, DMA analysis can be used to study martensitic transformations [35, 36], relaxation in amorphous alloys [37] and other effects that are poorly recorded by other methods. The studies conducted in this way show that most of the obtained HEAs have structural transformations in the temperature range from 100 to 300°C.

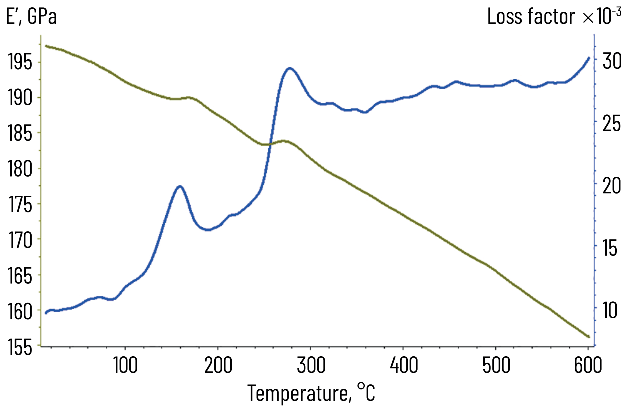


Fig. 3.11 Curves of dynamic mechanical analysis of high-entropy alloy $CrMnFeCo_2Ni_3$

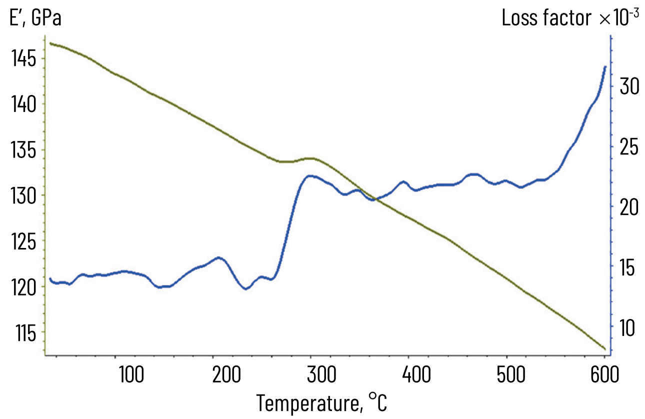


Fig. 3.12 Curves of dynamic mechanical analysis of high-entropy alloy $Al_5Cr_{15}Mn_{11}Fe_{18}Co_{17}Ni_{31}V_3$

3.7 RESEARCH ON THE HEAT RESISTANCE OF HIGH-ENTROPY ALLOYS

The heat resistance of high-entropy alloys was studied using the method of GOST 6130-71 "Methods for determining heat resistance", recording the ratio of the change in sample weight to its surface area (mg/cm^2). Using this method, the heat resistance of HEA samples that demonstrated low kinetics during heating and aging in an artificial air atmosphere at temperatures of 900°C or 1000°C was studied and the data were compared with standard alloys with different oxidation resistance.

To study the heat resistance, a STA 449 Jupiter F1 synchronous thermal analysis device was used. The study was carried out in an inert gas flow (high-purity argon 20 ml/min) and in a dynamic oxidizing environment (artificial air 20/80 O_2/N_2, 100 ml/min). The experiments were carried out on cast samples of the same size and shape. To establish the temperature and quantitative parameters of oxidation, two measurement modes were used: the study of oxidation kinetics and the study of heat resistance.

Mode 1. The samples were heated in air to 1450°C. The temperature of the onset of intensive oxidation was recorded using the thermogravimetry (TG) curve, which was determined by a sharp increase in the weight of the sample. The temperature of the onset of the exothermic effect and its enthalpy, which corresponds to the formation of an oxide film, were determined using the differential scanning calorimetry (DSC) curve. This mode allows to establish the characteristic temperatures of the onset of intensive oxidation with high accuracy (±1°C). The specific oxidation intensity was calculated as the ratio of the thermal effect to the surface area of the sample (J/g cm^2).

Mode 2. The samples were heated at the maximum possible rate of 50 K/min, subjected to isothermal holding in a stream of artificial air at 900°C and 1000°C for 4 hours with continuous control of the sample weight.

Heat resistance was estimated as the specific increase in the sample weight during the exposure time, related to its surface area (mg/cm^2.h).

Thermogravimetric diagrams of the oxidation of the samples were recorded and processed using the Netzsch Proteus software package.

There are compositions of the samples used for the studies in **Table 3.1**. In addition, Sample 7_1 was added to the study, which is close to Sample 7 but in its composition manganese was replaced by aluminum (actual composition in wt % of Al-15, Cr-17, Fe-23, Co-21, Ni-22).

For comparison of heat resistance, standard alloys G45, SM96, GX10CrNiMn18-9-1 were used. During the study, it was found that alloys G45, SM96 have low heat resistance compared to the studied samples of high-entropy alloys, therefore their values were not included in the final heat resistance comparison diagrams, these data can be found in **Table 3.11**.

Table 3.11 STA results of oxidation studies of standard alloys

No.	Alloy	Onset temperature of the intensive, oxidation °C	Oxidation intensity, J/g cm^2	Average oxidation at 900°C, mg/cm^2 h	Average oxidation at 1000°C, mg/cm^2 h
1	G45(C45)	948	2840	3.28	5.7
2	SM96	1113	358.3	0.85	2.31
3	GX10CrNiMn18-9-1	1142	1497	0.02	0.17

High-strength alloy SM96 with a special coating is used for the manufacture of blades of gas turbine engines, although it is excluded from the final comparison diagrams, it is heat-resistant, since compared to steel G45, its oxidation resistance is almost 4 times higher. Oxidation of this alloy occurs in two stages. The first stage begins at 1113°C and continues to 1318°C, in this temperature range there is moderate oxidation of the alloy, which leads to an increase in its weight by 0.63%. More intensive oxidation of this alloy begins at a temperature of 1318°C.

GX10CrNiMn18-9-1 steel showed sufficiently high heat resistance, therefore its results are shown in **Fig. 3.13** and **3.14** under number 8. Although this alloy has an temperature of intensive oxidation above 1000°C. Within prolonged exposure at 1000°C, its low oxidation intensity is initially maintained, but after 200 min exposure, the sample begins to oxidize intensively and the surface of the sample is quickly covered with a dense layer of oxide. After 30 minutes, an oxide layer forms on the surface of the sample, blocking access to the metal surface and the oxidation rate decreases, **Fig. 3.15**.

HEA Sample No. 1 when heated to 1000°C has a threshold for increasing the intensity of oxidation at a temperature close to 400°C and from this temperature gradually oxidizes (**Fig. 3.16**). Other HEA samples with manganese (Samples No. 5, 7) behave in a similar way. When exposed for 4 hours at 900°C, they continue to oxidize evenly, the intensity of oxidation decreases with exposure time, which is obviously a consequence of the oxide layer. But when heated to 1000°C, the intensity of oxidation remains approximately the same.

HEA No. 4 when heated to 1000°C practically does not oxidize during heating (**Fig. 3.17**). When exposed for 4 hours at 900°C, it oxidizes evenly with a very low intensity (average oxidation rate 0.001 mg/min). The same, low level of oxidation intensity is maintained when exposed at a temperature of 1000°C. HEA No. 6 behaves similarly, which is close in chemical composition to HEA No. 4 and contains Al at the base of its chemical composition.

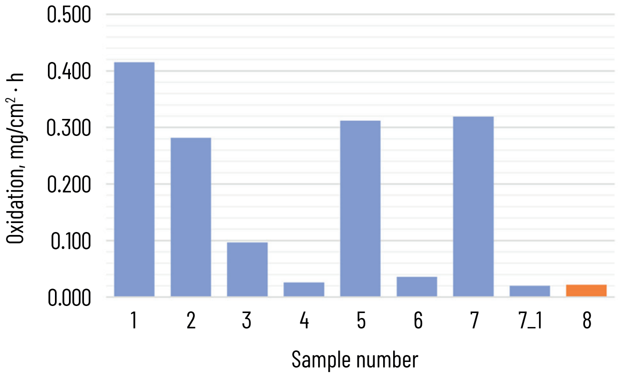


Fig. 3.13 Average oxidation of samples mg/cm^2·h at 4-hour isothermal holding at 900°C

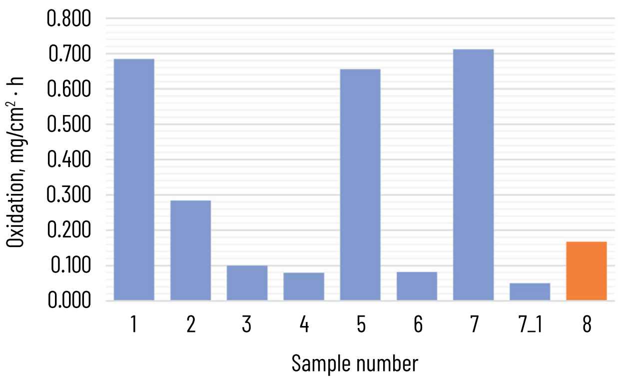


Fig. 3.14 Average oxidation of samples mg/cm^2·h at 4-hour isothermal holding at 1000°C

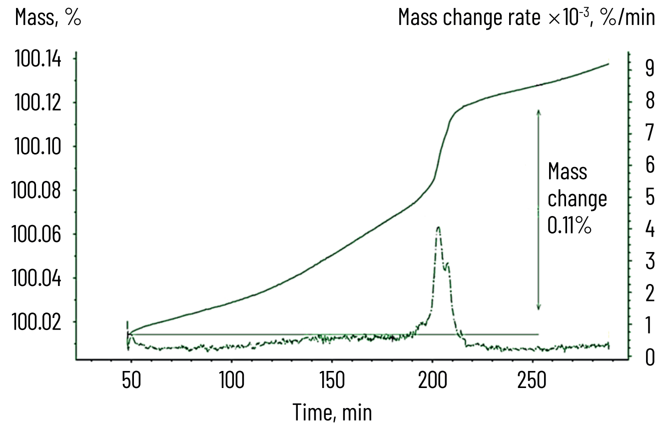


Fig. 3.15 Thermogravimetric diagram of steel GX10CrNiMn18-9-1 when exposed to artificial air at 1000°C

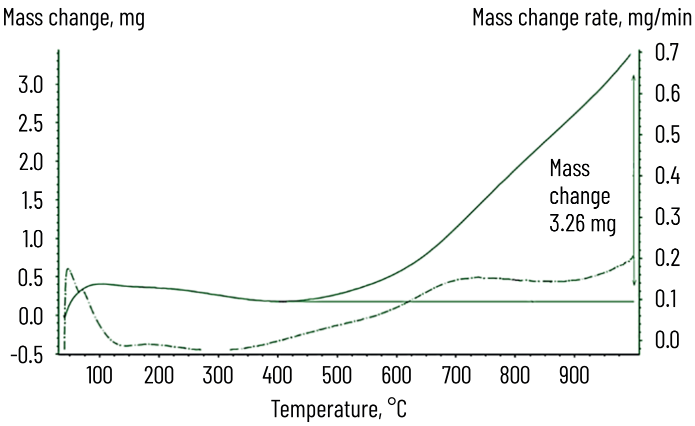


Fig. 3.16 Thermogravimetric diagram of the HEA Sample No.1 when heated to 1000°C

HEA Sample No. 3, similar in chemical composition, is oxidized more intensively, but still at a relatively low level. It demonstrates equally high heat resistance and its oxidation rate is in the range from 0.002 mg/min to 0.003 mg/min when exposed for 4 hours both at 900°C and at 1000°C.

HEA No. 2, when heated to 1000°C begins to gain weight of the oxide film at temperatures above 400°C, and already at a temperature of 516°C begins to oxidize intensively, rapidly gaining weight with an intensity of up to 0.219 mg/min (**Fig. 3.18**). The surface of the sample is quickly covered with a layer of oxide, which blocks access to the metal surface and already at a temperature close to 800°C the oxidation rate decreases, but above 900°C the oxidation intensity begins to increase again.

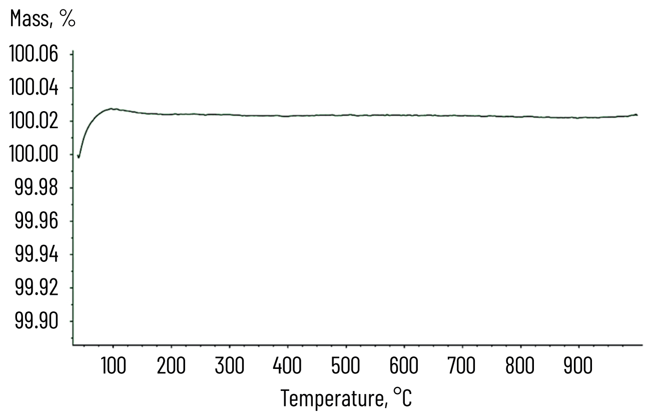


Fig. 3.17 Thermogravimetric diagram of HEA Sample No. 4 when heated to 1000°C

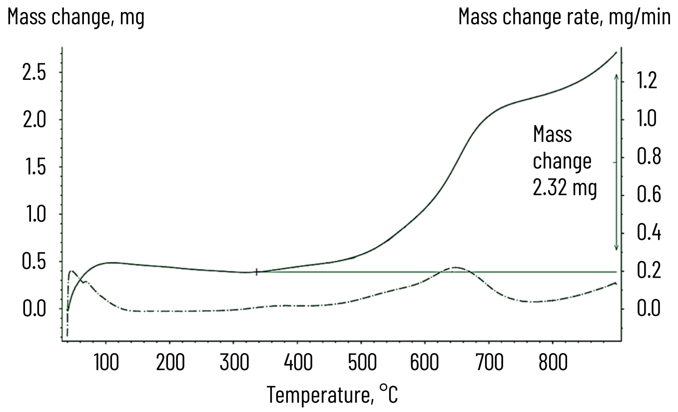


Fig. 3.18 Thermogravimetric diagram of the HEA Sample No. 2 when heated to 1000°C

After 4 hours at 900°C, the sample continues to oxidize evenly, but with a low oxidation intensity, since the oxide layer protects the surface of the sample. Approximately the same oxidation intensity is maintained after 4 hours at a temperature of 1000°C. Such a strong difference in heat resistance is probably directly related to the decrease in the chromium content in the sample.

A representative example is HEA Sample No. 7_1. Its composition is similar to that of HEA No. 7, but with manganese content replaced by aluminum. This substitution immediately altered the oxidation behavior. The heat resistance of this alloy at 900°C reaches the level of the reference alloy GX10CrNiMn18-9-1 (**Fig. 3.13**) and significantly surpasses it at 1000°C (**Fig. 3.14**). Furthermore, intensive oxidation is absent up to its melting point of approximately 1379°C.

HEA Samples No. 1, 5, 7 have average heat resistance, which significantly exceeds standard structural steels (G45) and even the heat-resistant alloy SM96. They begin to oxidize at 400—500°C, but the oxide layer at higher temperatures partially protects the materials.

HEAs samples No. 3, 4, 6, 7_1 practically do not oxidize at 900°C and 1000°C, surpassing steel GX10CrNiMn18-9-1 at temperatures above 900°C. Therefore, the oxidation behavior of the studied samples of high-entropy alloys differs depending on their composition. Thus, samples containing a combination of a significant amount of Al (6—11%) and Cr (14—18%), which contribute to the formation of protective oxide films Al2O3 and Cr2O3, have the best performance and an intensive oxidation temperature above 1000°C. Samples containing manganese and not containing aluminum have the lowest heat resistance in this alloy system. All samples with a high Mn content (~16—19%) showed the worst performance. HEA Sample No. 2 (Al ~11%, but Cr only ~13%) has worse resistance than HEA No. 3 (Al ~10%, Cr ~14%), which emphasizes the importance of the combination of these elements. The content of Copper (Cu) can worsen heat resistance, the most resistant samples are: No. 6 — has an average Cu content of ~20%, No. 7_1 does not contain copper at all (in its composition it is replaced by cobalt). HEA Sample No. 3 has the highest Cu content ~23.2%, which may also be the reason for the deterioration of heat and scale resistance indicators despite the presence of Al and Cr in sufficiently large quantities. This suggests that an excess amount of copper may be harmful and it is advisable to completely or partially replace it with cobalt to increase heat resistance.

CONCLUSIONS

A specially designed vacuum medium-frequency induction furnace provides reliable melting of high-entropy alloys (HEAs) at temperatures up to 1800°C with active mixing of the melt. This allows obtaining homogeneous ingots with precise chemical composition and minimizing the formation of non-metallic inclusions.

Thermodynamic analysis of HEAs compositions (estimation of mixing entropy, enthalpy, δ_r, $\Delta\chi$, VEC, Ω) showed that most of the studied alloys meet the criteria for the formation of solid solutions. In alloys with aluminum, the probability of the formation of ordered intermetallic phases of type B2 (NiAl) was revealed.

X-ray phase analysis confirmed the presence of FCC and BCC phases, in particular phases of type γ-Fe, B2-NiAl. In alloys with a high Mn content, two FCC phases with different lattice parameters are formed. The calculated lattice periods correlate with the theoretical VEC parameters.

Thermophysical characteristics of the alloys (liquidus/solidus temperatures, heats of fusion and crystallization) were determined experimentally based on STA studies. It was shown that the crystallization intervals for HEAs significantly affect their fluidity and dendritic morphology during casting.

The HEAs elastic properties were investigated by the method of dynamic mechanical analysis (DMA). It was found that the elastic modulus E' decreases with increasing temperature, and the loss tangent tgδ demonstrates stable viscoelastic behavior up to 600–700°C. This indicates good stability of the structure under thermomechanical loading.

The heat resistance of the alloys was tested at temperatures of 600–800°C. FeNiCrCuMn and FeNiCrCuAl alloys showed a slight change in mass, preservation of phase composition and microstructure, which indicates a high level of oxidative stability and suitability for long-term operation at high temperatures in air.

The casting properties of the HEAs (fluidity, shrinkage) were studied using spiral and U-shaped test molds. The best indicators were obtained for the the FeNiCrCuAl system alloys, which demonstrated a filling length of up to 320 mm, which exceeds the indicators of gray and special cast iron.

High-entropy alloys based on the FeNiCrCuAl system is promising heat-resistant casting material of a new generation. It combines good fluidity, high thermal stability, favorable microstructure and resistance to oxidation, which opens up wide possibilities for their practical application in critical machine components, heat exchangers, energy and chemical equipment.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

USE OF ARTIFICIAL INTELLIGENCE

The authors confirm that they did not use artificial intelligence technologies in creating the submitted work.

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4 CAST STRUCTURES WITH COMPOSITE AND REINFORCED NON-METALLIC FUNCTIONAL FILLER

ABSTRACT

The chapter presents the results of research on the scientific and technological prerequisites for obtaining steel hollow castings with composite and reinforced non-metallic filler by the lost foam casting method.

A system of equations was obtained that describes the gas-hydrodynamic conditions of lost foam casting with polystyrene patterns saturated with reinforcing elements (RE), and taking into account the heat exchange between RE and the matrix melt during mold filling and casting solidification.

Modern domestic and foreign materials for cast structures for protective purposes were analyzed and the prospects for the use of low-alloy and microalloyed steels were determined. It was established that optimal performance characteristics are achieved under the conditions of the correct selection of heat treatment modes, which provides a combination of high strength with sufficient plasticity.

To determine the influence of composite and non-metallic fillers on the possibility of obtaining a high-quality casting, computer simulation methods were used and the results obtained were verified by full-scale experiments.

The research conducted by the authors at the Physico-Technological Institute of Metals and Alloys of the National Academy of Sciences of Ukraine and carried out within the framework of project No. 2023.04/0029, state registration 0124U003980, supported by a grant from the National Research Foundation of Ukraine under the program "Science for Strengthening the Defense Capability of Ukraine" is of high scientific and practical importance for the manufacture of special-purpose foundry products and will be useful for specialists-manufacturers of foundry, scientists and scientific and pedagogical workers in the specialty "Metallurgy" (Foundry).

KEYWORDS

Reinforced cast structure, reinforcing filler, matrix melt, gas-hydrodynamic conditions, heat exchange processes, computer simulation, polystyrene foam pattern, cast steel, alloying, lost foam casting, heat treatment of steel, technological process.

Modern foundry production today is focused on a significant reduction in the metal content of products, simultaneously with the complication of their geometry and functional purpose. Therefore, the creation of scientifically based new technologies for the manufacture of hollow steel structures with special properties by the method of lost foam casting using reinforcing fillers is relevant and required additional research into the processes of heat and mass transfer and gas-hydrodynamics and the determination of optimal technological parameters.

To implement in industry a new design of cast hollow steel modules with a spherical surface and high-hardness compacted fillers and metal composites with a steel shell, the technology of lost foam casting was adapted, which made it possible to obtain a given binary design of modules of the system "steel shell – compacted filler in a bound state" and "steel shell – reinforced metal composite" in a single-cycle technological process and directly in the mold.

The new technological process for producing cast binary modules is based on the use of polystyrene foam patterns filled with the specified dispersed materials, which are installed in a mold, in which a vacuum is created and directly in the presence of the pattern, the liquid metal of the shell is poured. Under the conditions of heat exchange between the liquid metal and the polymer pattern, the latter undergoes thermal destruction, and its volume is filled with liquid metal. Under the influence of the heat flow from the metal, the filler forms a solid material in the form of a metal composite with a reinforcing steel phase, which corresponds in chemical composition to the shell metal. In this case, the liquid metal seeps into the filler due to the pressure gradient between the metal P_m and the porous filler P_f (P_m–P_f), since a vacuum is formed in the latter within (0.1…0.2) P_a (P_a – atmospheric pressure).

4.1 DETERMINATION OF THE THERMOPHYSICAL MODEL OF THE INTERACTION OF THE REINFORCING FILLER AND THE STEEL MATRIX MELT IN THE MOLD

The production of reinforced castings by lost foam casting are accompanied by complex gas-hydrodynamic and heat-mass exchange processes. When obtaining hollow castings by reinforcing them with metal and non-metallic fillers located in polystyrene foam patterns, new multi-component systems arise for the theory of casting processes: "metal – pattern – filler – mold" and "metal – reinforcing filler – mold". Therefore, the study of the regularities of heat and mass exchange in these systems in the manufacture of shell binary cast structures and their mathematical description is relevant. In this case, it is necessary to determine the influence of the presence of solid and porous polystyrene foam patterns, metal and non-metallic materials in the mold on the conditions of heat exchange in the mold. The phenomenon of liquid flow during lost foam casting is essentially a problem of unsteady flow with free boundaries. Molten metal flowing in the mold during lost foam casting destroys the polystyrene foam pattern, forming a gas gap between the molten metal and the pattern. The rate of destruction of the pattern and the pressure in this gap depend on the heat exchange in the mold, and in the presence of reinforcing elements this process is complicated. There is information on the development of a two-dimensional thermal model, which is based on the mass and energy balance in the gas gap between the polystyrene foam pattern and the molten metal. The pressure in the gap is determined by the mass and energy balance method, which directly takes into account such important process parameters as the permeability of the coating, foam characteristics, pouring temperature and metal properties, but does not take into account the presence of additional reinforcement [1].

Therefore, research devoted to the development of a thermophysical model of the interaction of the reinforcing filler, polystyrene foam pattern and liquid steel in the mold during lost foam casting was relevant.

At the same time, the development of a thermophysical model of the interaction of the reinforcing filler, liquid steel and polystyrene foam pattern in the mold during lost foam casting will make it possible to predict the conditions of the melt flow, its solidification and cooling in the mold, which makes it possible to create promising casting methods for obtaining high-quality reinforced structures, including hollow binary modules for protective structures.

The authors established the conditions of heat exchange in the mold in which the reinforcing elements are placed, under different flow regimes of the matrix alloy in the porous channels of the polystyrene foam pattern.

The process of interaction of molten metal with mono- and reinforced polystyrene foam pattern during lost foam casting was investigated.

According to previously established laws on the conditions of casting solidification, movement of matrix alloy (MA) in the mold in the presence of metal reinforcing elements (RE), their interaction with the polystyrene foam pattern and thermal destruction products in the form of liquid, gaseous and solid phases, a physical model of mass and heat transfer was developed during the formation of the structure and properties of cast reinforced structures in multicomponent systems new to the theory of casting processes: "metal — pattern — RE — mold" [2, 3].

At the same time, the boundary temperature conditions and the final temperature at the heat exchange boundary of the "MA-RE" system were established

$$T_k = \frac{T_L - T_S}{2}, \tag{4.1}$$

where T_L, T_S — liquidus and solidus temperatures for the matrix alloy, °C.

For the integrated MA-RE system, the heat exchange contact area will be $n.S_p$, $n.S_{MRE}$, respectively, where n —the number of reinforcing elements located in the mold cavity, pcs., and their mass will be

$$m = 0.785 \cdot n \cdot g_{MRP} \cdot R_{MRP}^2 \cdot L_{MRP}, \text{ kg} \tag{4.2}$$

where g_{MRP} — density, kg/m^3; L_{MRP} — characteristic length of the reinforcing element, m.

It should be noted that the vertical reinforcing elements installed in the mold (in this case, it is possible to consider them in the form of rods) complicate the flow area of the liquid metal (mold) and have a certain effect on the thermophysical and hydrodynamic processes occurring in it.

When obtaining castings, the resistance of the filler metal medium to be poured depends on the temperature conditions of filling the mold, the dimensions and geometry of the reinforcing elements and their placement in the mold cavity. It should be noted that the liquid alloy with dense packing of RE flows through "capillary" thin channels, which are formed by particles of these elements or in the cavity of the mold, in which RE are located at a fixed distance from each other.

To simplify the problem, it is possible to use the conditions of heat exchange in the form of a limit in a single channel of length L, filled with rods according to the heat balance scheme presented in works [3, 4] and in **Fig. 4.1, *a***, and has the form

$$c_p \cdot \rho \cdot V_{cp} \cdot F_c \cdot \left(T_b - T_b\right) = \alpha_c \cdot F_n \cdot \left(T_c - T_b\right)_c \qquad (4.3)$$

where T_{b2} – the average temperature at the channel outlet over the channel cross section, °C;

T_{b1} – the average temperature at the channel inlet over the channel cross section, °C;

C_p – the specific heat capacity, J/(kg×°C);

ρ – the MA density, kg/m^3;

F_c – the cross-sectional area of a single capillary channel, m^2;

V_c – the average flow velocity in the channel, m/s;

F_n – the total contact area of the liquid metal with the surface of the channel (filler), m^2;

T_c – the average wall temperature along the channel length, °C;

T_b – respectively, the average temperature of the liquid alloy along the channel length, °C;

α_c – the heat transfer coefficient at the boundary of the porous channel formed between the RE and the MA melt, W/m^2,°C.

It is also recommended to determine the heat transfer coefficient by formulas, the structure of which depends on the MA flow regime in the pore channels (laminar or turbulent) [4]. At the same time, for practical use and study of the kinetics of changes in the temperature of the matrix melt in the pore space, it is recommended to represent the contact surface of heat exchange in the system "matrix melt – reinforced phase" through the equivalent (integral) radius of the reinforcing element R_{ae} [2]. In this case, the heat transfer coefficient for the MA laminar flow in the channels formed by the RE is determined by the equation of the dimensionless heat transfer coefficient Nu_D [4]

$$Nu_{\overline{D}} = \frac{\alpha_c \overline{D}}{\lambda_c} = 1.86\left(\mathrm{Re}_{\overline{D}} \cdot \mathrm{Pr}\right)^{0,33} \cdot \left(\frac{\overline{D}}{L}\right)^{0,33} \cdot \left(\frac{\mu_b}{\mu_s}\right)^{0,14}, \qquad (4.4)$$

where $\overline{D}$ – the given channel diameter, m;

λ_c – Nusselt criterion, which characterizes the similarity of heat transfer processes at the interface between the wall and the fluid flow;

$\mathrm{Pr} = \frac{\nu}{a}$ – Prandtl criterion;

$\mathrm{Re} = \frac{V \cdot \overline{D}}{\nu}$ – Reynolds criterion;

n – viscosity coefficient, m^2/s;

α_c – thermal diffusivity coefficient, m^2/s;

μ_b – dynamic viscosity at metal temperature T_b, H×s/m^2;

μ_c – dynamic viscosity at wall temperature $T_s (T_s^3\ T_L)$;

T_L – liquidus temperature of the matrix alloy °C.

For turbulent MA flow regime in RE porous channels, the formula for *Nu* is recommended

$$Nu_{\overline{D}} = \frac{\alpha_c \cdot \overline{D}}{\lambda_c} = 0{,}036 \cdot \mathrm{Re}_D^{\,0{,}8} \cdot \mathrm{Pr}^{0{,}33} \cdot \left(\frac{\overline{D}}{L}\right)^{0{,}055}, \tag{4.5}$$

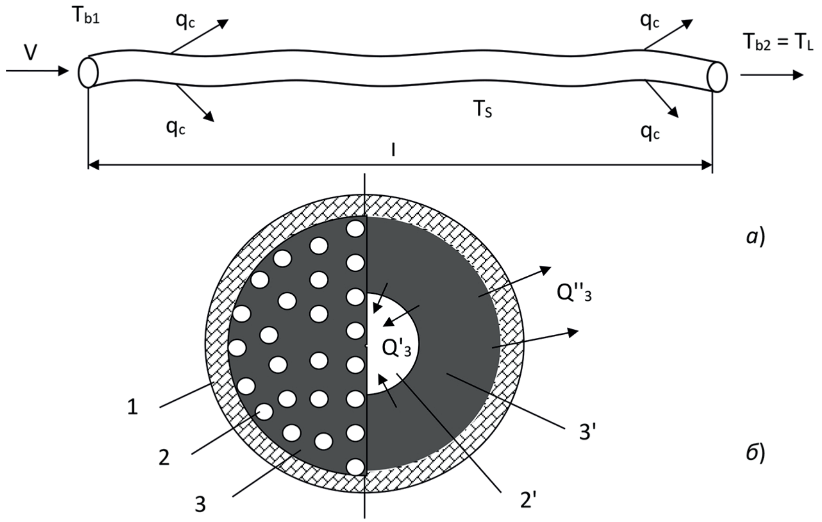


Fig. 4.1 Heat exchange scheme during melt flow in the pore space of the reinforcing phase along: a - the length; b - the cross-section of the mold with RE oriented in it: (*b*): 1 — shell (mold); 2 — reinforcing element; 3 — matrix melt; 2′ — equivalent cross-section of the reinforcing element; 3′ — equivalent cross-section of the matrix melt
Source: [3]

However, despite the achievements in the theory of MA melt flow in the RE environment located in the cavity of the mold, in the theory of lost foam casting the features of the interaction of thermal destruction products of the gasified pattern (GP) and their influence on the gasohydrodynamics of the process and the formation of the quality of cast blanks in the absence of a macroreinforcing phase were more often considered.

The RE presence directly in the polystyrene GP, and the latter is located in the cavity of the mold, allows to change the conditions of filtration and mass transfer of vapor-gas (VGP) and liquid products (LP), which are formed during the destruction of the pattern and modify the gas dynamics of the process, as well as the conditions for forming the quality of castings.

The features of VGP filtration through the known system: " VGP — coating — mold" and the new "VGP RE channel — GP — coating — mold" were considered, taking as a basis the physical model of the process of filling the mold with GP with "zero" open porosity, which is presented in the works [2, 5].

When filling the mold through the gap "metal – pattern" and channels around the reinforcing elements, the GP undergoes the VGP filtration process. During the mold pouring with liquid MA 1 (**Fig. 4.2**) at a speed W_1, the GP decomposes at a linear speed W_5, and since $W_1 < W_5$, a "meta l- pattern" gap d_1 is formed, in which a backpressure R_f is formed due to the VGP formation. At the same time, the LP covers the entire surface of the MA flow front in the form of a thin film "*D*" [6]. The heat flux from the liquid MA to the GP is transmitted by radiation and thermal conductivity through the LP film "*D*" and the gas-saturated gap "*d*". In this case, the heat exchange surface on the side of the pattern F_5 is reduced by the area of the RE F_a compared to the monopattern. In addition, part of the pattern destruction products at the time of the formation of the gap d_1 is filtered in the VGP form into the depth of the mold under the action of the $P_f–P_o$ pressure gradient, first through the refractory coating (RC) 2 and accumulates on the grains of the molding material (MM) 4 in the form of a condensed liquid phase (CLP).

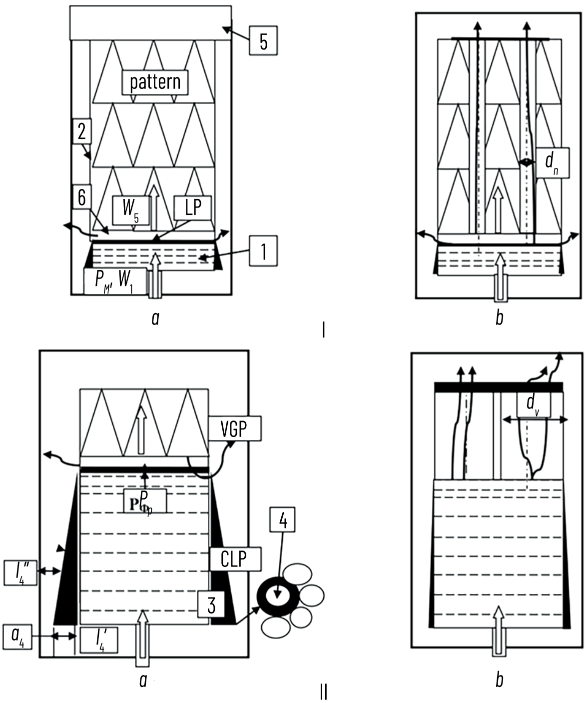


Fig. 4.2 Physical model of the interaction of a gasified pattern with metal during the period of filling the mold with: a - a mono pattern; b - reinforced pattern: 1 – metal; 2 – refractory coating on the-pattern; 3 – zone of low gas permeability (LGP); 4 – molding material (MM); 5 – mold; 6 – gap "metal – pattern"; products of thermal destruction of polystyrene: LP – liquid, VGP – vapor-gas; CLP – VGP condensate on MM grains; P_p, P_m – VGP pressure in the gap and metal, respectively; W_1, W_5 – linear velocity of destruction of the pattern and metal rise in the mold; I – initial stage of pouring, II – final stage of pouring
Source: [3]

At the same time, a zone of low gas permeability 3 (LGP) with a width of a_4 is formed at a distance of l_4 from the "metal- mold" boundary due to partial CLP overlap of the MM channels. In this case, the VGP flow passes through four zones in the mold: RC with a thickness d and gas permeability K_p, two MM layers with a thickness $l_{4'}$ and $l_{4''}$ and gas permeability K_4, and LGP with a width of a^4 with gas permeability K_{LGP}.

In the same period, when the mold is filled with MA, VGP is also filtered through channels with a diameter d_n–d_a, which formed around the RE by GP thermal destruction due to temperature exchange between the RE and the GP. At the same time, a new heat exchange system is also formed: "GP (VGP) – RE (pore channels)", which leads to additional GP thermal destruction and an increase in the channel diameter to the value d_y [2].

In this case, the VGP is filtered through the channel with an area F_d and the RC into the mold wall with the formation of a similar LGP. Under the action of the pressure gradient (P_p–P_v), the LP formation in a mixture with VGP is carried to the end surface of the mold, and does not accumulate in the pore channel or on the surface of the metal flow front.

Based on the presented physical model of VGP filtration in the mold, the kinetics of the change in the gas regime during the lost-foam casting (LFC) process was described using the well-known system of equations (6), which is presented in works [3, 5]

$$\begin{cases} \dfrac{dy}{d\tau} = \dfrac{\left(\dfrac{\alpha\Delta T}{r\rho_5(1+N)} - \left(1-\dfrac{\delta}{\delta_c}\right) + \dfrac{\lambda\Delta T}{\delta r\rho_5(1+N)}\right)}{\left(1+\dfrac{\alpha\Delta T}{r\rho(1+N)} - \dfrac{\rho_5\tau\left(1-\delta/\delta_0\right)}{y'(1+M_G\tau)\rho_c\left[\left(\delta/\tau W_1\right)^{0,05}\right]}\right)} - W_1, \\ \dfrac{dQ}{d\tau} = W_5\rho_5 m_G V_G F_5(1-\varphi) - \delta P_5 P_f K_4\varphi_G\left[\dfrac{c\left(l_4' - l_4''\right)+a_4}{\left(l_4' + l_4''\right)a_4}\right], \\ c = 0.0014\cdot\dfrac{r\cdot m_G\cdot\rho_5\cdot R_5}{a_4},\ l_4' = (3.2-0.012T_3)\tau, \\ a_4 = 0.015T_3,\ \varphi = 0.32\cdot K_P^{1/3},\ P_{\varphi i} = \dfrac{PQ}{F_5\delta}, \end{cases} \tag{4.6}$$

where α – heat transfer coefficient, W/(m^{2}K);

ρ_5 – pattern density;

ρ_p – liquid phase density, kg/m^3;

t – time, s;
y' – thickness of spheroids P_p, m;
ΔT – temperature difference between metal and melting pattern, K;
V_g – specific VGP volume, m^3/kg;
λ – thermal conductivity coefficient of vapor-gas phase, W/(m×K);
r – heat of fusion of pattern material, J/kg;
N – melting criterion;
δ – gap, m;
δ_0 – gap at which $W_5 < W_1$, m;
M_r – degree of destruction;
φ – accumulation of liquid GP products;
F_5 – cross-sectional area of pattern (casting), m^2;
P_5 – perimeter of pattern (casting) cross-section, m;
K_4 – gas permeability of the molding material, m^2/(N s);
K_p – gas permeability of the coating, units;
l_4', l_4'' – length of the molding material layer, m;
a_4 – LGP width, m;
φ_g – gas permeability reduction coefficient;
Q – VGP volume, m^3;
P_f – pressure in the gap, Pa;
T_3 – temperature of the alloy being poured, K;
τ_1 – time from the moment of pouring the metal into the mold, s.

Given that the GP has pore channels around the reinforcing elements with an area of ΣF_d, then the contact area of the heat flow of the metal with the GP F_k can be represented by the following equations (4.7)–(4.9)

$$F_K = F_5 - \sum_{i=1}^{i=n} F_i, m^2 \tag{4.7}$$

or

$$F_K = F_5 - \xi F_5, \quad \xi = \frac{\sum_{i-1}^{i=n} F_i}{F_5}, m^2 \tag{4.8}$$

and finally

$$F_K = (1 - \xi) F_5, m^2 \tag{4.9}$$

where F_k; F_5; F_i – area of thermal contact, monopattern and pore channels around RE, respectively, m^2; ξ – porosity degree of the pattern.

As a result of the formation of a new VGP filtration system, namely: "VGP — reinforced phase — pore channels — coating —mold", the total VGP filtration area can be determined by the following mathematical dependence (4.10)

$$F_{\Sigma} = \left(\delta \Pi_5 + \xi F_5\right), m^2. \tag{4.10}$$

At the same time, the cross-sectional area of the elementary pore channel F_i is a variable value, because under the action of heating its VGP contact surface, the GP material around the RE decomposes at a speed a_5', which leads to an increase in its diameter d_i. The change in the total area of the GP channels can be described by the following expression, assuming that the channels have a cylindrical shape (4.11), (4.12) [3]:

$$\sum F_i' = \sum_{i=1}^{i=n} \frac{\pi d_\tau^{\ 2}}{4}, m^2 \tag{4.11}$$

$$d_\tau = \left(\mathring{a} + \ a_5' T_G\right) d_n \tag{4.12}$$

where d_n — the initial diameter of the elementary pore channel, equal to the diameter of the reinforcing element d_a, m;

d_τ — the current diameter of the elementary pore channel around the reinforcing element, m;

a_5 — the linear melting velocity of the GP in the pore channel, m/s;

T_g — the VGP temperature, K;

τ — the current pouring time, s.

In order to use equations (4.11), (4.12) in the mathematical model (4.6), the following transformations should be performed, namely (4.13):

$$\frac{\xi_\tau}{\xi_n} = \frac{\left(d_n + 2a_5' T_G \cdot \tau\right)^2 4\pi}{4\pi d_n^{\ 2}}, \tag{4.13}$$

and finally, the variable porosity (14):

$$\xi_\tau = \frac{\left(d_n + 2a_5' T_G \tau\right)^2}{d_n^{\ 2}} \cdot \xi_n. \tag{4.14}$$

In this case, the system of equations of the gas dynamics of the casting process in the presence of GP with RE in the mold has the following form (4.15):

$$\begin{cases} \dfrac{dy}{d\tau}=\dfrac{\left(\dfrac{\alpha\Delta T}{r\rho_5(1+N)}-\left(1-\dfrac{\delta}{\delta_0}\right)+\dfrac{\lambda\Delta T}{\delta r\rho_5(1+N)}\right)}{\left(1+\dfrac{\alpha\Delta T}{r\rho_5(1+N)}-\dfrac{\rho_5\tau\left(1-\dfrac{\delta}{\delta_0}\right)}{y'(1+M_G\tau)\rho_{c_{-p}}\left[\left(\dfrac{\delta}{\tau W_1}\right)^{0.05}\right]}\right)}-W_1, \\ \dfrac{dQ}{d\tau}=(1-\xi_\tau)F_5W_5\rho_5M_Ga_5(1-\varphi)- \\ -\left(\delta P_5+\dfrac{\left(d_n+2a_5'T_G\tau\right)^2}{d_n^2}\cdot F_5\right)\varphi_\Gamma\Delta\rho K_4\dfrac{L_\Sigma-c\left(I_4'-I_4''\right)}{\left(I_4'-I_4''\right)a_4}, \\ P_{\varphi i}=\dfrac{PQ}{F_5\delta}, L=(3.2-0.012T_3)\cdot\tau_3, a_4=0.015T_3, \varphi_\Gamma=0.32\cdot K^{1/3}, a_5'=1\cdot10^{-3}. \end{cases} \quad (4.15)$$

To determine the coefficient, it is possible to use the data of work [7] and construct the dependence $d = f(T_g)$, where d – the diameter of the pore channel, and T_g – the temperature of the gas passing through this channel. According to the graph (**Fig. 4.3**), this dependence is expressed by a straight line. In this case, the equation for determining the coefficient a_5' has the following form (4.16)

$$a_5'=\frac{\Delta d}{2\Delta T_G\cdot 10}, \quad (4.16)$$

where 10 is the time of gas passage through the pore channel of the GP in the experiment, C.

Then the value of the coefficient is $a_5' = 1\times10^{-3}$ mm/s °C.

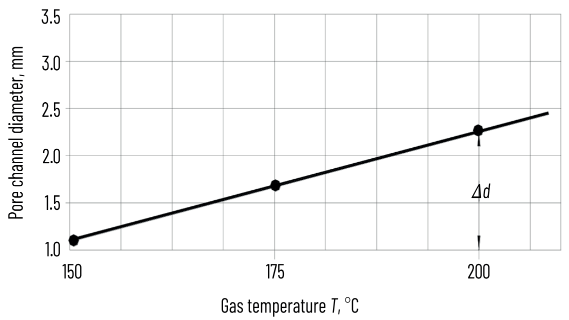


Fig. 4.3 Kinetics of change in linear dimensions of the pore channel in the polystyrene foam pattern

Now the system of equations (4.15) can be used to determine the parameters, including the back pressure of the VGP P_p, the gap "metal —pattern" δ and the rate of metal rise in the mold W_1 with a reinforced GP.

It is also important to note that the amount of LP products that accumulate on the surface of the metal flow front is also reduced by the value ($F_5-\Sigma F_d$). In this case, to determine the volume of LP accumulation, the time of its gasification on the contact surface for time t_g and the hardening coefficient R, it is advisable to use the system of equations (4.15) by supplementing it with the expression $\left(1-\xi_\tau\right)F_5$.

Then the system of equations describing the gas-hydrodynamic conditions of lost foam casting with polystyrene patterns saturated with RE, and taking into account the heat exchange between the RE and the MA during mold filling and matrix alloy solidification, has the final form (4.17):

$$\begin{cases} P_p = 0.13\varphi_G \dfrac{\eta T_p l_4}{c} a_5 t_G^{\,m-1}, \\ \xi_1 = \dfrac{1.13 b_4\left(T_p - T_m\right)\cdot\left[1+\dfrac{100\left(1-c_\tau\right)^3 \delta_1 3}{1.13 b_4\left(T_p-T_m\right)}\right]}{L_1\rho_1\left[1-\dfrac{c_1}{L_1}\left(T_3 - T_{kp}\right)\right]}\cdot\sqrt{t_G}, \\ C_\tau = \dfrac{\left(d_n + 2a_5{}' \cdot T_G \cdot \tau\right)^2}{d_n^2}, \\ P_M = \rho_1 g_1 W_1 t_G, \\ t_G = \left(\dfrac{\left(1-c_\tau\right)^3 \delta_1^{\,3}}{a_5}\cdot 10^3\right)^{\frac{1}{m}}, \\ \begin{cases} \tau = \dfrac{C_p \rho_1 V_c \sqrt{\xi}\cdot D_1}{\alpha_-\left(T_- - \left[T_1\right]\right)}, \\ \left(T_c - \left[T\right]\right)_c = \left(\dfrac{T_3 + \left[T_1\right]}{2} - \left[T_1 + KpP_5/25\right]\right), \end{cases} \\ Nu_{\overline{D}} = \dfrac{\alpha_c \overline{D}}{\lambda_c} = 1.86\left(\mathrm{Re}_{\overline{D}}\cdot \mathrm{Pr}\right)^{0.33}\cdot\left(\dfrac{\overline{D}}{L}\right)^{0.33}\cdot\left(\dfrac{\mu_b}{\mu_s}\right)^{0.14}, \\ Nu_{\overline{D}} = \dfrac{\alpha_c\cdot\overline{D}}{\lambda_c} = 0.036\cdot \mathrm{Re}_D^{\,0.8}\cdot \mathrm{Pr}^{0.33}\cdot\left(\dfrac{\overline{D}}{L}\right)^{0.055}. \end{cases} \tag{4.17}$$

where η — the coefficient of VGP dynamic viscosity;

T_p — the metal temperature, K;

T_m — the mold temperature, K;

C – the permeability, Darcy;

t_G – the gasification time of the pattern;

d_p – the diameter of the pore channel (reinforcing element);

φ_g – the SRC resistance coefficient;

b_4 – the heat storage capacity of the mold, $W \times s^{0.5}/m^2 \times K$;

l_4 – the mold wall thickness, m;

D_1 – the diameter (reduced thickness) of the casting, m;

F_1, F_p – the cross-sectional area of the casting and the pore space, respectively, m^2;

ξ – the porosity coefficient of the mold;

λ_c – the thermal conductivity coefficient, W/(m×K);

$\mathrm{Pr} = \frac{\nu}{a}$ – Prandtl criterion;

$\mathrm{Re} = \frac{V \cdot \overline{D}}{\nu}$ – Reynolds criterion;

n – the viscosity coefficient, m^2/s;

α_c – the thermal diffusivity coefficient, m^2/s;

μ_b – dynamic viscosity at metal temperature T_b, $N \times s/m^2$;

μ_c – dynamic viscosity at wall temperature T_s (T_s ³ T_L), $N \times s/m^2$;

T_L – liquidus temperature of matrix alloy °C.

Thus, hydro-gas-dynamic, thermophysical models were created that describe the features of gas dynamics and heat and mass transfer in molds with reinforcing elements, a polystyrene foam pattern saturated with RE, which allow predicting the flow conditions of the matrix alloy, its solidification, and cooling in molds, which makes it possible to create promising casting methods using gasifying patterns to obtain high-quality reinforced structures with various functional properties from iron-carbon and non-ferrous alloys.

4.2 ANALYSIS AND SELECTION OF STEEL GRADES FOR THE MANUFACTURE OF HOLLOW CAST STRUCTURES FOR MULTIFUNCTIONAL PURPOSES

High requirements for the level of physical and mechanical properties of cast alloys, as well as the technological possibility of forming hollow castings with metallic and non-metallic reinforcing phases by lost foam casting, determine the feasibility of developing new high-strength economical alloyed steels. Such steels should provide the required set of operational properties without the use of scarce and expensive alloying elements, as well as contribute to the creation of highly efficient casting technologies and optimal heat treatment modes to obtain high-quality parts of protective structures [8–11].

Modern requirements for materials, in particular, for multifunctional protective structures, provide for a combination of high strength, sufficient plasticity and resistance to dynamic loads. The choice of material is a key factor determining the reliability and durability of structures manufactured by casting methods.

In this regard, there is a need for systematic research of alloys suitable for forming thin-walled castings of complex configuration [12].

For the analysis, domestic and foreign analogues of steels and iron-based alloys used in the production of cast structures were considered [13–15]. Based on the comparative analysis, it was established that among such materials, low- and medium-carbon low-alloy, microalloyed and modified steels have the greatest prospects. The urgent need for protective structures and structural requirements for their component modules – the level of physical and mechanical properties of steels, the possibility of manufacturing structural modules with non-metallic and metallic reinforcing phases (NRP and MRP) requires the development of new high-strength economically alloyed cast steels that do not contain expensive and scarce alloying elements, highly efficient technologies for manufacturing cast elements of a cellular structure and optimal modes of their heat treatment. A review of world analogues of steels used for the manufacture of multifunctional modules of protective structures has established that the steels used for their manufacture must provide a tensile strength of 500...950 MPa; yield strength – 450...800 MPa, relative narrowing 15...30%; impact toughness 50...70 J/cm2. In addition, given the great need for protective structures, steels for cast modules should not contain scarce and expensive alloying elements – nickel, molybdenum, copper, etc. An analysis of modern technical literature has established that for cast modules of protective structures, the required level of physical and mechanical properties of steels of the C-Si-Mn system is currently provided exclusively by their complex alloying with chromium, nickel, molybdenum, vanadium and the corresponding labor-intensive heat treatment regimes. Thus, regulatory documents for foundry steels in the USA – A352...A732 and Germany – DIN1681 provide for the manufacture of cast parts used as elements of protective structures, steels of the C-Si-Mn system, which are alloyed with the above chemical elements. This makes it possible, after appropriate heat treatment regimes, to obtain metal in products with a yield strength of over 400 MPa.

Based on previous studies [13], it can be stated that the processes of high-quality and optimal additional alloying, microalloying with carbide and nitride-forming elements and modification with nitrogen can achieve the required physical and mechanical properties (tensile strength at rupture 550...900 MPa, yield strength at rupture 450...750 MPa, relative elongation 15...30%, impact toughness 55...75 J/cm^2).

The physical and mechanical properties were determined and the microstructure of the experimental steels was considered using modern testing equipment and analytical methods. Special attention was paid to the influence of heat treatment modes on the operational characteristics of the metal, since energy consumption and stability of the properties of cast parts during mass production depend on this.

The blanks for samples for various purposes were manufactured in dry, heated sand-clay molds. To determine the mechanical properties, samples were made from blanks with a diameter of 12 mm and a length of 70 mm, to determine the impact toughness of steels, blanks with dimensions of 12 mm×12 mm×60 mm were cast, from which standard samples were made.

To compare the physical and mechanical properties and the results of metallographic studies, samples from blanks made using the tooling developed by us and cut from a tertiary blank in accordance with the requirements [14] were used.

To determine the impact toughness of the studied steels, blanks with dimensions of 12 mm×12 mm×60 mm were cast, from which standard samples were made.

To study other properties of steels (for example, choosing the optimal heat treatment regime for steels, studying the structure, etc.), cylindrical blanks with a diameter of 20 mm and a length of 90 mm and the lower part of the riser of the sprue system were used.

In order to determine the correctness of the choice of the tooling developed by us, a comparative assessment of the quality of the metal in the blanks made using the proposed tooling and made using a tertiary blank (DSTU 8781:2018, option 2) or a square (**Fig. 4.4, *a***). The metal has almost the same properties, but a complex test is more effective and much cheaper for the manufacture of samples from experimental steels (**Fig. 4.4, *b***). Obtaining high-quality metal in the samples using this technology is ensured by a massive boss under the riser.

a *b*

Fig. 4.4 Pattern tooling for the production of cast blanks: *a* – square, riser and tertiary blank; *b* – complex tooling (without riser)

The analysis of a large amount of material presented in the works of scientists of the Physico-Technological Institute of Metals and Alloys of the National Academy of Sciences of Ukraine on the use of alloying, microalloying and modification processes of C-Si-Mn alloys has identified specific areas for improving these processes for lost foam casting: approximate temperatures of base melts before performing the processes of additional alloying, microalloying and modification of base steels and pouring them into molds and specific individual chemical elements and complexes of elements to minimize their quantity with the maximum increase in the properties of experimental steels [15].

The studies have established that the optimal content of the main chemical elements in medium-carbon steels to achieve high strength and ductility should be as follows, wt.%: C = 0.30...0.55; Mn = 0.40...1.20; Si = 0.30...0.60.

In order to achieve the required indicators of physical and mechanical properties for alloying, microalloying and modification of base steels, it is advisable to use the following chemical elements: for alloying and microalloying – titanium, niobium, chromium and vanadium, for modification – nitrogen and rare earth metals on a cerium basis.

Taking into account the interaction of chemical elements in the C-Si-Mn system, to determine the optimal chemical composition of steels that can provide the required level of physical and mechanical properties of the metal of cast modules and their corrosion resistance in various aggressive environments, the effect of changing the content of the main chemical elements within the following limits was studied: carbon – from 0.25% to 0.60%, silicon – from 0.30% to 0.90%, manganese – from 0.50% to 2.0%. The content of phosphorus and sulfur did not exceed 0.045% of each element. The nitrogen and vanadium content was calculated for each steel grade taking into account that the equilibrium temperature of dissolution (separation) of the vanadium nitride phase in a solid solution does not exceed 1030°C [16].

Previous studies conducted at the Physico-Technological Institute of Metals and Alloys of the NAS of Ukraine on the influence of microalloying and modification processes with vanadium and nitrogen on the properties of structural steels of the C-Si-Mn-Cr system of ferritic-pearlitic and pearlitic classes have established that the separation of dispersed particles of VN and AlN in a solid solution provides a comprehensive increase in the strength and plasticity characteristics of steels to the level of properties of steels alloyed with molybdenum, nickel, niobium, vanadium, etc.

In this case, the process of dispersion strengthening of steel is implemented during the tempering of the product after normalization or quenching, which should occur at temperatures 100...150°C lower than the equilibrium temperature of dissolution (formation) of the vanadium nitride (VN) phase.

According to the results of previous studies, 35KhGAFL steel was selected, which has the highest indicators of casting and physical and mechanical properties for casting the above-mentioned protective modules [17–21].

Based on thermodynamic calculations of the equilibrium temperature of formation of the nitride disodium phase in a solid solution, it was established that the optimal range of austenitizing heating of 35KhGAFL steel during normalization and quenching is 920–940°C with holding for 1 hour.

After normalization, the samples were cooled in air, and during quenching – in water. Tempering was carried out at temperatures of 510–600°C with holding for 1 hour and subsequent cooling in air. Physical and mechanical properties were determined after normalization, quenching and tempering (**Table 4.1**).

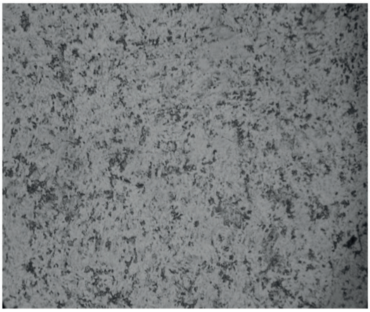
After normalization (austenization), a fine-grained structure is observed in 35KhGAFL steel samples: 6–7 points and 7–8 points, respectively. The choice of heat treatment modes allows to provide the necessary set of steel properties depending on the operating conditions of protective structures.

To reduce the cost of casting and energy consumption, it is recommended to carry out normalization at 930°C with air cooling. The properties obtained under this mode fully comply with the technical requirements, and the grain size of the steel is 7–8 points, which indicates an optimal fine-grained structure [20].

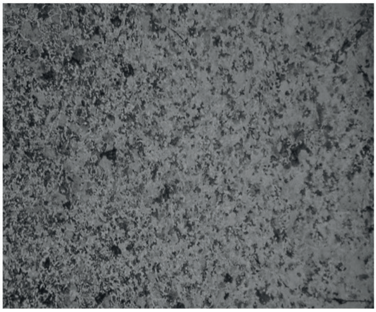
The microstructures of steels after normalization and tempering are shown in **Fig. 4.5.** The microstructure of 35KhGAFL steel after normalization at a temperature of 930°C is pearlitic-ferritic: pearlite is thin-lamellar, ferrite is located outside the austenite grains in the form of broken meshes. Tempering of steel after normalization contributes to an increase in hardness due to the dispersion segregation of the vanadium nitride phase inside the grains.

Table 4.1 Heat treatment modes and physical and mechanical properties of 35KhGAFL steel

Heat treatment modes		Physical and mechanical properties of steel				
normalization, quenching °C, cooling medium	σ_τ, MPa tempering °C	$\sigma_в$, MPa	ψ, %	KCU, J/cm^2	Hardness, HRC	
		no less than				
normalization at a temperature of 930°C, air	without tempering	600.0	850.0	22.0	72.0	20.0
	510	600.0	850.0	24.0	82.0	22.5
	550	600.0	890.0	24.0	82.0	22.0
	600	605.0	915.0	23.0	67.0	25.0
quenching from a temperature of 930°C, water	510	1010.0	1150.0	20.0	75.0	31.0
	550	795.0	980.0	27.0	84.0	26.0
	600	850.0	1010.0	24.0	75.0	26.0
Requirements according to the technical specifications	450…750		550…900	15…30	55…75	≥15



a



b

Fig. 4.5 Microstructures of the experimental 35KhGAFL steel after normalization at a temperature: *a* — of 930°C; *b* — normalization at a temperature of 930°C + tempering at a temperature of 510°C; ×200

Another urgent task during the production of castings using the lost foam casting process is to determine the level of non-metallic inclusions of medium and large sizes in the metal of the products. It is important to know not only the level of contamination of the metal with non-metallic inclusions, but also their morphology, size, shape and reasons contributing to their formation. In this case, it will be possible to use certain technological measures that will reduce their number or change their shape, for example, convert non-metallic inclusions from an acute-angled shape to a globular one, which will significantly increase the physical and mechanical properties of the metal.

The metal contamination index by non-metallic inclusions was determined by the linear method according to the requirements [21, 22] on unetched sections made from steel blanks. The results of the numerical values of each type of non-metallic inclusions and the total metal contamination index are given in **Table 4.2.**

Table 4.2 Metal contamination index of multifunctional modules by non-metallic inclusions of different morphology and the total contamination index

No.	Type of non-metallic inclusions	Contamination index of 35KhGAFL steel
1	Nitrides	0
2	Oxides	0.001127
3	Silicates	0.000407
4	Sulfides	0.008800
5	Total steel contamination index	0.002414

Analysis of the obtained results of the study of non-metallic inclusions in the recommended 35KhGAFL steel allowed to establish that the general index of contamination of the cast metal of samples cut from real modules made using polystyrene foam patterns is at the level of indicators for the metal of carbon steel products obtained using traditional casting technologies in one-time volumetric sand-clay molds [23].

Relatively large non-metallic inclusions of an oxide nature are observed in 35KhGAFL steel. Their appearance may be due to the presence of slag particles, since the samples were cut from the upper part of the cast module, or as a result of secondary oxidation of the melt during pouring the molds.

The heat treatment modes of the recommended steel do not significantly affect the morphology and number of non-metallic inclusions, with the exception of the normalization process. Prolonged cooling of the metal in air contributes to a partial redistribution of morphological types of inclusions – in particular, the proportion of sulfides increases, which is explained by a decrease in the solubility of sulfur in iron with a decrease in the temperature of the metal.

Based on the conducted studies, the optimal heat treatment regime is one that involves quenching from a temperature of 930°C in water with subsequent tempering at 510°C.

After such treatment, the steel is characterized by the following properties:

– tensile strength σ_v – not less than 1150 MPa;
– yield strength σ_t – not less than 1010 MPa;
– relative elongation δ – 16%;
– relative narrowing ψ – 20%;
– impact toughness KCU – 70 J/cm^2;
– hardness – 31 HRC.

The results obtained confirm that 35KhGAFL steel provides increased strength and ductility combined with good castability, which is crucial for the manufacture of thin-walled hollow elements of complex geometry [24].

4.3 DETERMINATION OF THE REINFORCEMENT INFLUENCE ON THE HYDRODYNAMICS OF MOLD FILLING AND THERMAL PROCESSES IN THE FUNCTIONAL FILLER

The influence of reinforcing steel elements and reinforcement directly from the liquid alloy of the shell on the hydrodynamics of mold filling and thermal processes in the functional filler was determined using computer simulation. Successful computer simulation can help reduce the number of tests and reduce the time for developing new castings due to a better understanding of the complex mechanisms and interaction of various technological parameters in the mold filling process, especially in the gasified pattern casting process [25, 26]. In accordance with the tasks of implementing technologies for obtaining lightweight high-strength steel hollow structures with non-metallic and metallic functional filler, the following types of them were proposed:

1 – steel shell filled with non-metallic functional material;

2 – steel shell with non-metallic functional material, which is reinforced with metal elements that simultaneously combine the shell and functional material;

3 – steel shell with non-metallic functional material, which is reinforced by solidification in its channels of liquid alloy of the shell, which at the same time combines the shell and functional material.

Computer simulation of the processes of pouring and solidification of the lost foam casting was performed using the Procast software. 3D drawings of the cell model of one element of the module (**Fig. 4.6**), gating system, reinforcement, core (functional filler) built in the CAD system were saved in IGES format and loaded into the simulation program. The element size when applying the mesh to the model, core and reinforcement was set to 2 mm. The total number of calculated elements was 739 thousand. The following materials were set from the database: Steel AISI 1040 – for the alloy, Sand LFC – for the ꞡ mold, Foam 30 kg/m^3 – for the model, Resin bonded sand permeable – for the core, Chill Carbon steel – for the reinforcement. The pouring temperature of the steel was set at 1580°C, the initial temperature of the mold, core, model and reinforcement, and the environment was 20°C. The heat transfer coefficients were set as follows: between liquid metal and foam – FOAMHTC 840, FOAMHTCMAX 10460, between liquid metal and mold/core – 500, between metal and reinforcement – 3000, between mold and core – 400. The boundary conditions were: inlet pressure on the upper surface of the riser 1.05 atm, temperature 1580°C, pressure around the mold 1 atm [9].

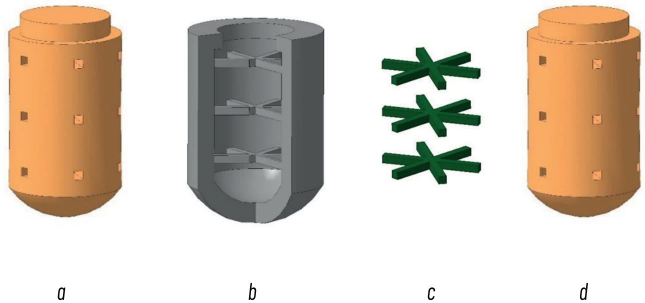


Fig. 4.6 General view of 3D models: *a* – cell; *b* – cell with membranes; *c* – reinforcement, *d* – core with channels

Fig. 4.7 shows the process of pouring an experimental cell with a functional filler without reinforcement. Under these conditions, the metal front moves from top to bottom with gradual spreading to the sides and the closing of two flows in the part opposite the supply point. In the case of the presence of polystyrene foam elements between the walls of the cell as a functional material, the nature of pouring is similar (**Fig. 4.8**). The presence of processes of filling thin channels of membranes (4x4 mm) is distinctive. Since the metal fills the cylindrical part of the cell, the metal enters each "beam" of the membrane from the main wall and moves to the point of their intersection.

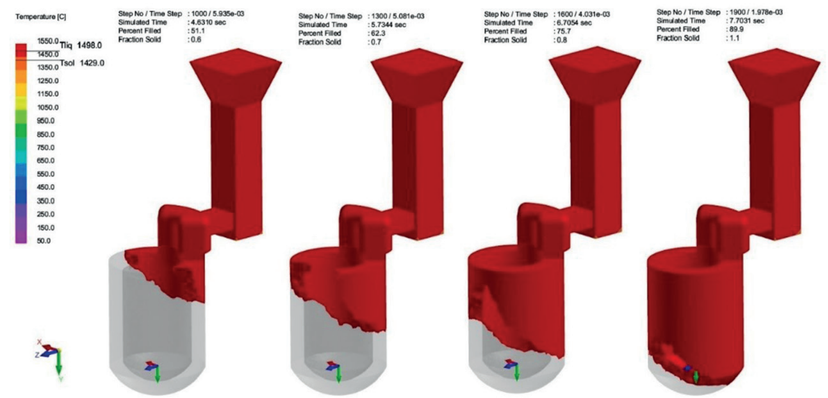


Fig. 4.7 The process of pouring an experimental cell (without reinforcement)

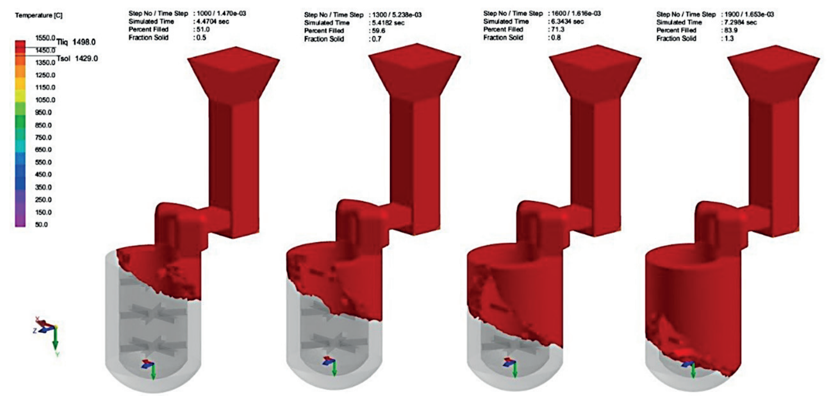


Fig. 4.8 The process of pouring an experimental cell with thin channels for reinforcement

The flow rate of liquid metal in the channels for reinforcement is shown in **Fig. 4.9.** At the beginning of filling the upper channel, the flow rate is about 2 cm/s. Then the speed increases to 4 cm/s. At the end of filling the channel, the speed briefly rises to 8 cm/s.

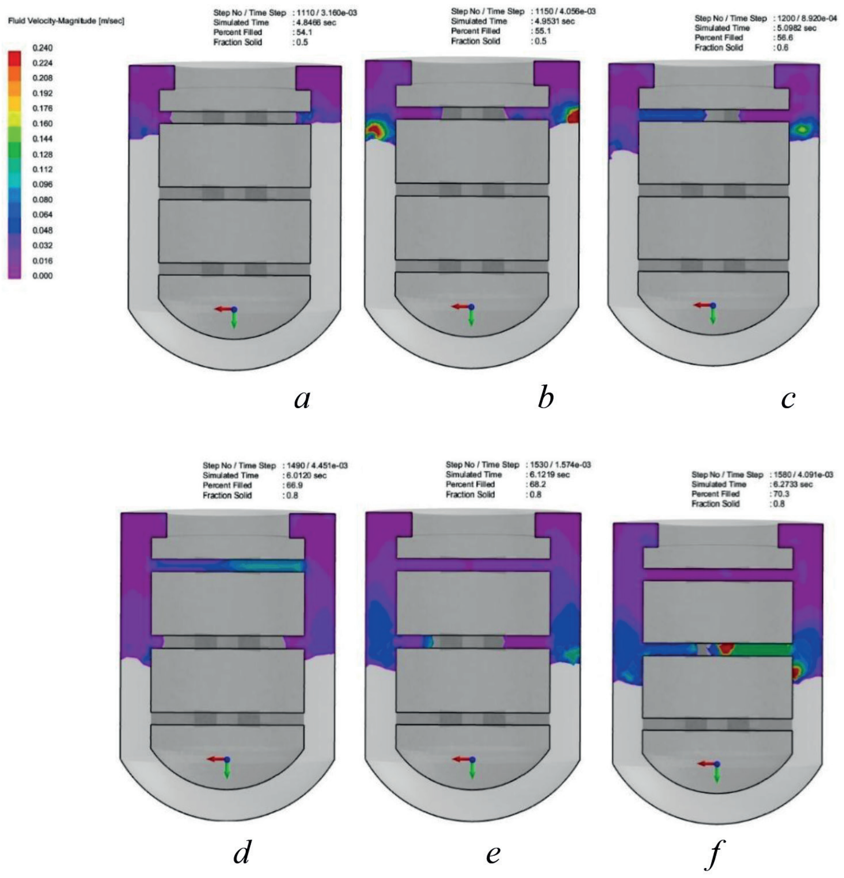


Fig. 4.9 The flow rate of liquid metal in the channels of the functional filler: *a* – 4.8 s, *b* – 5.0 s, *c* – 5.1 s, *d* – 6.0 s, *e* – 6.1 s, *f* – 6.3 s

A similar picture occurs when filling the middle and lower partitions. At the beginning of filling the channels, the speed is 2–3 cm/s. Then the speed increases to 6 cm/s, and briefly rises to 10–12 cm/s. It is believed that the optimal speed is 3–4 cm/s. When the metal moves through thin channels, a high speed contributes to their filling, since at a low speed the flow may stop due to its cooling.

Fig. 4.10, *a* shows the temperature fields of the longitudinal section of a casting with a functional filler, a casting with a functional filler and reinforcement (**Fig. 4.10, *b***), a casting with membranes and a functional filler (**Fig. 4.10, *c***).

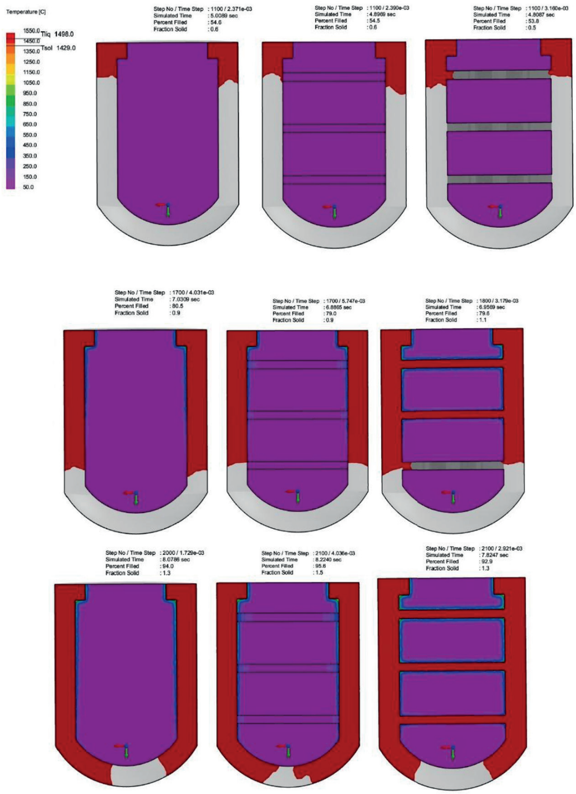


Fig. 4.10 Temperature fields (cell cross-section) during pouring: *a* – casting with functional material; *b* – casting with reinforced filler; *c* – casting with functional filler reinforced from the liquid phase of the shell metal

The nature of filling the casting cavity for the first two cases is the same. In the third variant, the nature of filling is somewhat different, which is associated with the presence of partitions. During pouring, the functional material is heated only in the contact zone to approximately 400°C. At the end of pouring, the upper part of the functional filler is heated to a depth of up to 2 mm to a temperature of 700°C.

Fig. 4.11 shows the temperature fields of the longitudinal section of the casting during solidification and cooling of the metal. **Fig. 4.12** shows the solidification time of the section of the castings. 30 seconds after filling the casting, the functional filler is heated to a depth of up to 7 mm. Complete heating of the functional filler in the first variant occurs in 180 s, in the variant with reinforcement – in 130 s, in the variant with reinforcement from the liquid phase of the shell metal – in 100 s.

The highest temperature to which the functional filler is fully heated in the first case is 850°C, in the case of using reinforcement – 1050°C, in the case of casting with membranes – 1150°C. Thus, the best conditions for sintering the functional filler are created in the second two variants.

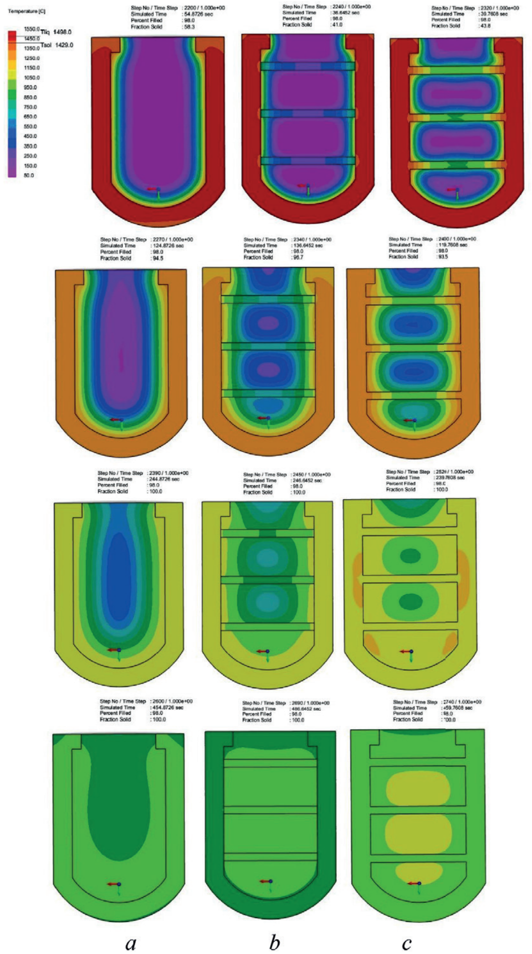


Fig. 4.11 Temperature fields (cell cross-section) during solidification and cooling: *a* – casting with functional material; *b* – casting with reinforced functional material; *c* – casting with functional filler, which is reinforced from the liquid phase of the shell metal

The presence of reinforcement or membranes affects the solidification processes (**Fig. 4.12**). The reinforcement acts as a refrigerator and reduces the solidification time of the casting by 11 s. The membranes harden quite quickly (12 s) and partially cool the casting, but reduce the solidification time of the casting by only 6 s.

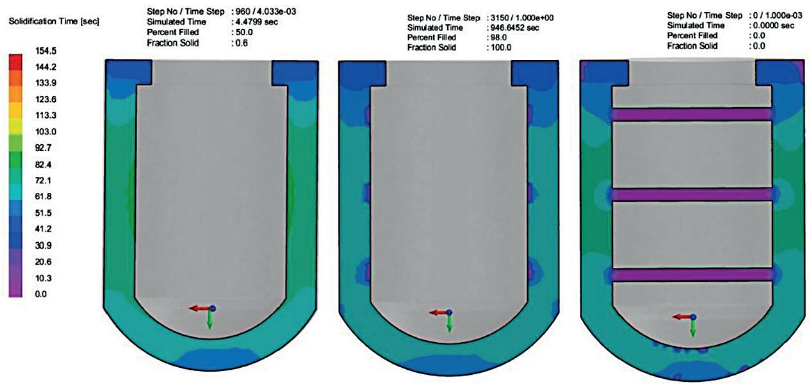


Fig. 4.12 Casting solidification time: *a* — casting with functional material; *b* — casting with reinforced functional material; *c* — casting with functional filler, which is reinforced from the liquid phase of the shell metal

The nature of filling the cell without membranes, determined on the basis of simulation, is typical for the upper feed for lost foam casting due to the presence of a polystyrene foam pattern, which exerts thermomechanical resistance. In the presence of membranes, significant changes in the nature of filling the main wall of the cell do not occur, due to the fact that the volume of the membranes is 3.5% of the total volume of the cell. However, the metal flow rate in the membranes is 3–4 times higher than the metal flow in the cavity of the main wall of the casting, which is due to hydrodynamic pressure.

The results of the study of the temperature fields of the casting and the functional filler during pouring, solidification and cooling of the metal showed that when using reinforcement and the presence of metal membranes, better conditions are created for sintering the functional filler due to the heat of the matrix metal.

The increase in the heating rate of the functional filler in the presence of steel reinforcement is associated with the higher thermal conductivity of the steel, which is heated by the heat of the casting. In the case of a casting with membranes, they increase the area of the contact surface for heat exchange of the metal with the functional filler. In addition, the casting with membranes has a larger mass, respectively, the amount of heat transferred by the matrix metal to the functional filler increases.

Reducing the hardening time, i.e. increasing the hardening rate, creates conditions for increasing the mechanical properties of the casting.

In addition to the hardening rate, the level of mechanical properties of steel is affected by the presence of casting defects, so the work analyzed the shrinkage that is formed in the cell casting. The shrinkage fields of the first and third types of shells are presented in **Fig. 4.13.** The simulation results showed that in a casting without partitions, shrinkage is concentrated in the pouring part. At the same time, in a casting with a filler, which is reinforced from the liquid phase of the shell metal, shrinkage cavities are also present in the center of the partitions. This is explained by the formed "thermal node", which occurs when six "beams" are connected, which solidifies without being fed with liquid metal from the main walls of the shell or pouring.

To prevent shrinkage in the center of the partitions, another design was proposed, in which the central part has the shape of a ring. The simulation results of the solidification of this version of the casting **(Fig. 4.14)** showed that there is a certain porosity in the partitions (reinforcement formed from the liquid phase of the shell metal). However, the size of the shrinkage defects has significantly decreased compared to the previous version.

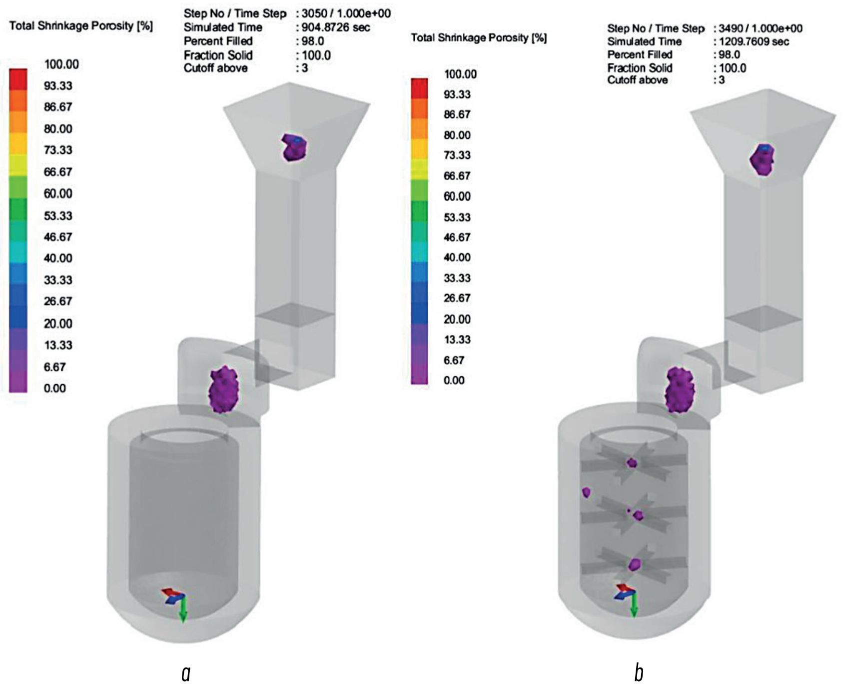


Fig. 4.13 Shrinkage fields: *a* – casting with functional filler; *b* – casting with functional filler reinforced from the liquid phase of the shell metal

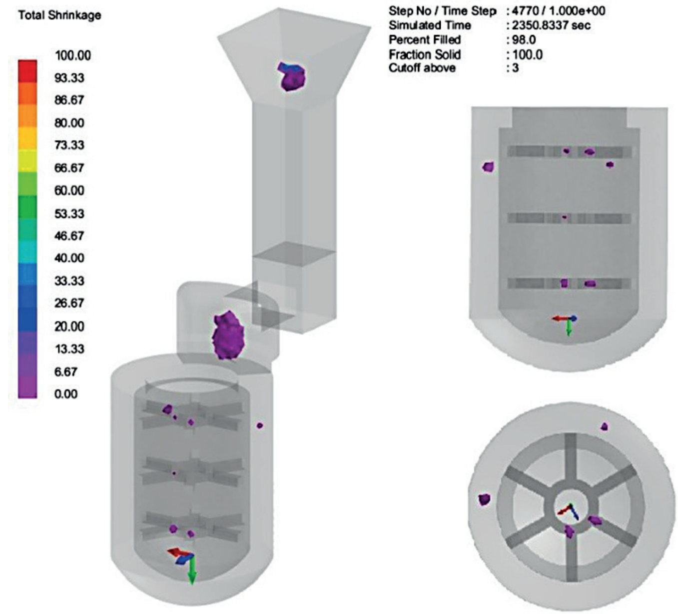


Fig. 4.14 Porosity in a casting with a changed geometry of the reinforcement

Thus, the conducted studies have shown the feasibility of using solid reinforcement and reinforcement from liquid metal to increase the mechanical adhesion of the shell metal with the functional filler and create better conditions for its sintering for the purpose of strengthening.

4.3.2 STUDIES ON THE SELECTION OF A FUNCTIONAL FILLER

The functional filler of the metal shell must satisfy several parameters – availability, low mass, refractoriness, etc. At the same time, the filler must have sufficient hardness to resist the penetration of objects (fragments, bullets, etc.) into them, and have a low density so as not to significantly increase the total mass of the protective module.

The properties of some common materials (**Table 4.3**) that can be used as fillers are analyzed. The most accessible and cheap is quartz sand, which has a sufficiently high refractoriness and hardness, is characterized by a small bulk mass. Electrocorundum and silicon carbide are more refractory and hard, but they are more expensive and have a higher density. An accessible material that has a low bulk density is expanded vermiculite, but is characterized by low refractoriness and low hardness.

Table 4.3 Characteristics of non-metallic fillers

No.	Name	Chemical formula	Density, kg/m^3	Bulk weight, kg/m^3	Melting temperature (fire resistance), °C	Mohs hardness
1	Crystalline quartz (quartz sand)	SiO_2	2650	1400–1700	1713 (1650)	5.5–7.0
2	Electrocorundum	Al_2O_3	3990	2400	2050	9.0
3	Expanded vermiculite	$(Mg, Fe^{2+}, Fe^{3+})_3[(OH)_2(Al, Si)_4 \cdot 4H_2O$	380	200	~1300	1.0–1.5
4	Silicon carbide	SiC	3210	1900	2730	9.5

For practical testing of the behavior of functional fillers in combination with the shells of protective structures, cylindrical samples were filled with different fillers. Polystyrene cylinders were made – outer diameter 66 mm, inner 40 mm, height 50 mm. As fillers, quartz sand of fraction 0.16–0.2 mm, fraction 0.8–1.0 mm, expanded vermiculite of fraction 1.0 mm, normal electrocorundum of fraction 0.8 mm (F24) were used. Liquid glass was used as a binder, which was added in an amount of 7% by weight of the core mixture.

8 samples of models with different fillers were made (**Fig. 4.15**):

1 – quartz sand of fraction 0.16–0.2 mm;
2 – a mixture of vermiculite and quartz sand of fraction 0.16–0.2 mm;
3 – quartz sand of fraction 0.16–0.2 mm mixed with aluminum shavings;
4 – quartz sand of fraction 0.8–1.0 mm;
5 – quartz sand of fraction 0.8–1.0 mm mixed with polystyrene granules;
6 – quartz sand of fraction 0.8–1.0 mm with polystyrene foam membranes;
7 – vermiculite;
8 – normal electrocorundum.

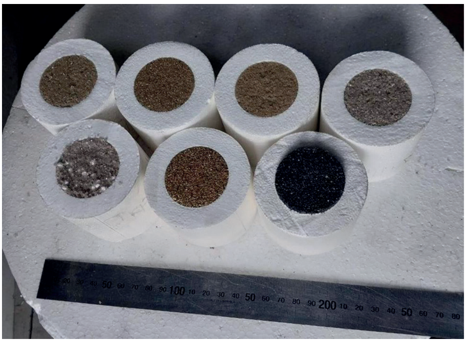


Fig. 4.15 Cylindrical samples with different fillers

The core mixtures were obtained by mixing the components until the refractory particles were completely "wetted" with liquid glass. Then the mixture was "stuffed" into the cylinder hole and left for 24 hours in a warm room to cure and dry the mixture. After that, the elements of the gating system were glued and a refractory coating was applied (**Fig. 4.16, *a***). After the coating dried, the pattern blocks were molded in dry quartz sand using the traditional LFC technology. The molds were poured with liquid steel 45L. After the castings cooled, they were knocked out of the mold (**Fig. 4.16, *b***) and separated from the sprues (**Fig. 4.17**).

a *b*

Fig. 4.16 Samples: *a* – pattern blocks; *b* – casting bushes

Fig. 4.17 Cast samples with different fillers

To study the interaction of fillers with the shell metal, a longitudinal section of the cylinders was performed (**Fig. 4.18–4.20**). Samples with quartz sand were characterized by metal penetration to a depth of 1 mm, and samples with a mixture of vermiculite and quartz sand – to a depth of 2–3 mm. Aluminum chips, which were added to the sand to "bind" the sand grains, melted only in a 5 mm thick layer adjacent to the shell metal.

Coarse sand had larger porosity between the sand grains, which should contribute to better metal penetration. However, no significant increase in the penetration depth was observed, only within 1–2 mm. In the filler with the addition of polystyrene foam granules, the thickness of the penetration layer increased to 3 mm, but the cavities formed after the polystyrene foam granules burned out did not fill with metal. Moreover, the formed cavities reduced the filler's resistance to spalling. When using polystyrene foam membranes, the shell metal penetration layer into the filler increased to 3–4 mm.

Samples with expanded vermiculite had shells and were characterized by significant defects. This is explained by the low fire resistance of this filler. Because of this, the mixture with vermiculite also had high spalling.

In samples with electrocorundum filler, the penetration layer was 1–2 mm. These samples were also characterized by average spalling. The reason for this is that the material used consists of particles of the same fraction. For example, quartz sand by its nature consists of particles of different sizes. In this case, the binder creates more bonds, since small grains are located between large ones. Therefore, to increase the strength of corundum fillers, it is necessary to mix several fractions to get more bonds in the mixture. Also, samples with corundum had a greater mass than samples with quartz sand.

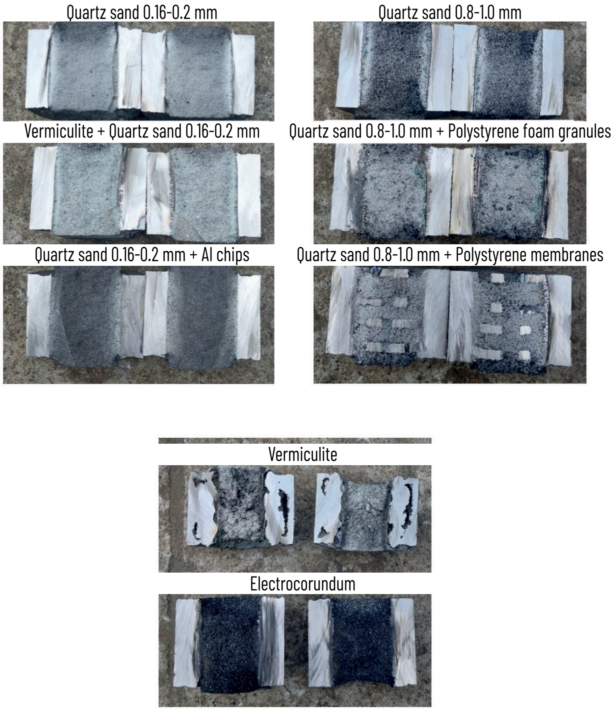


Fig. 4.18 Sections of cast samples with fillers

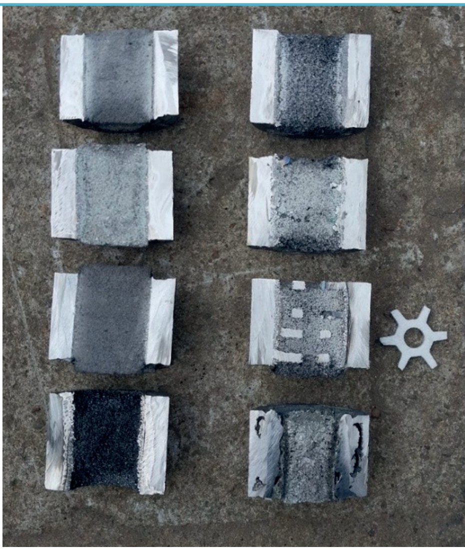


Fig. 4.19 Sections of cast samples with different fillers

Fig. 4.20 Section of samples with quartz sand filler and membranes obtained by liquid-phase reinforcement

The conducted studies have shown that a mixture of quartz sand with liquid glass is the most suitable functional filler for shell modules. Adding vermiculite to quartz sand may also be promising in order to reduce the mass of the cast module. The use of reinforcement of the filler from the liquid phase of the shell contributed to an increase in the metal penetration layer and the formation of a metal composite.

4.3.3 DEVELOPMENT OF TECHNOLOGY FOR MANUFACTURING MODULE CASTING

Taking into account previous experience in obtaining similar castings, a gating-feeding system was developed, the general view of which is shown in **Fig. 4.21,** for a 500x500 mm module casting. The lower metal supply was selected to ensure uniform filling and uniform gasification of the pattern. To compensate for shrinkage, a riser was placed above the casting.

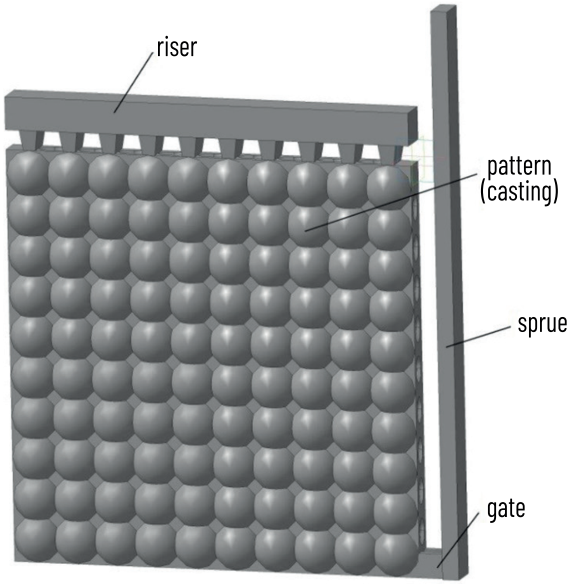


Fig. 4.21 General view of the gating system

Simulation of the pouring and solidification processes of the module casting by lost foam casting was performed using the Procast software.

The parameters necessary for simulation – the properties of 45L steel, polystyrene foam and quartz sand – were selected from the database. The pouring temperature of the steel was set to 1580°C, the initial temperature of the mold – 20°C.

The results of the simulation of pouring a casting of a module 500x500 are shown in **Fig. 4.22**. The total pouring time is 45 s. Filling occurs from one side of the gates. The metal front moves from right to left and from bottom to top simultaneously. This nature of pouring is due to the thermomechanical resistance of the polystyrene foam pattern.

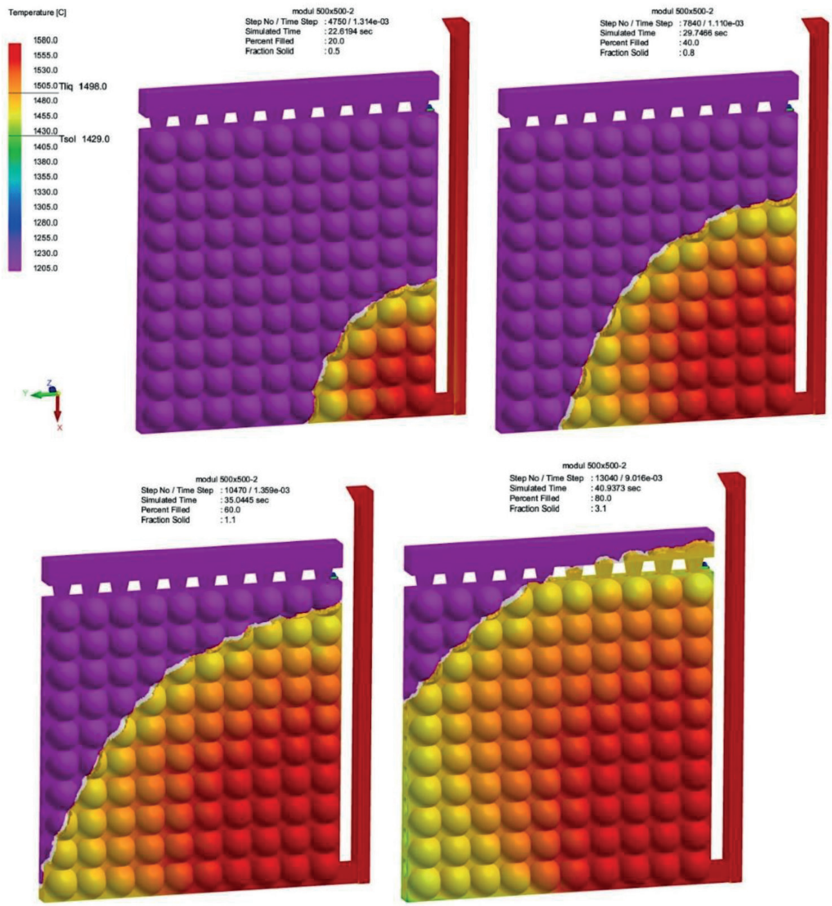


Fig. 4.22 Hydrodynamics of pouring a casting of a module 500x500

An important parameter of the pouring process that affects the formation of casting defects is the melt velocity in the mold. Therefore, the melt flow velocity when filling the casting cavity was investigated.

As the simulation results show (**Fig. 4.23**), the melt front velocity is within 3–5 cm/s throughout the entire pouring time. In the gate and the cell near it, the flow velocity reaches a value of 15 cm/s, which is due to the hydrodynamic pressure created by the metal in the sprue.

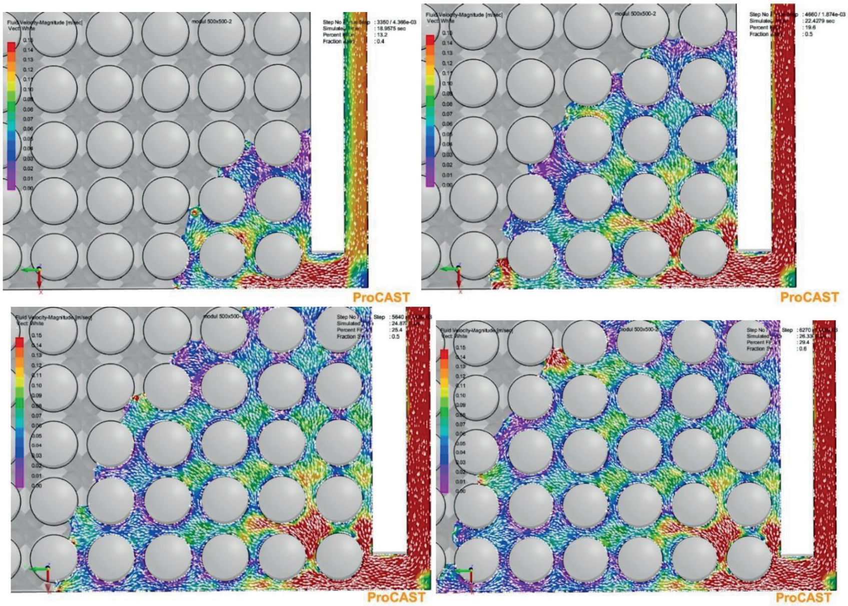


Fig. 4.23 Melt velocity during pouring of the casting

The results of simulation the solidification process of the casting showed that the solidification of the casting body occurs almost uniformly (within 60–90 s) (**Fig. 4.24, *a***). The solidification time of the riser is twice as long, which contributes to the feeding of the walls of the casting with liquid metal from it. The sprue solidifies last, since it contains the hottest metal, and the layers of molding sand around it heat up during pouring, respectively, the temperature gradient between the sprue metal and the mold decreases, slowing down the solidification rate. As a result, shrinkage is concentrated in the riser and the sprue (**Fig. 4.24, *b***).

The porosity in the casting was also studied. The simulation results demonstrated (**Fig. 4.25**) that the porosity of a shrinkage nature is absent in the casting body.

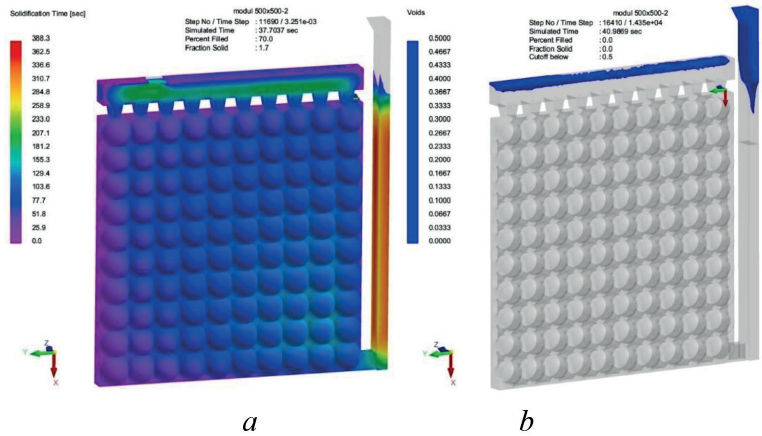


Fig. 4.24 Module casting: *a* — solidification time; *b* — shrinkage

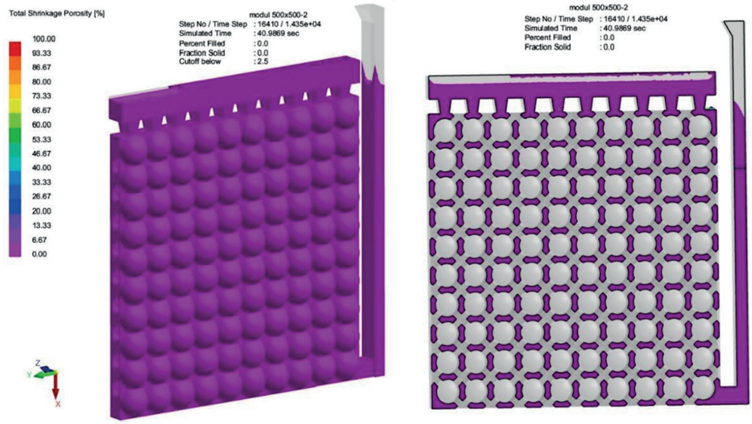


Fig. 4.25 Porosity in the 500x500 module casting

The gating system developed in this way ensures gradual and uniform gasification of the polystyrene foam pattern, contributing to the removal of destruction products from the mold. The melt front velocity of 3–5 cm/s contributes to the rapid replacement of the pattern, but allows to avoid the "coverage" mode of the pattern and the formation of gas defects due to this. During solidification, due to the equilaterality, the casting solidifies almost simultaneously, and shrinkage cavities are concentrated in the riser.

4.3.4 VERIFICATION OF THE TECHNOLOGICAL PROCESS

To verify the technological process of manufacturing hollow cast structures with composite and reinforced non-metallic functional filler from developed steels according to LFC, laboratory and experimental verifications of calculations, simulation and the developed route technological process were carried out.

In this test evaluation, the developed methods for calculating basic parameters and a set of technological divisions, types and characteristics of materials, limits of variation in the parameters of the technological processes of obtaining polystyrene foam patterns, reinforcing composite, preparation and application of refractory coatings on these patterns, as well as pouring the mold and obtaining castings were subject to the developed test evaluation. A casting drawing was previously developed and a pattern was cut out of an EPS 150 (PSB 25–30) polystyrene board on a 3D milling machine, the cavity of which was filled with a reinforcing mixture (**Fig. 4.26**).

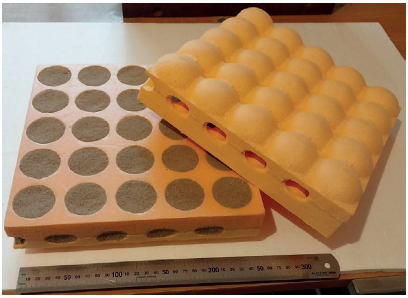


Fig. 4.26 Polystyrene foam pattern of the protective module

In the following, the stages of the technological process were sequentially performed, steel of the required chemical composition was melted and high-quality castings were obtained (**Fig. 4.27**).

Fig. 4.27 Reinforced steel castings of the protective module, which were manufactured using the developed technology

Thus, the created technological processes for obtaining hollow cast structures with composite and reinforced non-metallic functional filler from developed steels using LFC make it possible to obtain reinforced structures that can be used in protective structures.

CONCLUSIONS

Based on the mechanism of interaction of matrix alloy (MA) in the mold in the presence of metal reinforcing elements with polystyrene foam pattern and thermal destruction products in the form of liquid, gaseous and solid phases, a computational model of heat and mass exchange processes was developed with the determination of the heat transfer coefficient in the criterion form (based on the Nusselt, Prandtl, Reynolds criteria) for the flow of liquid MA in the mold.

The task of developing a technological process for obtaining lightweight high-strength steel hollow structures with a non-metallic functional filler, which is a binary part of a single structure and counteracts impact dynamic loads upon contact with high-speed bodies, was solved. Additional reinforcement was carried out in the systems "metal shell – functional filler – solid reinforcing phase or reinforcing phase formed from liquid shell metal", which has not yet been studied in the theory of foundry production, and therefore there are no analogues.

According to the results of research on the features of the hydrodynamic conditions for filling the mold cavity with liquid steel and in the presence of a solid reinforcing phase and thin channels formed in the functional filler, it was established that the time for filling the mold cavity is 7.5…8.0 s for all types of objects under study and the metal flow rate in the thin channels of the filler is 5..7 cm/s, which are optimal for obtaining steel shells when lost foam casting.

The presence of solid metal reinforcement and liquid, solidifying metal of the shell in its thin channels placed in the functional filler affects the heat and mass transfer processes in the mold. Thus, with intensive heating of the functional material due to heat transfer from the reinforcing phase, the functional material heats up during the solidification of the metal shell to a temperature of 1050°C in 130 s (solid state) and during the formation of the reinforcing phase from the shell metal to 1150°C in 100 s. Under such thermophysical conditions, the possibility of sintering (melting) of the non-metallic (metallic) functional layer around the reinforcing phase is created and thereby significantly additionally enhances the operational characteristics of the binary module structure.

It is also determined that the filling of the shell in the thin channels formed in the functional material occurs when pouring metal, which guarantees the specified geometric dimensions of the reinforcing phase and, accordingly, its mechanical properties, which also enhances the operational parameters of the binary module structure.

It was determined that a mixture of quartz sand with liquid glass is the most acceptable functional filler for shell modules. Adding vermiculite to quartz sand may also be promising in order to reduce the mass of the cast module. The use of filler reinforcement with the liquid phase of the shell contributed to an increase in the metal penetration layer and the formation of a metal composite.

According to the results of research on the selection of the optimal chemical composition of steels with specified mechanical properties for hollow structures for the construction of various types of modular protective structures, 35KhGAFL steel with the chemical composition, wt.%: C = 0.30…0.40; Mn = 0.60…0.90; Si = 0.55…0.65; Cr = 0.20…0.70; N = 0.012…0.015; V = 0.08…0.11; S and P ≤ 0.025 of each element; Al = 0.015…0.025. It was established that the best set of mechanical properties for 35KhGAFL steel can be achieved after quenching from a temperature of 930°C in water and tempering at a temperature of 510°C: σ_v = 1150 MPa, σ_τ = 1010 MPa, δ = 16%, ψ = 20%, KCU = 70 J/cm^2, hardness – 31 HRC.

Technological processes for obtaining hollow cast structures with composite and reinforced non-metallic functional filler from developed steels according to LFC have been created and tested, which make it possible to obtain reinforced structures, in particular for protective structures.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

USE OF ARTIFICIAL INTELLIGENCE

The authors confirm that they did not use artificial intelligence technologies in creating the submitted work.

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