REPUBLIC OF AZERBAIJAN

On the rights of the manuscript

THEORETICAL AND EXPERIMENTAL DEVELOPMENTS OF METAL-GLASS POWDER COMPOSITIONS

Specialty: 3312.01 – Materials technology

Branch of science: Technical

Applicant: **Tahir Gaffar oglu Jabbarov**

ABSTRACT

Dissertations for the degree of Doctor of Technical Sciences

Baku – 2024

Dissertation work was carried out at the Azerbaijan State University of Oil and Industry

Scientific advisor: Doctor of Technical Sciences, Professor
Mustafa Baba oglu Babanli

Official opponents:
Doctor of Technical Sciences, professor
Abbas Abdurakhman oglu Guvalov

Doctor of Technical Sciences, associate professor
Ziya Sahavaddin oglu Aliyev

Doctor of Technical Sciences, professor
Nizami Shayi oglu Ismayilov

Doctor of Technical Sciences,
Ramin Ismatbay oglu Karimov

Dissertation Council ED 2.02 of the Higher Attestation Commission under the President of the Azerbaijan Republic, acting on the basis of the Azerbaijan State Oil and Industry University

Chairman of the Dissertation Council: Doctor of Technical Sciences, Professor
Ibrahim Abulfaz oglu Habibov

Scientific Secretary Dissertation Council: Doctor of Philosophy, associate professor
Shukur Nariman oglu Nasirov

Chairman of the scientific seminar: Doctor of Technical Sciences
Gahraman Soyun oglu Hasanov

GENERAL DESCRIPTION OF THE DISSERTATION

The actuality of the work. The most important achievement of powder metallurgy technology is the ability to create unique combinations of various substances (components) in one material. This advantage of powder metallurgy technology has made it possible to create the widest range of so–called composite materials - dispersed-hardened and reinforced, pseudo-alloys. The production of various kinds of coatings is largely based on this feature of powder metallurgy.

The creation of new wear-resistant materials is a priority area of powder metallurgy. At the same time, researchers are faced with two tasks: improving the properties of materials, considering the increasing requirements for them, and reducing the cost of materials using cheaper and more affordable components, as well as simplifying the technological cycle of manufacturing wear-resistant products.

In this context, the creation of wear-resistant powder materials based on iron occupies a leading place among the technological processes of powder metallurgy. For example, numerous studies on the disposal of industrial waste have been conducted recently. In our opinion, such more commonly used wastes are cast iron shavings and glass production waste. The transformation of cast iron chips and glass waste into powder will allow them to be used as components of an iron-based powder charge.

The use of iron, cast iron, and glass powders in the charge is formed when pressed in a closed mold into an elastic-plastic medium. Cast iron and glass do not have plastic deformability; in this case, the compaction of the powder charge can occur only due to plastic particles of iron, i.e., the main component of the pressed charge. The issues of compaction of the elastic-plastic medium, which is the medium "iron-cast iron-glass" are not studied and therefore are of serious scientific and practical interest.

Object of research. The object of the dissertation research is powder composite metal-glass materials synthesized from powders of iron, cast iron and glass, intended for the manufacture of anti-friction parts.

Subject of study. The subject of the study is the compaction kinetics of powder material from an elastic-plastic medium, factors affecting the characteristics of the quality of interparticle splicing, features of the formation of the structure and properties of the composite powder material of the “iron-cast iron-glass” system.

Aim and objectives of the study. The aim is to develop a new scientific direction on compaction of an elastic-plastic medium, "iron-cast iron-glass" and to evaluate the processes of pressing and sintering of "iron-cast iron-glass" powder materials under various conditions and parameters of pressing and sintering technology.

To achieve this goal, the following tasks were set and solved:

1. Selection of the composition of the powder charge of an elastic-plastic medium consisting of iron, cast iron, and glass powders.
2. Development of mathematical models of the process of cold pressing of an elastic-plastic medium, under various conditions of passive deformation.
3. Theoretical and experimental evaluation of plastic deformation of porous blanks made of "iron-cast-iron-glass" during radial compression in a rigid mandrel.
4. Construction of a unified mathematical model of pressure treatment processes of powder charges and porous blanks made of "iron-cast iron-glass”.

5. Evaluation of the compaction of porous bodies made of "iron-cast iron-glass" with the participation of press equipment of different shapes.
6. Estimates of force and kinematic parameters during plastic deformation of porous blanks made of "iron-cast iron-glass”.
7. Development of mathematical models of the sintering process of metal-glass materials based on iron. Analytical description of the sintering kinetics of these materials.
8. Evaluation of the main advantages of using metalized glass in iron-iron powder materials and calculation of the diffusion coefficient of components.
9. Experimental study of the processes of pressing and sintering of metal-glass materials.
10. Development of prerequisites for the introduction of research results into production in the conditions of the Republic of Azerbaijan.

Research methods. In the dissertation work, modern research methods are applied:

- the well-known provisions of the theory of composite powder materials for constructing a mathematical model of static deformation, and stability.
- numerical and numerical-analytical methods for solving boundary value problems for calculating the stress-strain state.
- a model is constructed using FCM clustering of experimental data to derive fuzzy IF-THEN rules describing the relationship between composition and properties, as well as the relationship between material properties and technological parameters.

Experimental work on obtaining samples and parts, i.e. on pressing, sintering, and steam-thermal oxidation was carried out using modern equipment, installations, and devices of the companies

“KowoLindberg” (USA), Mappesmap “Elino” (Germany). Studies of mechanical and tribotechnical characteristics were carried out according to standard methods, and studies of microstructures on a metallographic microscope “NEOFOT–21 (Germany)” and on the TescanVega 3 scanning electron microscope.

Dilatometric studies to determine the kinetics of sintering and shrinkage patterns were carried out on a high-temperature dilatometer DIL402-2 (NETZSCH). The reliability of theoretical and experimental results has been confirmed in laboratory and production conditions. Pilot-industrial testing of the technology for obtaining powder composite material "iron-cast iron-glass" was carried out in production conditions during the manufacture of parts 8TЛL.210.005 "Bushing”.

The results of the dissertation can be applied not only to the machine-building (mechanical engineering), oil, and gas enterprises of the Republic of Azerbaijan but also to the enterprises of the CIS member countries and other countries.

The main highlights submitted for defense:

1. New composition of the charge made of composite powder material of the type "iron-cast iron-glass".
2. Mathematical models of the process of cold pressing of porous bodies in an elastic-plastic medium.
3. Experimental evaluation of plastic deformation of porous blanks made of "iron-cast iron-glass".
4. Mathematical model of pressure treatment processes of powder charges and porous blanks made of "iron-cast iron-glass".
5. Resulting equations for compaction of porous bodies in an elastic-plastic medium.
6. Processes of compaction of porous bodies made of "iron-cast iron-glass" in molds of different shapes.

7. Results of evaluation of force and kinematic parameters during plastic deformation of sintered porous blanks made of "iron-cast iron-glass".
8. Mathematical model of the sintering process of metal-glass materials based on iron.
9. Based on theoretical and experimental studies the technology of production of wear-resistant powder products from "iron-cast iron-glass" was developed.
10. Models of the relationship between the composition of the "iron-cast iron-glass" material and its properties in the form of fuzzy "IF-THEN" rules were obtained by applying the method of fuzzy clustering of C-means to experimental data. Similarly, fuzzy "IF-THEN" rules describing the relationship between technological parameters and material properties are obtained.

Scientific novelty. Mathematical models of the compaction of powder material from an elastic-plastic medium have been developed. It is determined that with an excessive increase in radial deformations, the porosity of the compresses remains practically unchanged. The process of compaction of sintered "iron-cast-iron–glass" consists of two stages: the first is a change in the shape and volume of the body, and the second is only a change in shape without compaction of the body.

Based on the application of the method of fuzzy clustering of C-mean experimental data, fuzzy "IF-THEN" rules describing the relationship between the composition of the "iron-cast iron-glass" material and its properties are constructed. These rules allow describing the dependence under consideration in the conditions of inaccuracy, uncertainty, and complexity of a large volume of experimental data. Based on the constructed rules, a material with the specified characteristics is synthesized (i.e., the composition of the material at which the specified characteristics can be achieved is determined).

Fuzzy "IF-THEN" rules describing the relationship between the technological parameters and the properties of the "iron-cast iron-glass" material are constructed. These rules are a linguistic model that allows us to interpret the dependencies contained in complex and imperfect experimental data. Based on the rules, a material with the specified characteristics is synthesized (i.e., the number of initial components of the charge and the values of technological parameters at which the specified characteristics can be achieved are determined).

The behavior of metal-glass porous bodies during compaction under conditions of limited passive deformation is established. Radial compression of a body with rigid walls can be considered the most energetically advantageous, and the greatest energy costs are necessary for the compaction of the material by the method of free precipitation. With radial compression in a rigid frame of porous "iron-cast-iron-glass" bushings, the density of the compacted body is evenly distributed along the radius.

Using the methods of microstructural analysis and hardness testing of a porous body, a new understanding of the distribution of porosity of the material, grain deformation, and their relationship was obtained, and hardness tests allowed determining the mechanical properties of the components of the stress-strain state of the body.

A mathematical model of the processes of pressure treatment of powder charges and porous billets made of "iron-cast iron-glass" has been constructed, which made it possible to determine during plastic flow the participation with general tensor ratios of the scalar ratio linking the components of the stress tensor.

Estimates of the force and kinematic parameters during the deformation of sintered porous blanks made of "iron-cast iron-glass" are made. It has been determined that it is not possible to achieve a pore-free state of an elastic-plastic material during precipitation; therefore, an excessively large force is required to achieve zero porosity.

Mathematical modeling of the sintering process of metal-glass materials based on iron is carried out. It is established that with a topologically continuously transforming structure of a powder material during sintering, a quantitative analysis of the kinetics of changes in the linear parameter of the porous structure can be carried out using the general laws of diffusion coalescence of a dispersed system.

The main advantages of using glass in metal-glass materials are determined. In the microstructure "iron-cast iron-glass" after sintering, in addition to the metal matrix, pores and free inclusions of glass, because of the interaction of the metal with glass, a new phase in the form of fayalite and hematite may be present.

According to experimental data, the diffusion coefficients of the components of the charge from "cast iron-cast iron-glass" are calculated. It is determined that at high temperatures, volumetric diffusion is of paramount importance, which is expressed by a decrease in the mechanical strength of the particles, an increase in their plasticity, and their ability to volumetric flow in the metal under the action of surface tension forces.

The practical value of the work. Considering the developed theoretical provisions of pressing powder charges and porous blanks, as well as the sintering of presses and using experimental research data, a technology to produce wear-resistant powder materials from "iron-cast iron-glass" has been developed. The use of cast iron and glass production waste as part of the charge made it possible to reduce the cost of the developed wear-resistant material significantly.

Prerequisites and recommendations have been developed for the introduction of research results into production, in the manufacture of friction components of loaded pumps and other parts used in the oil and gas industry of the Republic of Azerbaijan.

Implementation of results in the industry. The scientific developments and technical solutions presented in the dissertation are aimed at creating and improving various methods of pressing and sintering composite materials of the "iron-cast iron-glass" type, saving material and energy resources. The results of the dissertation development were implemented at the Aznefthimmash enterprises in the production of wear-resistant parts used on equipment and installations of the oil and gas industry of the Republic of Azerbaijan.

Approbation of the work. The materials of the dissertation were reported, discussed, and approved at:

1. Republican Conference of young scientists and graduate students. Baku, December 1997.
2. Scientific-Technical conference for graduate students and young researchers of Azerbaijan Technical University (AzTU), Baku, April 12-15, 2002.
3. 46th Student scientific and technical conference AzTU, Baku, May 1-3, 2003
4. Scientific-Technical Conference of graduate students and young researchers dedicated to the 80th anniversary of the National Leader of the Republic of Azerbaijan Heydar Aliyev. Baku, May 12-15, 2003.
5. XIX Republican scientific conference of Higher School students. Baku (the conference was held in accordance with the order of the Ministry of Education of the Republic of Azerbaijan dated 31.01.2003 No. 93), May 16-17, 2003, Azerbaijan University of Architecture and Construction (AzUAC).
6. International scientific-practical conference on Modern Problems of the Physics of Metals, AzUAC, Baku, October 9-11, 2007.

7. International Conference on Thermophysical and Mechanical Properties of Advanced Materials and 4th Rostocker International Symposium on Thermophysical Properties for Technical Thermodynamics. AzTU, Baku, September 17-18, 2015.
8. V International scientific-practical conference on Modern Problems of the Physics of Metals". AzUAC, Baku, June 10-11, 2016.
9. International scientific-practical conference on Intellectual Technologies in Machinery Construction”. Baku, September 28-30, 2016
10. Republican scientific-technical conference of students and young researchers on Youth and Scientific Innovations. - Baku, AzTU, May 3-5, 2017
11. 2nd International scientific and technical conference on Problems of Metallurgy and Materials Science. Baku, November 28-30, 2017
12. 10th World Conference on Intelligent Systems for Industrial Automation, WCIS-2018, 25-26 October 2018, Tashkent, Uzbekistan.
13. International Conference on Research in Natural and Engineering Sciences (ICRNES 2020) Konya, Turkey.
14. Fifth International Iron-Steel Symposium. April 1-3, Karabuk, Turkey.
15. 11th World Conference on Intelligent System for Industrial Automation, WCIS-2020, AISC1323, Tashkent, Uzbekistan.
16. Second International Scientific-Practical Conference “Modern Information, Measurement and Control Systems: Problems and Perspectives 2020” (MIMCS 2020) dedicated to the 100th anniversary of ASOIU, December 07-08, 2020, Baku, Azerbaijan.
17. "Problems of water transport" XVIII International scientific and technical conference. Azerbaijan State Maritime Academy, Baku, May 4-5, 2023

The materials presented in the dissertation work are used in the course and graduation works for bachelor and master's theses at Azerbaijan State University of Oil and Industry and Azerbaijan Technical University.

Organization where the dissertation was realized. Azerbaijan State University of Oil and Industry in the "Material Science and Technology Processing" department.

Personal contribution of the applicant in the research. In the dissertation, work on substantiating the relevance of the tasks set by studying the literature data, on choosing research methods and applying them in solving conceived scientific problems, on the execution of planned experiments at all stages of the study, generalization and systematization of the results obtained was carried out directly by the applicant. The analysis of the results of experiments, as well as the discussion of work at scientific conferences, the compilation of scientific articles based on the results obtained were also carried out by the author himself.

Structure of dissertation. The dissertation work consists of an introduction, six chapters, conclusions and recommendations, a list of used literature, including 264 titles and applications.

The work is presented on 310 pages of computer text, contains 76 figures and 11 tables. Chapter 1 consists of 61366, Chapter 2 of 62300, Chapter 3 of 49728, Chapter 4 of 57801, Chapter 5 of 37904, Chapter 6 of 61140 characters. The total volume of work consists of 380930 characters.

Publications. The main results of the dissertation obtained by the author are published in 17 articles and conference proceedings. Received copyright certificate No. 1752508 on April 8, 1992.

MAIN CONTENT OF THE WORK

In the introduction, the substantiation of the actuality of the work is given, the goals and objectives of the research are formulated, and the main results of scientific novelty and practical significance are outlined.

The first chapter contains a literature review about the problems of creating self-lubricating composite materials with a heterogeneous structure. It has been established that the attention of researchers in the field of creating powder materials with a heterogeneous structure is focused on the principle of obtaining such materials using industrial waste. It is indicated that such waste suitable for the production of powder materials with a heterogeneous structure can be cast iron shavings and glass production waste.

The possibility of creating new wear-resistant powder materials synthesized from a mixture of iron and cast-iron powders has been studied and analyzed. It has been established that to produce the iron-iron compositions, the most effective component may be white cast iron powder, the carbon of which interacts effectively with the iron matrix during sintering. The results of the study of iron-iron compositions show that the sintering of iron-iron compositions must be activated by the presence of a liquid phase in the system. Such a component of iron-iron compositions can be, for example, glass, which has a lower melting point than iron and cast iron.

It is established that an important factor for the successful operation of wear-resistant composite powder materials is the design of friction units, where the conditions for the supply of lubricant to the friction zone are determined. Five design designs of friction units have been selected for the operation of porous wear-resistant powder materials. They are as follows:

– Porous products that work only due to the supply of lubricant in their pores.

– Porous products with increased lubrication reserve due to additional tanks in the friction unit;

– Porous products with additional periodic or continuous supply of lubricant into the gap.

– Porous products with periodic oil recharge in compensation tanks.

– Porous products with filtration lubrication systems, through a porous wall.

The test results showed that the bushings made of porous powder wear-resistant materials have significantly less wear under conditions of liquid friction compared to the antifriction component - cast iron, which does not have an oil reservoir in the form of pores.

Based on the literature review, it can be noted that powder wear-resistant materials are of great interest from a materials science point of view. For example, even though there are numerous studies on cold pressing and sintering of plastic media, and there are no studies on elastic plastic media. Consequently, in the study of plastic media, laws and regulations can be applied theoretically for plasticity, and elastic ones – the theory of elasticity. In the case of developing processes for the formation of an elastic-plastic medium, neither one nor the other theory is suitable. Therefore, we need another extraordinary approach.

Today, the intensive development of powder metallurgy poses the task of modeling technological processes using computer graphics for researchers. In this case, the task of modeling the process of pressing a powder charge from an elastic-plastic medium in a closed mold is facilitated. Existing models of compaction of metal powders [211][1], while satisfactorily describing the functional dependencies between individual parameters, cannot serve for the above purposes. First, they are, as a rule, static, while a consolidated powder body is a non-equilibrium thermodynamic system with nonlinear internal dynamics, which means that the equation of state of its environment of other parameters must include time. This condition satisfies only the theory of hot processing of porous materials by pressure. In addition, the technological regimes are very sensitive to changes in temperature and pressing speed, which, as a rule, do not take into

1.Hewift R.L., Wallace W. de Molherbe M.S. The effects of Abrain- hardening in powder compaction//Powder Metallurgy, 2002, 16, № 31, pp.88-106.

account the existing models of the process of compaction of an elastoplastic medium.

Therefore, for adequate modeling of technological pressing of charge components, it is necessary to use an extended system of external and internal thermodynamic parameters, τ, time t, temperature T, external pressure P (or loading rate P), as well as a set of generalized rheological parameters characterizing the physicochemical properties powder particles and their shape (μ_R). The compaction process should be described by a differential equation in the form:

$$\frac{d\tau}{dt} = \Phi(\tau, t, T, P\{\mu_R\}) \qquad (1)$$

where $\frac{d\tau}{dt}$ is the rate of change in the relative density of the porous material during compaction; $\Phi(\tau, t, T, P\{\mu_R\})$ - some function of external and internal parameters. The equations of state of the system should be obtained as the result of integrating expression (1). In [112][2] an attempt is made to construct a phenomenological theory of the pressing process, only homogeneous processes in a closed mold that meets the above requirements. Also, the ways of applying it as a basic model for describing metal powder pressing processes and modeling technological production processes are considered. Consequently, such a model does not meet the conditions of compaction of an elastic-plastic medium, where it is necessary to consider both the theory of plasticity and the theory of elasticity.

Thus, as can be seen from the literature review, there is currently no stable theory of pressing powder materials containing both plastic and elastic elements. Therefore, the development of new models that take into account the radial compression of a porous body, the stages of compaction, the conditions of both passive and active deformation, and other parameters of pressing an elastic-plastic

2. Нигматулин, Р.И. Основы механики гетерофазных сред //- М: Наука, - 2008.- с. 336.

medium is a very urgent task.

In addition, it is necessary to evaluate (mathematically) the compaction during one-sided, two-sided pressing and pressing with a floating matrix. This will allow to determine a more energetic option for compacting materials. For example, radial compression of porous bushings made of "iron-cast iron-glass" can be investigated to determine its energy during compaction.

It is necessary to build a unified mathematical model of the pressure treatment processes of powder charges and porous blanks made of "iron-cast iron-glass". In this case, it is possible to obtain the resulting equations for compaction of porous bodies, in the presence of an elastic-plastic medium. In addition, for compaction of such materials, the shape of the forming tool during pressing is of no small importance.

An essential point is the mathematical modeling of the sintering process of metal-glass powder presses. Thus, it is possible to analytically describe the kinetics of sintering of powder materials, the diffusion processes of iron and carbon with the participation of glass and other inclusions of endogenous and exogenous origin. It is also possible to evaluate the main advantages of using in the composition of powdered ferruginous, citallized glass. Moreover, the pre-exponential multiplier of the diffusion coefficient of powder alloy and citallized glass can be determined.

Finally, the developed models of pressing, sintering, annealing, and other processes can be a theoretical basis for processing the technological modes of these operations. Based on these models, it is possible to build experimental studies correctly, reducing the number of experiments based on correct accurate predictions.

In the second chapter, the compositions of powder mixtures are selected, and the properties of their components are investigated. To improve the interfacial interaction, and, consequently, increase the mechanical properties and wear resistance, it is necessary to introduce components into the charge containing glass that have better wet ability with it [2][3].

3.Oksidləmə paramerlərinin ЖЧ50СТ6 ovuntu kompozisiya materialının mexaniki xassələrinə təsiri. Cabbarov T.Q., Soltanov A.B.

Such an effect can be caused using cast iron powder as part of the charge, since cast iron contains a large amount of silicon and manganese, which, when heated in an oxidizing environment, form hard-to-recover oxides.

It is known that metal oxides are better wetted with each other than pure metals with oxides [3][4].

It should be assumed that during the sintering process, silicon and manganese oxides can be well wetted by glass, forming strong compounds. This concept was the basis for the choice of iron, cast iron and glass to produce the composite sintered materials. To eliminate the shortcomings inherent in known materials, either containing scarce components or having low properties, a charge was developed for obtaining a metal-glass material, protected by an author's certificate [50][5]. In its composition is used a powder obtained from gray cast iron chips produced according to ТУ16-89 ВАИК41 1100.006ТУ and containing (by weight %): carbon – 3.0 - 3.8; silicon – 1.5 – 2.8; manganese – 0.5 - 1.0; phosphorus – 0.05 - 0.1; sulfur – 0.05-0.1. The charge is obtained by mixing iron powders of the ПЖ2МЗГОСТbrand in a Y-shaped mixer for 2.4 ks 9849-74 – 40 - 88 wt.%, cast iron – 10 - 50 wt.% and vacuum glass grade C88-5 OCT 11027. 037-79 – 2 – 10. The selection of the content of cast iron powder in the range of 10-50 wt.% is explained by the fact that this interval have been studied before and is the most suitable, from the viewpoint of the manufacturability of the charge and ensuring sufficiently high properties of the sintered material.

The choice of the composition of the material "iron-cast iron-glass" was substantiated by theoretical [174][6] and experimental methods [8][7].

4.Oksidləşdirilmiş dəmir-çuqun-şüşə sistemli ovuntu kompozisiya materialının tribotexniki xassələrinə bişirmə temperaturunun müddətinin təsiri.Cabbarov T.Q.,Soltanov A.B.

5.Шихта для получения износостойкого спеченного материала на основе железа //Авторское свидетельство №1752508, 8 апреля 1992 г.Джаббаров Т.Г., Мамедов А.Т.

6. Soft Computing and Its Application. World Scientific. Aliev, R.A., Aliev, R.R.

7. Konstruksiya ovuntu poladları üçün xrom tırkibli legirləyici əlavələrin seçimi. M.B. Babanlı, CabbarovT.Q.

When theoretically substantiating the composition of the charge, fuzzy rules "IF-THEN" were defined. These rules describe the relationship between the composition of the material and properties. The rules are built based on experimental data, using C-means fuzzy clustering [216][8].

The task of fuzzy clustering of C-means consists in partitioning a set of data $X = \{x_1, ..., x_n\}$ in an n-dimensional space into c fuzzy clusters. It is formulated as follows:

Objective function: $$J_m = \sum_{i=1}^{n} \sum_{j=1}^{c} u_{ij}^{m} \left\| x_i - v_j \right\|^2 \to \min$$

Constraints: $$u_{ij}^{m} = \frac{1}{\sum_{j=1}^{c} \left(\frac{\left\| x_i - v_j \right\|}{\left\| x_i - v_k \right\|} \right)^{\frac{2}{m-1}}},$$

$$v_j = \frac{\sum_{i=1}^{n} u_{ij}^{m} x_i}{\sum_{i=1}^{n} u_{ij}^{m}},$$

$$1 \le m < \infty,$$

here u_{ij} - the degree of belonging of the data object x_i to the j-th fuzzy cluster; $\left\| \cdot \right\|$ - Euclidean distance; m- is a parameter that determines the fuzziness of clusters; v_j - is the center of the j-th fuzzy cluster.

8. ЖЧ30Ст6 ovuntu kompozisiya materialının struktur və xassələrinə presləmə təzyiqinin təsiri. Cabbarov T.Q., İbrahimov A.

The objective function, the value of which must be minimized, is the sum of the distances of the cluster elements to the centers.

Experimental data are characterized by uncertainty. The input variables of the model are the quantities of the initial charge components. The output variables are the mechanical properties of the “iron-cast iron-glass” composite material. The goal is to build a model of the relationship between the composition of the material and its properties, taking into account the uncertainty.

The fuzzy partition (standard) used in the construction of the rules is shown in Figure 1.

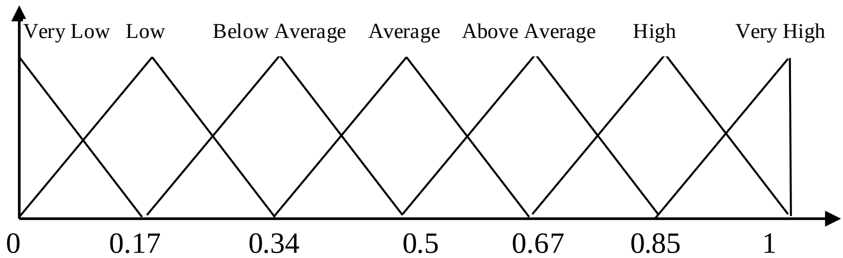


Figure 1. Fuzzy partitioning

A graphical representation of the rules is given in Figure 2. To calculate the composition of the material according to the given characteristics, the Mamdani fuzzy inference algorithm was applied. This algorithm is summarized below.

According to Mamdani's fuzzy inference algorithm, for given values of input variables $(y_1^*,...,y_n^*)$, the value of the output variable of the model $z_l^*, l=1,...,L$ is calculated as follows:

1. The values of membership functions $\mu_{A_{j1}}(y_1^*),...,\mu_{A_{jn}}(y_n^*)$ of fuzzy input terms $A_{j1},...,A_{jn}$

2. The degree of activation of the rules is determined:

$$\alpha_j = \mu_{A_{j1}}(y_1^*) \wedge ... \wedge \mu_{A_{jn}}(y_n^*) \ ,$$

where $\wedge$ - is the logical minimum operation (min).

3. The "truncated" membership functions $\mu'_{B_{jl}}(z_l)$ of the output term B_{jl} are calculated:

$$\mu'_{B_{jl}}(z_l) = \alpha_j \wedge \mu_{B_{jl}}(z_l)$$

4. Based on the operation of combining fuzzy sets, the final fuzzy set is calculated with a membership function μ_Σ for the output variable:

$$\mu_\Sigma(z_l) = \mu'_{B_{1l}}(z_l) \vee \ldots \vee \mu'_{B_{cl}}(z_l) \ ,$$

where $\vee$ is the logical maximum operation (max).

5. A crisp value $z_l^*, l = 1,\ldots,L$ of the output variable is calculated based on the defuzzification using the center of gravity method:

$$z_l^* = \frac{\int_{\underline{z}_l}^{\overline{z}_l} z_l \cdot \mu_\Sigma(z_l)}{\int_{\underline{z}_l}^{\overline{z}_l} \mu_\Sigma(z_l)},$$

where $\underline{z}_l$ and $\overline{z}_l$ respectively are the lower and upper bounds of the universe (range) for z_l, $\int$ is the symbol of the integral.

The resulting rules can be used to determine the composition of the material according to the given characteristics.

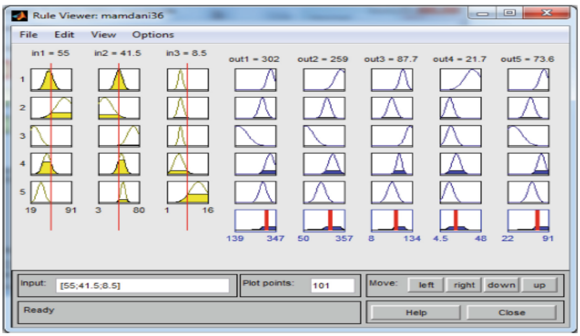


Figure 2. Graphical description of fuzzy rules

For example, suppose you want to get a material with the following characteristics:

$$z_1=302; z_2=259; z_3=88; z_4=22; z_5=73.6,$$

where z_1 is the tensile strength (σ_s, MPa); z_2 - ultimate strength in bending (σ_b, MPa); z_3-hardness (HB, MPa); z_4-impact strength (KC, kJ/m^2); z_5- relative density (θ,%) of the composite material "iron-cast iron-glass".

The calculation based on the obtained rules showed that these characteristics are achieved with the following composition:

$$y_1=55; y_2=41.5; y_3=8.5,$$

where y_1 is the amount of iron powder (in wt.%); y_2-cast iron powder (in wt.%); y_3-glass powder (in wt.%).

During the experimental justification of the choice of charge mixture composition, the iron and glass content, as well as the dispersity of their particles were chosen as parameters for optimization. Pressing of prismatic samples (55x10x10 mm) was carried out under pressure of 1000 MPa under normal conditions, and sintering at 1150 °C in endothermic gas medium for 3.6 ks. [6][9]. The highest mechanical properties have samples containing 30-50 wt.% cast iron with particle sizes from 100 to 160 mkm and 2-6 wt.% glass powder (50-200 mkm).

The friction coefficient (f) and wear (J) of the material were studied under dry friction on a standard machine СМЦ-2 under the scheme "prismatic sample - sleeve" of steel 45 hardened to hardness 50 HRC. The pressure on the sample was constant and was 4.0 MPa, with a sliding speed of 1.0 m/s. The specimens were pressed under normal conditions at a pressure of 1000 MPa and sintered in an endo-gas at 1150 °C.

The choice of such a high pressure of pressing is explained by poor compressibility of the charge, because of powders of glass and cast iron. The dependence of f and J on the content of iron (a) and glass (b) powders, shows that with an increase in the content of iron powder in the charge (at the content of glass powder 6 wt.%) from 10

9.Разработка композиционных порошковых материалов «железо-чугун-стекло» для деталей бытовой техники. Дис.на соиск. уч. степ. канд.техн.наук. Джаббаров Т.Г to 50% f and J tend to decrease. Further they sharply increase that is connected with intensification of wear caused by low mechanical properties of the material of this composition. Thus, the best antifriction properties have the material containing 50 wt.% cast iron, which was used for the study. Higher antifriction properties, are achieved at 6% glass content in the charge. With an increase in the content of glass powder in the charge to 10%, the brittleness of the material increases, which leads to chipping of solid particles, and hence to abrasive wear. With a decrease, f and J also deteriorate significantly, which is associated with the worse mechanical properties of the material.

The effect of temperature and sintering time on f and J was studied.

With increasing sintering temperature from 1050 to 1150 °C, f and J improve, which is explained by hardening of the material and glass sitalization. Increasing the sintering duration at 1150°C in the range of 1 - 3 hours, at first improves f and J, and then worsens them. This is due to the formation of large accumulations of molten glass. Studies were also carried out on the effect of glass grade. Samples were pressed in a press-form with a "sweating" matrix at a pressure of 1000 MPa and sintered at 1150°C. It follows from the data given in Table 1 that a wear-resistant powder material on the basis of iron (compositions 1 - 3) has rather high mechanical and antifriction properties. The use of a different grade of glass in the composition of the charge (compositions 4, 5) leads to their reduction, which is associated with the fact that vacuum glass contains more SiO_2, MnO, Ba_2O_3, [51][10], which are well wetted with particles of iron and cast iron having oxides on the surface.

The main condition in this case is the presence of metal oxides on the surface, the melting temperature of which must significantly exceed the melting temperature of the glass. Reducing the content of cast iron and glass to less than 10 and 2 wt.%, respectively, leads to a decrease in the mechanical properties of the material, and increasing their content to more than 50 and 10 wt.%, complicates the process of pressing powder charge.

The method of increasing the strength of metal-glass materials was developed. This method consists in the fact that before sintering, the pressings are subjected to steam-thermal oxidation in an Elino-type furnace at a temperature of 570 – 600 °C for 7.2 k/seconds. The sintering of oxidized samples is carried out in an endothermic gas environment in a furnace of “KOYO LINDBERG”-type at a temperature of 1150°C with an isothermal exposure time of 3.6 ks.

In order to inhibit oxide reduction, the samples are placed in metal trays and covered with talcum powder on top. Last mentioned activates the interfacial interaction of iron, silicon, manganese and glass oxides.

The microstructure of materials ЖЧ10С2 and ЖЧ20С4, pressed at pressures of 400, 700 and 1000 MPa, vaporized is presented in Fig.3. In the process of sintering of the "iron-glass" system, the glass melts, and the interaction of free silica with metal oxide occurs at its border with the metal. Further, the oxides are dissolved in the glass and complex compounds are formed - silicates.

In the materials of the "iron-cast-iron-glass" system, this mechanism proceeds somewhat differently. Since cast iron contains an active reducing agent in the form of included graphite, there is a risk of removing oxides from the surface of the metal during heating, and, therefore, their wetting with glass is not observed.

Therefore, the principle of formation of heterogeneous particles on the surface of "related" phases and inclusions, which ensure their interphase interaction during sintering, is proposed.

This principle is realized by carrying out of steam thermal oxidation of unbaked blanks. It is established that the difficult-to-reduce oxides SiO^2, MnO and iron oxides formed during sintering dissolve well in glass [221][11], (Fig. 4).

Sintered alloys ЖЧ10С2 and ЖЧ20С4 have a pronounced heterogeneous structure - a metal matrix and uniformly distributed glass inclusions.

---

10. Development of composite powder materials "iron-iron-glass" for details of home appliances. D. thesis for the degree of Candidate of Technical Sciences. Jabbarov T.G.
11. Влияние режимов спекания порошковых оксидированных заготовок на их механические свойства. Джаббаров Т.Г., Бабаев А.И.

Table 1

Compositions of charges and properties of materials obtained from them

Composition №	The content of components in the charge, wt.%		Brand of glass	Cast iron composition, wt.%					The size of the glass powder, mcm	The size of the cast iron powder, mcm	The ratio of the fineness of cast iron and glass powders	Properties of sintered materials			
	Cast Iron Powder	Glass Powder		C	Si	Mn	P	S				σ_s, MPa	σ_b, MPa	KC, kJ/m^2	f
1	10	2	C88-5	3,8	1,5	0,5	0,05	0,05	10	100	1:0,1	490	1050	125	0,15
2	30	6	C88-5	3,4	2,1	0,75	0,075	0,075	50	150	1:0,3	475	970	116	0,13
3	50	10	C88-5	3,8	2,8	1,0	0,1		100	200	1:0,5	453	907	95	0,14
4	30	6	№40	3,4	2,1	0,75	0,075	0,075	50	150	1:0,3	340	750	78	0,22
5	30	6	№46	3,4	2,1	0,78	0,075	0,075	50	150	1:0,3	350	760	80	0,21

The structure of the metal matrix is represented by pearlite and ferrite, structurally free cementite is also observed in the ХЧ20С4 alloy. During the sintering process, the glass particles changed their form from fragmented to more rounded (Fig. 5). The first level of heterogeneity is observed between the metal matrix and glass inclusions, the second is in the matrix itself, which contains both hard and soft inclusions.

An increase in pressing pressure from 400 to 1000 MPa increases σ_s, σ_b KC of vapor-oxidized and sintered materials (Fig. 6 – 8). σ_b significantly increases with an increase in pressure from 400 to 700 MPa, and its further increase to 1000 MPa somewhat slows down the intensity of its increase.

In alloy ЖЧ20С4, in these conditions, the strength even decreases somewhat (Fig. 6). This is explained by the fact that increasing the pressing pressure up to 1000 MPa for an alloy with a cast iron content of 20 and 4 wt.% glass leads to the destruction of glass particles, which is the focus of cracks and breaks in pressing. The increase in the content of cast iron and glass in the batch also contributes to the increase in the strength of the materials. At the same time, if an increase in the content of cast iron, and therefore carbon, leads to the enrichment of austenite with the latter, then the increase in glass improves the wettability of the particles of the multicomponent system.

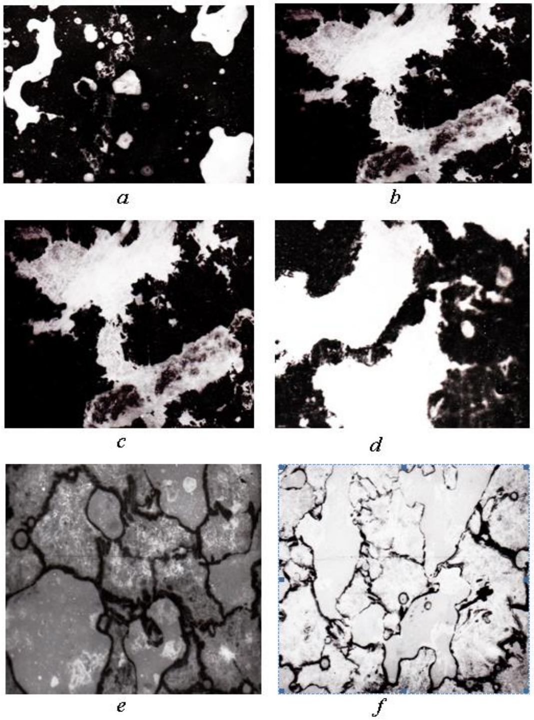


Figure 3: Iron-iron-glass microstructure, ×400:
a, b; c, d; e, f; pressing pressure 400;700 and 1000 MPa, respectively, a, c, e; b, d, f iron and glass content 10 and 2; 20 and 4 wt.%, respectively

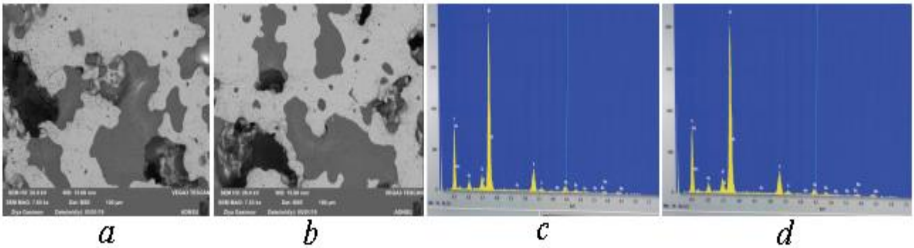


Figure 4: Saturation of glass particles with Mn, Si and Fe- as a part of iron, "iron-iron-glass" materials:
a, c-iron-glass; b, d-"iron-iron-glass"

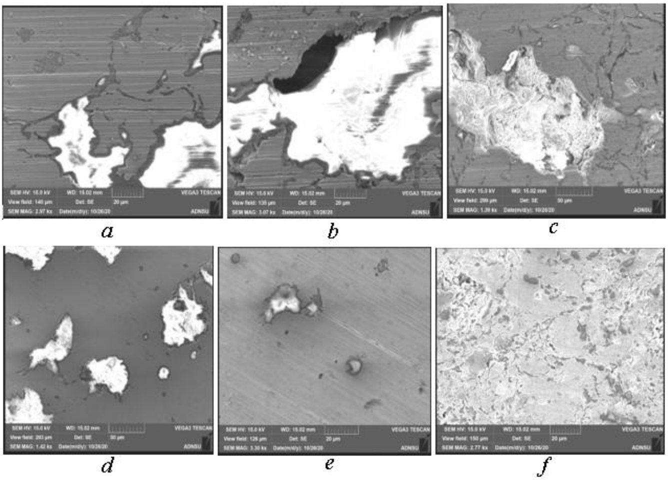


Figure 5. The change in the shape of glass particles during sintering: a, b; c, d; e, f; pressing pressure 400; 700 and 1000 MPa, respectively a, c, e; b, d, f the content of cast iron and glass 10 and 2; 20 and 4 wt.%, respectively

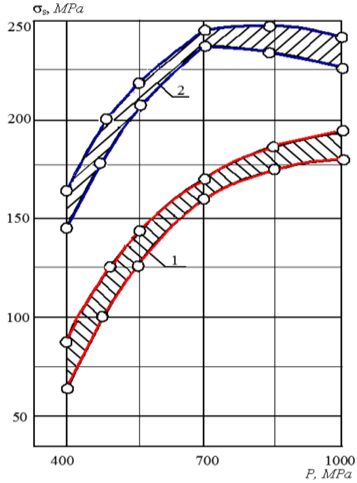


Figure 6. Dependence of σ_s on the content of iron and glass in the charge and on the pressing pressure: 1; 2 – iron and glass content in charge 10; 20 and 2; 4 wt.% respectively

σ_b with increasing pressing pressure increases sharply (Fig.7). It increases with an increase in the content of cast iron and glass, respectively, to 20 and 4 wt.%. Probably, the more glass, and hence the liquid phase in the alloy, the stronger the impregnation of the porous frame with liquid occurs during sintering, accompanied by shrinkage and homogenization of the alloy.

The graph of the dependence of the KC of samples on the pressing pressure does not differ from the similar graph $\sigma_b$and (Fig.8). However, an increase in the content of cast iron and glass in materials almost does not increase the KC of samples due to the fact that they are naturally fragile components. Along with studies of the process of steam oxidation of "iron-cast iron-glass" presses, the effect of oxidation in air on mechanical properties was also studied.

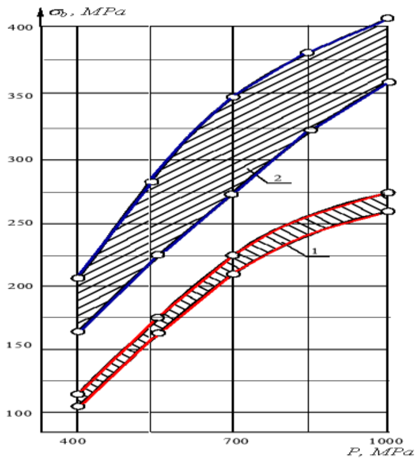


Figure 7. Dependence of σb materials on the iron content and glass in the charge and pressing pressure: 1; 2 - content cast iron and glass in batch 10; 20 and 2; 4 wt.% respectively

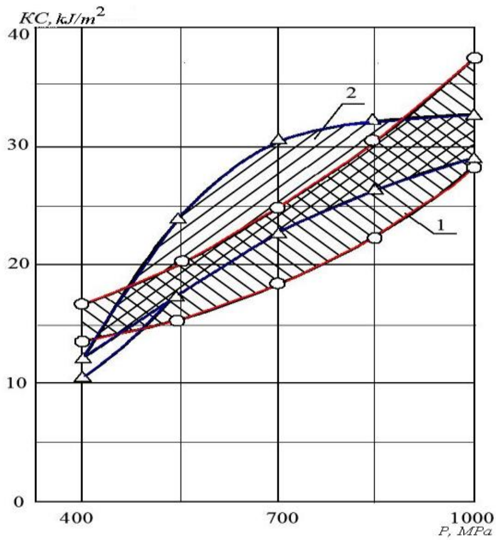


Figure 8. The dependence of the KC of materials on the content of cast iron and glass in the charge and the pressing pressure: 1; 2 – the content of cast iron and glass in the charge 10; 20 and 2; 4 wt.% respectively

Oxidation was carried out in a conventional furnace without a protective medium at temperatures: 200, 400 and 600°C with isothermal exposures: 1, 2 and 3 hours. The pressings were obtained under pressure of 1000 MPa by pressing under normal conditions. Oxidized compacts were sintered in an endo-gas furnace at a temperature of 1150°C. As a result of studying the influence of the oxidation temperature on the properties of the sintered material, it was found that the best properties are obtained at an oxidation temperature of 200° C and an isothermal exposure of 1 hour. However, the highest hardness of the samples is found at an oxidation temperature of 400°C. with an increase in the oxidation temperature to 600°C, the impact strength of the samples decreases sharply, which is explained by an increase in the brittleness of the material during oxidation.

The study of the dependence of the mechanical properties of the sintered material on the duration of oxidation at a temperature of 200 ° C showed that the highest σ_s, σ_b and KC and HB samples are detected at an oxidation duration of 1 hour. This is due to structural changes in glass and the chemical interaction between metal oxides and glass [52][12]. Glass is saturated with iron better, and the matrix is better saturated with silicon. The dissolution of silicon in α – iron increases the impact strength of the material by 1.5 times, leads to a decrease in the lattice parameters and an increase in its plasticity.

In the latter, the relationship between the technological parameters of pressing – sintering and the mechanical properties of oxidized samples was studied. According to Figures 9 and 10, in general, the best mechanical properties of the samples are achieved at an oxidation temperature of 200°C and an isothermal exposure of 1.0 hours, and therefore further experiments were carried out using these modes. As can be seen from Fig. 9, with an increase in the pressing

---

12. Исследование радиального и осевого уплотнения пористого тела методами механики сжигаемого континуума. Мартынова И.Ф., Скороход В.В., Штерн М.Б.

pressure of the presses, their mechanical properties increase, which is consistent with generally accepted patterns.

Thus, the oxidation of compressions before sintering does not change the nature of the formation of the mechanical properties of the material depending on the pressing pressure. Therefore, to obtain samples from "iron-cast iron-glass" with high mechanical properties, the most acceptable is a pressing pressure of 1000 MPa.

With an increase in the sintering temperature of samples pressed under a pressure of 1000 MPa, from 1050 to 1100°C, σ_s, σ_b and KC slightly increase, and HB tends to decrease.

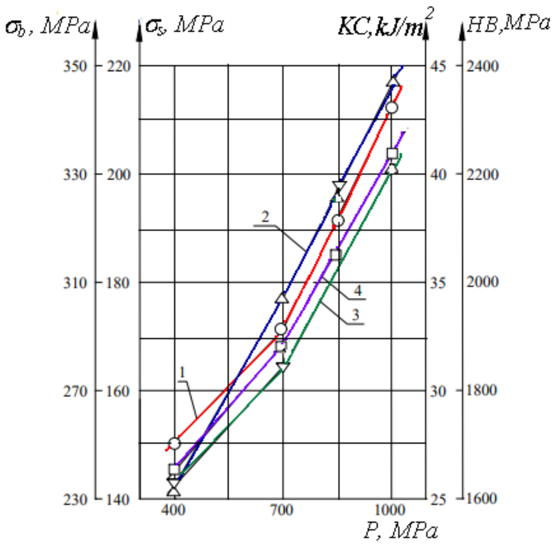


Figure 9. Dependence of the mechanical properties of the ЖЧ50С6 material on the pressing pressure: 1 - σ_s; 2 - σ_b; 3 – KC; 4 – HB

A further increase in the sintering temperature of the samples to 1150°C causes a significant increase in all mechanical properties (Fig.10). Therefore, this temperature can be considered optimal for this class of materials. Apparently, the wetting of particles having "related" phases (oxides) formed as a result of oxidation on the surface is intensified at this temperature.

An increase in the sintering time from 1 to 2 hours increases σ_s, KC and reduces σ_b HB, which is associated with the sitalization of the glass, and, consequently, an improvement in its viscosity. A further increase in the sintering time to 3 hours reduces the σ_s,σ_b and KC of the material, and HB, on the contrary, sharply increases. This is due to the increased migration of molten glass and increased heterogeneity of the material structure. In other words, large accumulations of glass are formed, which, positively affecting the hardness, increase the fragility of the material (Fig.11).

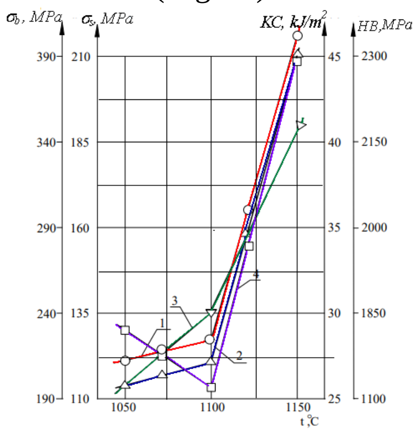


Figure 10. Dependence of the mechanical properties of the material ЖЧ50С6 from the sintering temperature: 1 - σ_s; 2 - σ_b; 3 – KC; 4 – HB.

Tribotechnical characteristics of the material subjected to steam oxidation before sintering are given in Table 2, from which it can be seen that under dry friction conditions at a load of 2-8 MPa, the coefficient of friction of the compositions decreases with an increase in the content of cast iron and glass. Apparently, graphite inclusions and complex compounds (silicates) play a positive role here, which are more the higher the content of cast iron and glass in the alloy. Samples were obtained in a mold with a "sweating" matrix.

In terms of wear resistance, the alloy ЖЧ10С2 has better performance compared to the alloy ЖЧ20С4. If these alloys are qualified according to their performance, then the following sequence can be used: the ЖЧ10С2 alloy with a porosity of

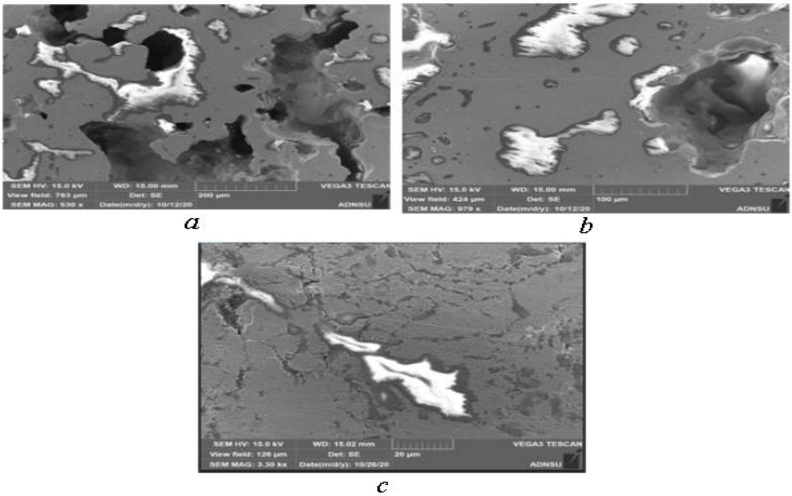


Figure 11. Formation of large accumulations of glass in the structure with a sintering duration of 3 hours: a-ЖЧ10С2; b-ЖЧ20С4; c-ЖЧ50С6

20% has a working capacity of up to 6 MPa, 14% - up to 8 MPa, 10% - up to 10 MPa; the ЖЧ20С4 alloy with a porosity of 22% - up to 4 MPa, 13-16% - up to 6 MPa. This is due to the fact that with an increase in the content of cast iron and glass, the latter reduce the mechanical properties of the alloy to a greater extent. At a load of 2 MPa, the difference in performance is not so clearly traced as with increased loads.

The effect of temperature and duration of oxidation on the tribotechnical characteristics of the ЖЧ50С6 material was studied under dry friction conditions under a load of 2 MPa. The samples were pressed under a pressure of 1000 MPa under normal conditions. The lowest f and J have samples oxidized at a temperature of 200 ° C with an isothermal exposure of 2 hours. An increase in the oxidation temperature leads to the formation of large oxide inclusions, which negatively affect both the mechanical and tribotechnical properties of powder samples.

An increase in the duration of oxidation also adversely affects the antifriction properties.

Table 2

Tribotechnical characteristics of "iron-cast iron-glass" in dry friction

Friction load, MPa	Sample pressing pressure, MPa		
	400	700	1000
2	$\frac{0,194-0,20}{30}$ $\frac{0,155-0,163}{12}$	$\frac{0,194-0,20}{8}$ $\frac{0,163-0,18}{12}$	$\frac{0,155-0,175}{8}$ $\frac{0,175-0,182}{6}$
4	$\frac{0,165-0,17}{110}$ $\frac{0,136-0,145}{250}$	$\frac{0,194-0,21}{102}$ $\frac{0,139-0,145}{86}$	$\frac{0,155-0,19}{62}$ $\frac{0,145-0,155}{76}$
6	$\frac{0,155-0,159}{310}$ $\frac{0,148-0,155}{445}$	$\frac{0,177-0,18}{160}$ $\frac{0,129-0,134}{243}$	$\frac{0,155-0,16}{92}$ $\frac{0,142-0,145}{510}$
8	$\frac{0,143-0,147}{2000}$ $\frac{0,124-0,126}{2000}$	$\frac{0,150-0,155}{380}$ $\frac{0,136-0,14}{1900}$	$\frac{0,131-0,136}{274}$ $\frac{0,130-0,136}{1200}$
10	-	$\frac{0,143-0,146}{800}$	$\frac{0,147-0,25}{242}$
12	-	-	0,153 – 0,155

The lowest f and J are achieved only at an oxidation temperature of 200 °C and an isothermal exposure of 1.0 hours. Intensive overgrowing of the surface of iron and cast iron particles, as well as pores and pore channels with oxides, does not have the best effect on the formation of mechanical and antifriction properties. Nevertheless, it should be noted that the principle of forming “related” phases and inclusions on the surface of heterogeneous particles in order to improve the mechanical and antifriction properties of sintered materials is effective. Judging by the data in Fig. 18, the optimal modes of compact oxidation are: temperature - 200°C and duration - 1.0 hour.

Mathematical models of cold pressing of porous bodies and "iron-cast iron-glass" in an elastic-plastic medium have been developed. For a theoretical assessment of the compaction of the elastic-plastic medium, we used a charge consisting of powders of special gray cast iron, iron grade ПЖ2М3 (ГОСТ9849-86 State Standart of the Russian Federation) and vacuum glass grade С88-5 ОСТ11027. The composition of gray cast iron consisted (in mass. %) carbon 3.6 – 3.8, silicon 1.5 – 2.8, manganese 0.5 – 1.0, phosphorus 0.05 – 0.1, sulfur 0.05 – 0.1. This cast iron is produced according to ТУ16-89 ВАИК411100.006 ТУ. The content of the charge components was distributed as follows, mass %: cast iron powder – 45; vacuum glass – 5 and iron powder – the rest. This state of the components ensured the production of an elastic-plastic medium.

After cold pressing at a pressure of 700 MPa and sintering of the presses at a temperature of 1150 °C in an endothermic gas medium, a porous body with a porosity of 12% was obtained.

Based on the ideas about the root-mean-square stresses and strain rates in a porous body developed in [104][13], in [105][14], a model of the plastic behavior of porous bodies consisting of an elastic-plastic medium is proposed. Unlike existing models, this model allows us to characterize the behavior of plastic deformation of a porous body not only by its current porosity, but also by the measure of plastic deformation accumulated in the base material.

Thus, the theory of plasticity of a porous body proposed in [104][13] takes into account the geometric and physical factors of hardening of

13. Уравнение пластичности пористого тела, учитывающее истинные деформации материала основы. Мартынова И.Ф., Штерн М.Б.
14. Влияние схемы прессования на напряженно-деформированное состояние изделий типа втулок. Штерн М.Б. и др.

this medium. In accordance with the general methodology of continuum mechanics, the components of strain and stress velocity tensors that describe the macro-state of the elastoplastic medium under study must satisfy the basic conservation laws. Therefore, there is an equilibrium equation

$$\frac{d\sigma_z}{dz} + \frac{d\tau_{rz}}{dr} + \frac{\tau_{zz}}{r} = 0 \qquad (2)$$

$$\frac{d\sigma_r}{dr} + \frac{d\tau_{rz}}{dz} + \frac{\sigma_r - \sigma_\varphi}{r} = 0 \qquad (3)$$

and the continuity equation

$$\dot{\varepsilon} = \frac{1}{\rho}\frac{d\rho}{dt} = \frac{\dot{\theta}}{1-\theta}.$$

According to [104][13], strain rates are related by an associated law, which leads to concentricity ratio between stress deviators and strain rates

$$\frac{\dot{\varepsilon}_z - \frac{1}{3}\dot{\varepsilon}}{\sigma_z - \frac{1}{3}\sigma} = \frac{\dot{\varepsilon}_r - \frac{1}{3}\dot{\varepsilon}}{\sigma_z - \frac{1}{3}\sigma} = \frac{\dot{\varepsilon}_\varphi - \frac{1}{3}\dot{\varepsilon}}{\sigma_\varphi - \frac{1}{3}\sigma} = \frac{\dot{\gamma}_{rz}}{\tau_{rz}}, \qquad (4)$$

and also to the equation

$$\dot{\gamma} p \varphi(\theta) = \dot{\varepsilon} \tau \psi(\theta). \qquad (5)$$

Equation (5) characterizes the compression of a porous elastoplastic medium, irreversibly changing its volume. This ratio shows that the material is compacted only when the hydrostatic pressure is not equal to zero, although it can take place at a constant P. If the material is non-porous, then the ratio $\varphi : \psi = 0$.
Therefore, $\dot{\varepsilon} = 0$, that is, the material is not compacted.

It has been determined that with sufficiently large radial compressions of the porous body, the change in volume is negligibly small, that is, as the radial deformations increase, the porosity practically does not change. The results obtained for radial compression allow us to conclude that in the range of porosity $1/3 < \theta < 2/3$, the conditions for material compaction during radial compression are more favorable than with uniaxial compression.

The process of forming a sintered porous body from "iron-cast iron-glass" can be divided into two stages. On the first of them, there is a change in both the shape and volume of the body, and on the second, only a change in shape, that is, the compaction of the body does not occur. At the first stage of formation, the ratio of volumetric and radial deformation is of great importance.

The compaction of glass-to-metal porous bodies under conditions of limited passive deformation has been studied. The results of densification of sintered porous "iron-cast-iron-glass" in the case of radial compression of the porous element (in the presence of rigid walls at the ends and compression in a closed mold) are obtained. The main results link the force parameters required to achieve a given density to its current and initial value. In our opinion, it is advisable to conduct a comparative analysis of the energy consumption of the deformation schemes considered in the work. Apparently, the energy intensity is one of the main criteria that allows you to choose the optimal scheme for obtaining a material with a given porosity.

Let us derive a general formula for the dependence of the work expended on the deformation path. In the general case, work A is calculated by the formula:

$$A = \int_0^t \frac{1}{\rho} \cdot \sigma_{ij} dt \qquad (6)$$

The postulate of the uniqueness of the dissipative function [171][15],

15. Influence of the pressing scheme on the stress-strain state of products such as bushings. Stern M.B. and etc.

as well as the relationship between density and porosity, allows us to bring this expression to the form:

$$A = \frac{1}{\rho_k} \int_0^t \sigma_{ij_0} \dot{\varepsilon}_{ij_0} dt\,, \qquad (7)$$

It is assumed that the specified material is ideally rigid-plastic, incompressible and has the properties described in the framework of the Saint-Venech-Mises model. Therefore, the following ratio is correct:

$$\frac{\dot{\gamma}_0}{\tau_0}\left(\sigma_{ij_0} - P_0 \sigma_{ij}\right) = \dot{\varepsilon}_{ij_0}\,, \qquad (8)$$

with the help of which we transform the expression for A into

$$A = \frac{1}{\rho_k} \int_0^t \tau_0(\gamma_0) \cdot \dot{\gamma}_0 dt \quad (9)$$

или $$A = \frac{1}{\rho_k} \int_P^{\gamma_0} \tau_0(\gamma_0) \cdot d\gamma_0 \qquad (10)$$

Thus, it can be concluded that the most energetically advantageous is radial compression with rigid walls. Less advantageous is one-sided pressing and even less advantageous is radial compression with unlimited longitudinal deformation.

The greatest energy costs are required to compact the material by free upsetting.

Radial compression of porous iron-cast-iron-glass bushings hardened in a rigid mandrel, which is an energetically more favorable process, has been carried out.

It has been established that with radial compression of porous bushings in a rigid mandrel, the density of the compacted body is uniformly distributed along the radius. The result obtained in this case can be considered as an initial approximation to the true solution of the problem, which is found by iteration.

An experimental evaluation of the plastic deformation of porous workpieces made of "iron-cast iron-glass" has been carried out. At the same time, to assess the plastic deformation of a porous body, the methods of microstructural analysis (Fig. 12.) and hardness tests were used.

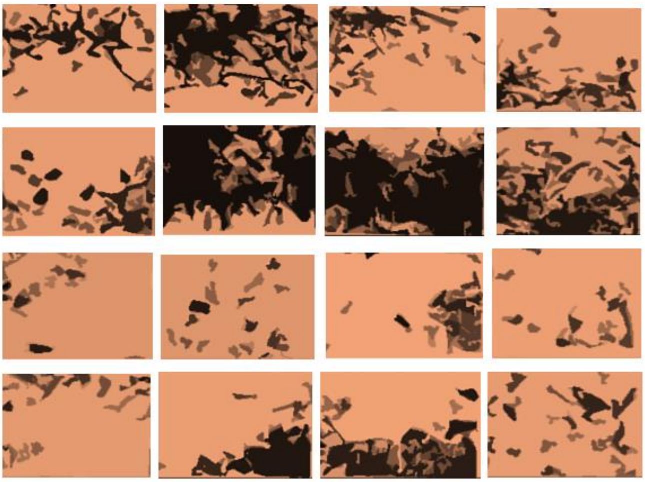


Figure 12. Microstructure of a quarter of the axial section of the sample after an unsteady pressing process through a conical matrix, x400

Microstructural analysis gives an idea of the distribution of material porosity, grain deformation and their relationship, and hardness tests are used to determine the mechanical properties and components of the stress-strain state of materials.

Hardness tests and microstructural analysis of sintered cylindrical blanks deformed during free upsetting and pressing in conical dies showed the validity of theoretical calculations performed by the finite element method.

The third chapter discusses the theoretical provisions for compaction of porous workpieces made of "iron-cast iron-glass". A mathematical model of the processes of pressure treatment of powder mixtures and porous workpieces from "iron-cast iron-glass" is constructed. It has been established that in the case of plastic flow, along with general tensor relations, there is a scalar relation connecting the components of the stress tensor.

The scalar properties of a compacted porous body is characterized by equations expressing the dependences of the hydrostatic pressure *p* and the shear stress intensity τ on the porosity and parameters characterizing the state of the powder material and the porous body. The functions p and τ must satisfy the equation:

$$\frac{dp}{dS}S+\frac{d\tau}{dS}=0, \qquad (11)$$

in this case, *p* is a monotonically increasing, bounded function $S=\ell/\gamma$ and τ increases at S≤ 0, reaches a maximum at S = 0, and decreases at S≥ 0: at $|S|\to\infty;\ \ \tau\to 0$

During plastic deformation of compacted materials, hydrostatic pressure can affect shear deformations, and tangential stresses can lead to a change in volume.

Along with this, there is a form of defining equations expressed by the equation of the loading surface

$$f(p,\tau,\theta,\chi_k)\cong\tau-\tau(p,\ \theta,\ \chi_k)=0 \qquad (12)$$

and the ratio

$$\frac{dF}{dP}\cdot\gamma=\frac{df}{d\tau}\cdot\ell \qquad (13)$$

In the case of a strictly convex loading surface, these two forms are equivalent.

The solution of the problem of the unsteady process of pressing a porous cylindrical billet through a conical matrix of the finite element method, as well as pressing a porous and bimetallic billet of variable cross-section through a conical matrix of the finite element method is proposed. According to the porosity distributions, zones of large and small deformations are determined. As the studied material, blanks were used-sintered "iron-cast iron-glass" (charge content – iron powder ПЖ2М3-47%, gray cast iron powder – 47%, vacuum glass powder – 6% by weight).

The stress-strain state during bilateral compaction of porous workpieces in rigid cylindrical matrices by the finite element method is considered. The cases of compaction of bimetallic billets are also considered. The double-sided sealing of porous bimetallic cylindrical blanks in closed cylindrical matrices shows that the "plastic" elements of the bimetal are deformed (and consequently compaction) to a relatively large degree

Moreover, a solid layer of metal is embedded inside the "plastic", which is confirmed by experiments [223][16].

The force and kinematic parameters during plastic deformation of sintered porous blanks made of "iron-cast iron-glass" were evaluated. It is determined that, despite the finite values of compaction pressures (equal to the yield strength of the base material) corresponding to zero porosity values, it is impossible to achieve a non-porous state of the material during precipitation. This should be explained by the fact that, theoretically, an infinitely large effort is required to achieve zero porosity.

In the fourth chapter, mathematical modeling of the sintering process of metal-glass materials based on iron was realized. To improve the interfacial interaction and intensification of diffusion phenomena, and, consequently, to increase the mechanical properties and wear resistance of iron-glass materials, they must be alloyed with components that are more wetted by glass. Such an effect can be caused, for example, using the cast iron powder in the composition of the charge, since cast iron contains a relatively large amount of silicon and manganese, which have the property of forming difficult-to-recover oxides when heated.

---

16. Analyisis of the Influence of the Shape of the Matrix on the Compaction of Porous Powder Bodies of “Iron-Cast Iron-Glass”11th World Conference “Intelligent System for Industrial Automation” (WCIS-2020), Jabbarov T.G.

It should be expected that these oxides will be well wetted by the glass during the sintering process and thereby contribute to its strong connection with the metal base [218][17].

During the period of the rapid rise of temperature used before the start of isothermal exposure, in the time of the sintering of active powders, a significant compaction is usually achieved at speeds much higher than the speed after the transition to isothermal (liquid phase) sintering.

For the mathematical description of shrinkage, the choice of a dependent variable becomes crucial. As such a dependent variable, it is recommended to use the relative pore volume υ_c / υ_n, where υ_n and υ_c are the pore volumes of the sample before and after sintering. When sintering bodies with different densities to close values of the porosity ratio of bodies Π_c/Π_n after and before sintering (Π is porosity, defined as a fraction of the volume of a porous body) with a significant change in the density of a porous body before sintering,

d_n [g/cm^3], the ratio Π_c/Π_n cannot be constant during sintering, which follows from the dependencies

$$\upsilon_c/\upsilon_n = [d_n(d_k - d_c)]/[d_c(d_k - d_n)] \qquad (14)$$

$$\Pi_c/\Pi_n = (d_k - d_c)/(d_k - d_n), \qquad (15)$$

where d_c is the density of a porous body after sintering;

d_k is the density of a compact substance (without pores).

$$\Pi_c = 1 - \frac{1-\Pi_0}{1-\left(\frac{\Delta V}{V_0}\right)^2}, \qquad (16)$$

The theoretical relationship between the volumetric shrinkage $\Delta V/V_0$ and the maximum value of interparticle contacts achieved during sintering for powders with spherical particle shape is obtained based on the analysis of the geometry of the contact zone.

17. Modelling of the Sintering Process of Iron Based Metal-Glass Materials.- Proqress in physics of metals.Jabbarov T.G., O. A. Dyshin, M. B. Babanli,I. I. Abbasov

During sintering according to the mechanism of volumetric or surface self-diffusion, the approach of particles does not accompany the formation of a contact; there is no bulk shrinkage in this case. If the baking is carried out due to the viscous flow or diffusion of vacancies in the contact of the boundary capable of absorbing vacancies indefinitely, then in this case the following relationship is obtained between the relative convergence of particles, i.e. linear shrinkage$\Delta l/l_0$, and volumetric shrinkage$\Delta l/l_0$.

$$\Delta V/V_0 = 3\,\Delta l/l_0 \qquad (18)$$

In idealized models of sintering kinetics, it is usually assumed that any one mass transfer mechanism works during sintering and that mass transfer is carried out at the point of contact between two identical spheres. However, it must be taken into account that when sintering real samples, particles can have different shapes and sizes and each particle comes into contact with several particles at once, and in practice the contact is not ideal (point) and at the points of contact, particles usually flatten during compaction. However, most importantly, mass transfer in real samples is controlled not by any one process, but by several.

The initial stage of sintering is characterized by the formation and growth of the neck between the particles, accompanied by shrinkage of the sample, except in cases when mass transfer occurs only due to evaporation/condensation or volumetric and surface diffusion. Shrinkage in the initial stage of sintering reaches only a few percent and occurs until the pores in the sample are almost completely interconnected and permeate the entire volume.

With a topologically continuously transforming structure of the powder material during sintering, a quantitative analysis of the kinetics of changes in the characteristic linear parameter of the porous microstructure L ($L$is the average grain size of the sample) can be carried out using the general theory of diffusion coalescence of dispersed systems. If the main mechanism of the mass transfer is surface diffusion, then the kinetic equation for L takes the form:

$$L^4 = L_0^4 + \frac{B_1 \gamma D_s \cdot \delta^4}{kT} \cdot t\,, \qquad (19)$$

where D_s is the surface diffusion coefficient; $\Delta L = L - L_0$ is the thickness of the layer in which surface diffusion is carried out, of the order of atomic diameter δ; γ is the surface tension; k is the Boltzmann constant; T is the absolute temperature; t is time; B_1 is a numerical constant approximately equal to 30; L_0 is the initial value parameter L before sintering.

Equation (19) satisfies many experimental data for oxide and metal powders. For metallic island films, coalescence occurs mainly by the mechanism of surface diffusion of adatoms (adsorbing atoms).

Differentiating (19) by *t*, we obtain the differential equation of the kinetics of the change of *L*:

$$\frac{dL}{dt} = \frac{B_1 \gamma D_s \cdot \delta^4}{4L^3 kT} \qquad (20)$$

Thus, for a mathematical description of the sintering process of a powder mixture, a system of nonlinear differential equations of the kinetics of compaction and grain growth at successive temperature regimes is constructed. By "storing" solutions of these equations at the junctions of temperature regimes and integrating the resulting system of equations using the fourth-order Runge-Kutta method, a numerical time discretization of continuous porosity and grain curves is constructed.

The investigated mixture of iron powders, gray cast iron and sitallized glass (sitall) is considered as a system of two components *A* and *B*. Component *A* is a compound of iron with sitall Fe_2SiO_4 (called fayalite), and component *B* is a compound of iron with carbon *FeC*(cast iron). The heterodiffusion coefficient of this binary system is calculated using the Darken formula. The heterodiffusion coefficient $\tilde{D}$ of a binary system of components *A* and *B*, according to

Darken, is expressed in terms of partial diffusion coefficients D_A and D_B using the ratio

$$\tilde{D} = c_B \cdot D_A + c_A \cdot D_B, \qquad (21)$$

where c_A and c_B are the concentrations of components *A* and *B* (in our case, $c_A = c_B$=0.5).

In the rheological description of the kinetics of sintering under pressure (comprehensive compression), the diffusion-viscous flow mechanism is used and the Mackenzie-Shuttleworth model is adopted. In accordance with this mechanism, thermal slippage occurs along the grain boundaries and a decrease in the pore volume due to the ejection of void vacancies to the surface.

When a liquid phase is formed, along with a change in capillary forces in the contact of particles, with the appearance of a melt wetting the particles, the surface area of the interaction of the components increases significantly, leading to an acceleration of the sintering process. At the same time, in the process of sintering the powder body, in general, a decrease in porosity and an increase in granularity are detected, and then shrinkage and stabilization of both porosity and granularity occur (Fig.13 and Fig.14).

The fifth chapter presents the experimental studies of the structure and properties of "iron-cast iron-glass" powder compositions. The interaction of solid lubricants (graphite, copper inclusions) and inclusions (cast iron, glass) in powder composite materials is shown. In the "iron-cast iron-glass" powders of cast iron and glass in the charge were introduced without additional processing. This was aimed at revealing the possibility of sintering of cast iron with iron powder, since sintering of compacts was carried out at a temperature of 1100 – 1150 ° C. Glass powder was injected into the iron-iron charge in an amount of 6 wt.%. The wear resistance of such a material was slightly less than that of iron-graphite ЖГр3 (Fig. 15, curves 1 and 3), which is apparently due to the lower strength of the iron-iron matrix after sintering. At the same time, there were no noticeable advantages compared to a similar material containing graphite (Fig.15, curves 2 and 4). Solid lubricants, complementing each other, reduced the wear rate of the metal–glass material by 6-8 times during friction without lubrication (Fig. 15, curve 4).

Thus, doubling the amount of solid lubricant of various nature in the material led to an increase in wear resistance by more than 6 times.

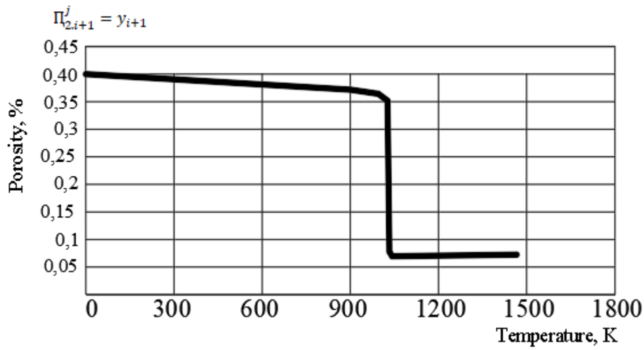


Figure 13. Dependence of porosity on temperature

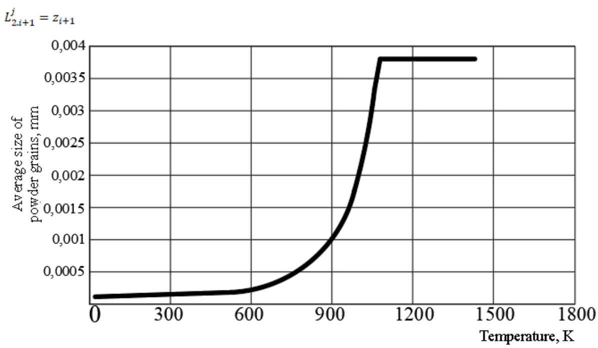


Figure 14. Dependence of the average size of powder grains on temperature

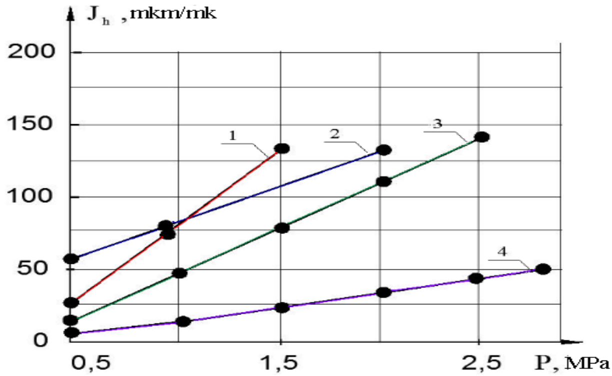


Figure 15. The dependence of the wear intensity on the specific load of metal–glass material of various composition (in mass fractions): 1 – 30% cast iron, 6% glass and 64% iron; 2 – 2% molybdenum disulfide, 6% glass, 30% cast iron and 62% iron; 3 - 3% graphite and 97% iron;4. 3% graphite, 2% graphite disulfide, 6% glass, 30% cast iron and 59% iron Vsk = 0.84 m/s, friction without lubrication.

When creating powder composite materials, the usage of multifunctional additives, metallized (slow) iron and glass powders was proposed. This allows us to combine 2-3 elements in one powder that affect different properties. Metallization consists in the chemical reduction of the calculated amount of metal (copper, nickel, tin, etc.) into particles of cast iron and non-metallic powders (graphite, sulfides, oxides, nitrides of carbides [160][18].

The effect like the synergism of two solid lubricants was obtained after using metallized powders as additives to the matrix of powder antifriction materials. The insertion of a solid inclusion in the form of copper powders of cast iron and glass made it possible to reduce the wear rate of "iron-cast iron-glass"by more than three times compared

18. Прессование структурно неоднородных систем с различным агрегатным состоянием фаз в технологических процессах утилизации тонкодисперсных порошковых отходов черной металлургии. Цеменко, В. Н. // ВестникУлГТУ. -Ульяновск: УлГТУ, - 2004. №2, -с. 39-41.

with materials of a similar composition from a mechanical powder mixture (Fig. 16).

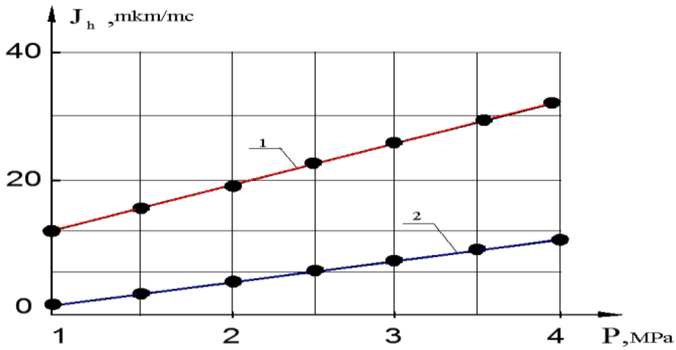


Figure 16. Dependence of the wear intensity on the friction load of powder materials: 1 – bronze with 6% glass and 30% cast iron (both powders are not metallized); 2 – bronze with 6% glass and 30% cast iron (both powders are copper-plated); Vsk = 1 m/s, friction without lubrication of oil-soaked samples.

The strengthening of the lubricating effect in this case can be explained by a stronger fixation of metallized particles in the matrix, preventing their staining and removal from the friction zone.

Different by nature solid inclusions with the same amount of them in the matrix material, inadequately affect the wear intensity of the composite material (Fig.17).

As the research results have shown, it is not advisable to introduce solid inclusions in an amount of more than 10% due to a noticeable decrease in the antifriction properties of the composite material. To dramatically increase the wear resistance and load capacity, it was possible to introduce a bronzographite matrix of equal amounts (by 6 wt.%) copper powders of low-temperature glass and refractory oxides. The intensity of wear during friction without lubrication of such a material decreased by 7 – 10 times, the coefficient of friction by 1.5 times, and the load capacity increased to 12 MPa (Fig.17, curve 3).

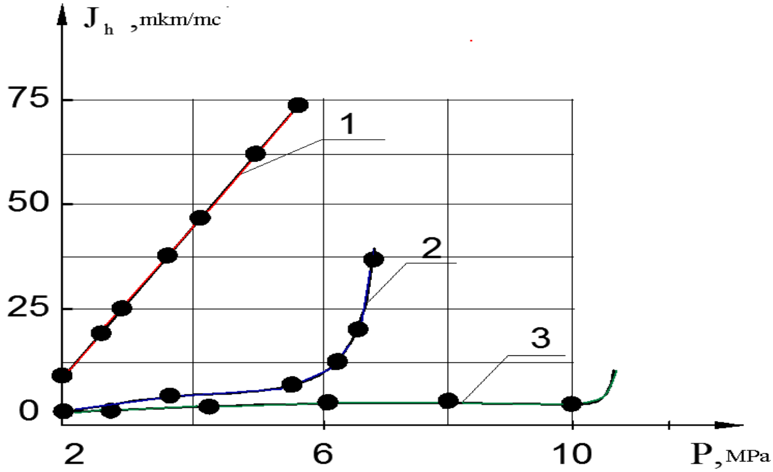


Figure 17. The dependence of the wear intensity on the friction load of powder bronzes containing copper powders: 1 – 8% of low–temperature glass; 2 – 8% of refractory oxide; 3 - 5% of glass and oxide. Vsk = 1 m/s, friction without lubrication of oil-soaked samples

It has been determined that the simultaneous introduction of solid lubricants and solid inclusions and chemical metallization of the initial powders of these additives make it possible to regulate the course of structure formation and the formation of tribo-technical characteristics of composite materials made of "iron-cast iron-glass".

Chemical copper plating of cast iron and glass powders gives a serious positive effect in the direction of increasing the antifriction properties of powder compositions made of "iron-cast iron-glass". However, the presence of porosity in the structure of these compositions after sintering of the order of 10÷15%, (Fig. 18.) does not allow to raise their load capacity to the level of 20 MPa, i.e. sintered compositions of iron-cast iron-glass are operable at a friction load of up to 5÷6 MPa.

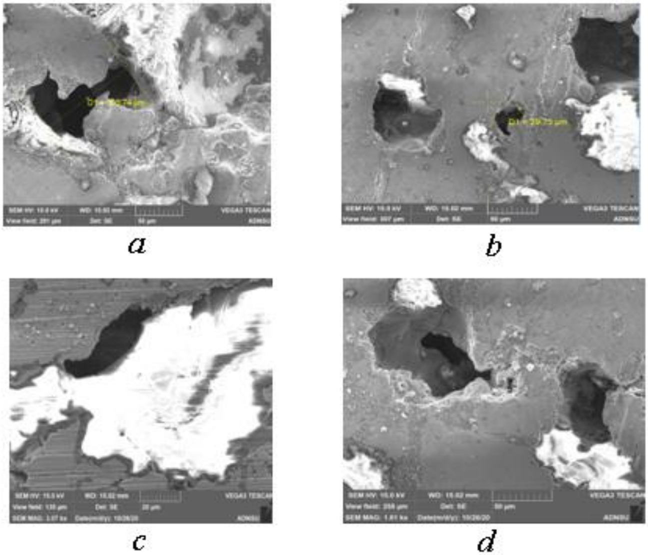
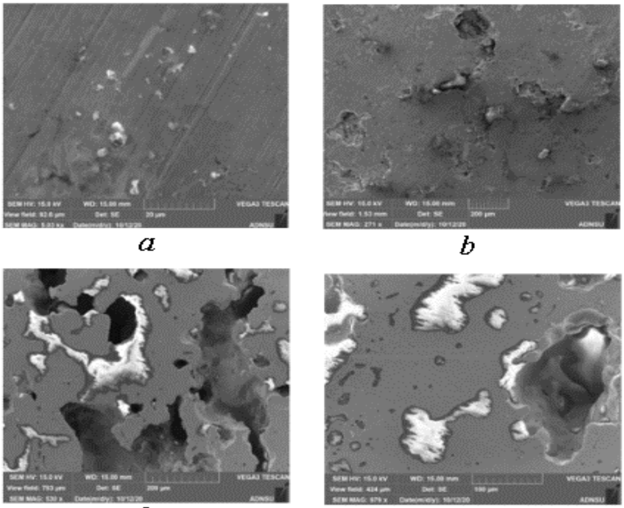


Figure 18. SEM-images of the pore distribution in the main (a, c) and central (b, d) zones of the "iron-cast iron-glass" KM

Further improvement of the operability of these compositions requires additional operations that provide a significant reduction in their porosity. The presence in the structure of the plastic matrix as a ferritic and perlite phase, solid inclusions in the form of copper cast iron, not dissolved in the matrix and copper inclusions in the form of glass at high density, in our opinion, will ensure high performance of this composition under dry friction conditions (Fig.19).

It is defined that to increase the load capacity of sintered compositions made of "iron-cast iron-glass" when working in dry friction conditions, it is necessary to double-seal them.

The use of extrusion of porous blanks from "iron-cast-iron-glass" allowed reducing their porosity by 10%, that is, with the initial porosity of the blanks of 15%, their final porosity was 4-5%. This leads to the hardening of the matrix of the material and the uniform distribution of solid particles of copper-plated cast iron and glass in the matrix. In this scenario, the structural components of the material also significantly improve its tribo-technical characteristics.



a b c d

Figure 19. SEM-images of the distribution in the matrix structure of solid inclusions of copper cast iron (a, b) and copper inclusions of glass (c, d) in the KM "iron-cast iron-glass"

Since this not only strengthens the matrix, but also fixes solid inclusions of cast iron and glass in it. In addition, the compaction of the material also improves the uniformity of the distribution of graphite inclusions and free copper inclusions, which can play a serious role in friction as solid lubricants. Thus, the presence of free copper inclusions in the structure during friction plays the role of a plastic component, plastically “flows” in the direction of movement of the contacting surfaces, while facilitating sliding. Free inclusions of graphite, as a solid lubricant, prevent macro-setting of the contacting surfaces, reduce the coefficient of friction.

According to the graphs (Fig.24) the increasing in the friction load from 3 MPa to 4 MPa, the friction coefficient of the material under dry sliding conditions practically changes little. Although it should be noted that a load of the order of 4 MPa is an essential value for dry friction. Further, with an increase in the friction load to 10 MPa, the coefficient of friction of the composition gradually increases. At the same time, its sharp drop, indicating catastrophic wear of the material, is not observed. Such a low level of the coefficient of friction of the material in the range of 2-10 MPa under dry friction conditions is associated with a positive interaction of solid and plastic inclusions (cast iron, glass and free copper inclusions), solid lubricant (graphite inclusions) and a strong matrix.

Chemical metallization (copper plating) of the initial powders of cast iron and glass, as well as additional compaction of sintered "iron-cast iron-glass" under extrusion conditions allowed increasing the density and, consequently, the antifriction properties of the material. Therefore, for example, the "iron-cast iron-glass" that underwent such treatment showed high wear resistance at a friction load of 6 – 8 MPa in dry friction conditions at a sliding speed of 1 m/s. Thus, the developed material of the "iron-cast iron-glass" type can be recommended for operation in friction units under extreme operating conditions. Such friction units are available on various oil and gas production equipment, for example, on rocking machines on submersible pumps, hydraulic turbines, diesel engines, etc.

In compact multiphase compositions, the strength concentration dependence often has a non-monotonic complex character, which is caused by the individual properties of the forming phases and their morphology. In this regard, the patterns of destruction and strength of elastic-plastic materials, such as "iron-cast iron-glass", are important. Stereological analysis of the fractures showed that the crack trajectory passes mainly along the intercrystalline boundaries of cast iron-glass and sections of the binding phase (iron), (Fig.20.)

Sintered materials are manufactured, bypassing the melting stage. Therefore, the content of impurities in them is often higher than in cast ones (which affects the structurally sensitive characteristics, for example, the temperature of transition of refractory metals from a brittle state to a plastic one). The increased content of impurities also determines the peculiarities of the composition of the border zones.

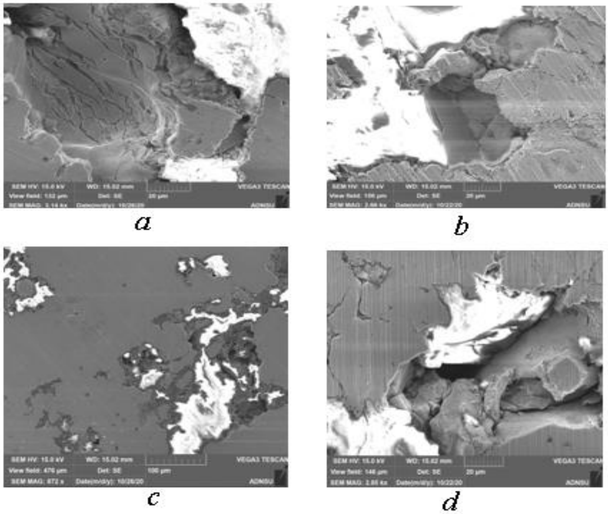


Figure 20. SEM- images of the crack trajectory along the intercrystalline boundaries of cast iron-glass (a, b) and sections of the binding phase (iron) (c, d)

The segregation of silicon, oxygen, copper, and manganese was revealed by the method of micro-X-ray spectral analysis of border zones in sintered "iron-cast iron-glass"[221][19] (Fig.21).

The presence of such relatively low-melting segregations causes high recrystallization rates and high-temperature creep for non-stoichiometric phases of introduction. The role of micrograin boundaries is also great in superplastic deformation, which is characteristic of many fine-grained or hot-pressed materials.

The cases considered by author, illustrating the relationship of the properties of sintered compositions of "iron-cast iron-glass" with porosity and grain size, does not exhaust the whole variety of aspects of this problem.

---

19. Saturation of glass particles with meal during sintering of a composite material of the iron-glass system JabbarovT.G., AslanovJ.N, ShahmarovaR.S.

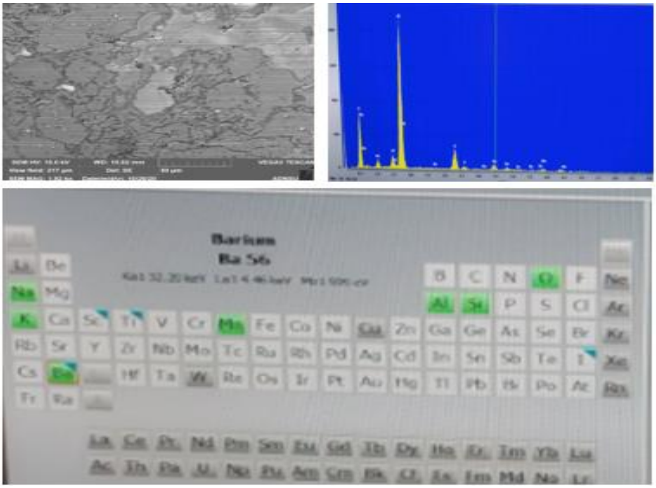


Figure 21. SEM images of the distribution of Si, Mn, Cu and O2 on the border zones in the sintered composite "iron-cast iron-glass".

It is also possible to note the role of boundaries and pores as stoppers on the path of crack propagation, their effect on fracture viscosity, patterns of formation of properties during sintering of powders dissolving in each other. Quantitative description of the properties of sintered bodies is very difficult and requires further development of theoretical concepts and accumulation of experimental data.

The significance of such works is quite obvious, especially in connection with the use of automatic process control systems in powder metallurgy.

In the sixth chapter, copper plating of cast iron and glass powders is proposed before entering them into an iron-based charge. It is shown that when using these powders in the charge in copper form, a high effect is achieved on the compressibility of the charge based on iron and the sintering capacity of the workpieces.

As a result, this leads to a significant increase in the mechanical properties of "iron-cast iron-glass" compositions (Fig.22).

The reason for obtaining significantly higher mechanical properties of these compositions is the plastic flow and sliding of copper powders during cold pressing of the charge and the participation of liquid phases of copper and glass during sintering.

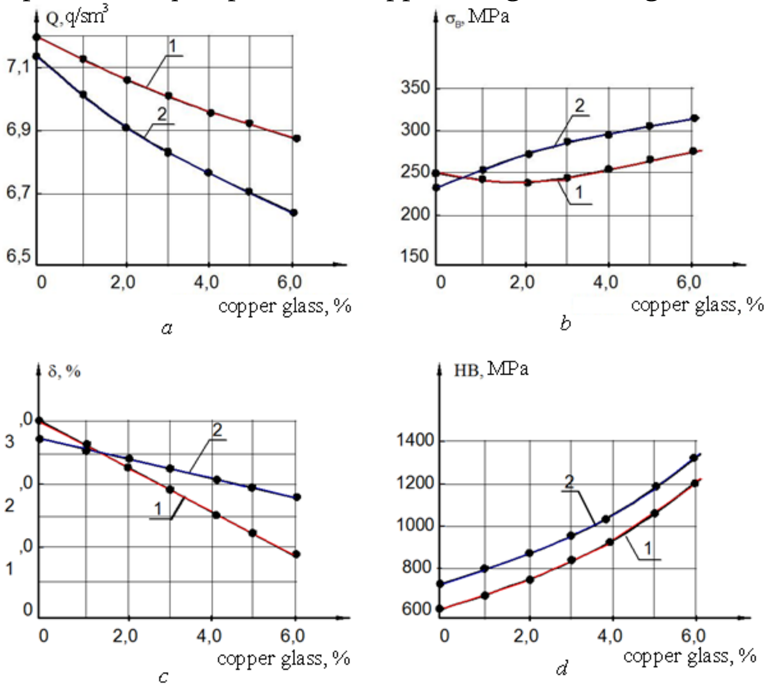


Figure 22. Dependence of density (a), tensile strength (b) elongation (c) and hardness (d) of sintered iron-cast iron-glass compositions: 1 – pulverized iron powder; 2 – reduced iron powder. The amount of copper powder cast iron in all cases was – 30 wt.%

The use of reduced iron powder and copper powders of cast iron and glass makes it possible to increase the strength characteristics of sintered "iron-cast iron-glass" compositions obtained based on reduced iron powder and copper powders of cast iron and glass. Other advantage is in possibility to reach a strength limit of almost 330 MPa, which is 120 MPa higher than the strength of the same compositions made under analogous conditions but based on cast iron and glass powders without copper plating. This difference, due to the use of copper powders of cast iron and glass, persists even after heat treatment (quenching + tempering) (Fig.23).

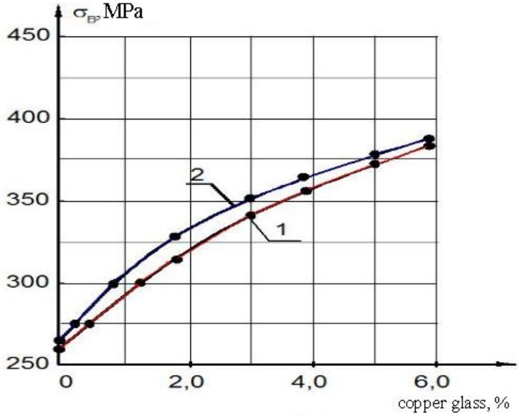


Figure 23. Dependence of the strength of iron-cast iron glass compositions after quenching and low–temperature tempering: 1,2 – quenching, 900 ° C, water; 1 – sprayed powder; 2 - reduced powder.

The amount of copper powder cast iron in all cases was 30 wt.%

In "iron-cast iron-glass" compositions obtained from iron powders and copper powders of cast iron and glass, chemical and structural uniformity is achieved at lower temperatures than in "iron-cast iron-glass", in which cast iron and glass powders were introduced without copper plating and which makes it possible to reduce the runoff temperatures of these compositions (Fig.23).

We used fuzzy clustering of experimental data to obtain fuzzy "IF-THEN" rules [219][20] describing the relationship between material properties and technological parameters (a task similar to constructing fuzzy rules describing the relationship between material properties and its composition, discussed on page 15-17).

20. Synthesis of Optimal Technological Parameters of "iron-cast-glass" Grinding Composite Materials Using Fuzzy Logic and Big Data Concepts.JabbarovT.G., Gurbanov.N.A

As an example, the composite material "iron-cast iron-glass" was considered. This fuzzy model can be used for the analysis and synthesis of materials [174][21].

The input variables of the model are technological parameters. The output variables are the mechanical properties of the composite material "iron-cast iron-glass". The fuzzy partitioning (standard) used in the construction of the rules is shown in Figure 1. A graphical representation of the rules is given in Figure 24.

The obtained rules can be used to determine the technological parameters according to the specified characteristics of the material.

For example, suppose it is necessary to obtain a material with the following characteristics:

$$z_1=382;\ z_2=358;\ z_3=80;\ z_4=38,$$

where z_1 is the tensile strength (σ_b, MPa); z_2- bending strength (σu, MPa); z_3-hardness (HB, MPa); z_4-impact strength (CS, kJ/m^2). Calculation based on the obtained rules using the Mamdani fuzzy inference algorithm (this algorithm is described on pages 15-19) showed that these characteristics are achieved with the following technological parameters:

$$y_1=800;\ y_2=1170;\ y_3=8.9,$$

where y_1 is the pressing pressure (P, MPa); y_2 is the sintering temperature (t^0C); y_3 is the sintering duration (τ-1×10^{3}sec) of the composite material "iron-cast iron-glass".

As an example, the composite material "iron-cast iron-glass" was considered. This fuzzy model can be used for the analysis and synthesis of materials describing the relationship between the properties of the material and technological parameters (Fig.24).

The addition of cast iron and glass powder in copper form improvesthe plasticity of the powder charge, activates the processes

21.Fuzzy Logic-Based Material Selection and Synthesis.Babanli,M.B.

where y_1 is the pressing pressure (P, MPa); y_2 is the sintering temperature (t^0C); y_3 is the sintering duration (τ-1×10^3sec) of the composite material "iron-cast iron-glass".

As an example, the composite material "iron-cast iron-glass" was considered. This fuzzy model can be used for the analysis and synthesis of materials describing the relationship between the properties of the material and technological parameters (Fig.24).

The addition of cast iron and glass powder in copper form improves the plasticity of the powder charge, activates the processes of pressing and sintering compositions, and causes an increase in the viscosity of such compositions while reducing the effect on these properties of pressing pressure.

The use of reconstituted iron powders together with copper powders of cast iron and glass for the manufacture of "iron-cast iron-glass" compositions by conventional pressing and sintering is a new way to increase their strength without additional alloying or the use of other production operations.

It is determined that the best strength and structural characteristics are achieved when using reduced iron powders than sprayed ones. This is due to the higher degree of sponginess of the reduced iron powder particle.

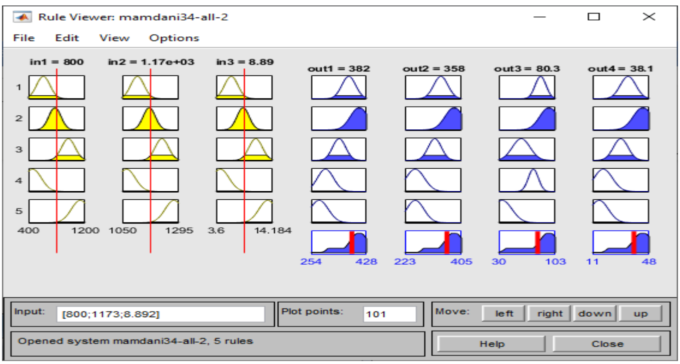
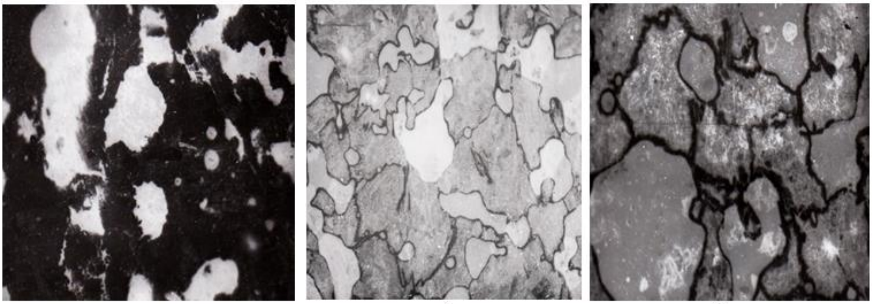


Figure 24. Graphical description of fuzzy rules

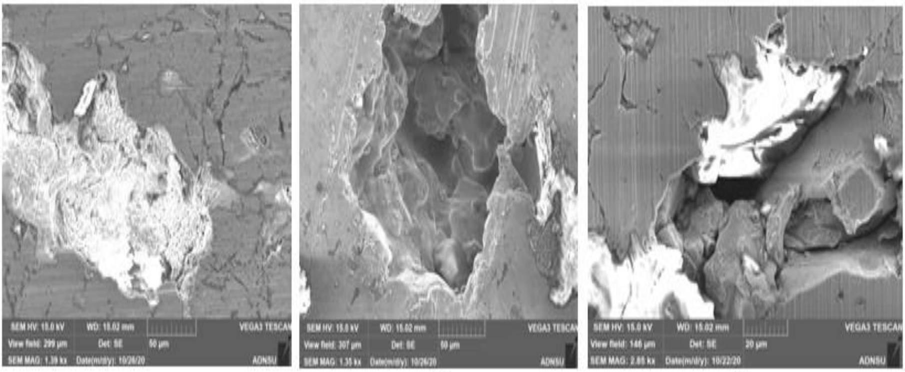
In this case, the diffusion of alloying elements occurs mainly along the boundaries of particles and planes with the greatest destruction of the lattice, and in the case of a study of a sprayed powder, the composition is alloyed mainly by volumetric diffusion.

The features of sintering of "iron-cast iron-glass" pressings containing copper powders of cast iron and glass are investigated. An attempt has been made to study the kinetics of the initial stage (under the influence of capillary stresses only) of sintering by dilatometric measurements. It is defined that in the initial stage there is an “active” shrinkage, that is, it corresponds to intensive sintering, and with subsequent heating, the shrinkage rate decreases significantly. Along with dilatometric measurements, metallographic studies of the structure of annealed samples were also carried out using optical and electron microscopy (Fig.25, Fig.26, Fig.27). An important feature of the process under discussion also consists in the fact that the experimentally fixed shrinkage significantly depends on the size of the powders. So, the pressing of copper cast iron powders with a particle size of 50 microns during heating to 500 °C at a rate of 0.3 deg/s reduces its porosity by 8% (from 35 to 27%, Fig.25.), while pressing with the same initial porosity, but at r = 160 mkm under similar conditions, shrinkage is not detected at all (Fig. 26). The sintering intensity is significantly influenced by the size of the powders, the smaller they are, the faster sintering goes. Thus, a new technology to produce the multicomponent powder compositions using plastic and elastic components in the charge has been developed. At the same time, technological solutions for compaction and hardening of such systems are given by applying effective methods of molding and alloying the developed compositions.



a b c

Figure 25. Microstructure of the composite material "iron-cast iron-glass" (20% by weight. honey cast iron, 4% by weight. copper glass and other iron),×500: a -P=400 MPa, $t_{sintering}$= 1150 ^oC, $\tau_{sint.}$= 1h.; b -R=700 MPa,t_{sint}.= 1150 ^oC, τ_{sint}.=1h.; c-1000 MPa, $t_{sint.}$= 1150 ^oC, τ_{sint}.=1h.



a b c

Figure 26. SEM images of the composite material "iron-cast iron-glass", (20%. wt. copper cast iron, 4%.wt. copper glass and the rest of the iron):

a–P=400 MPa, $t_{sint.}$=1150 ^oC, $\tau_{sint.}$= 1h.;

b–R=700MPa $t_{sint.}$=1150 ^oC,$\tau_{sint.}$=1h.;

c –P=1000 MPa,$t_{sint.}$=1150^oC, $\tau_{sint.}$= 1h.

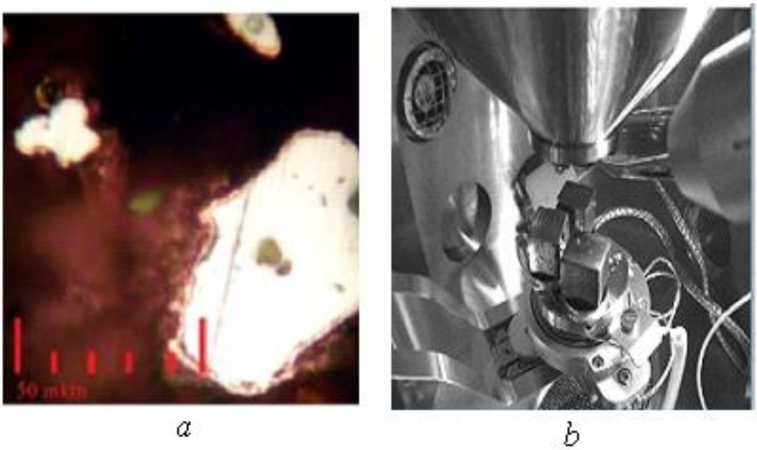


Figure 27.SEM of the image of the microplate (a) of the composite material "iron-cast iron-glass":

(20%. wt. copper cast iron, 4%.wt. copper glass and the rest of the iron, P =1000 MPa, $t_{sint.}$= 1150 ^{o}C,$\tau_{sint.}$=1h.) and the location of the micro-grinders on the SEM desktop (b)

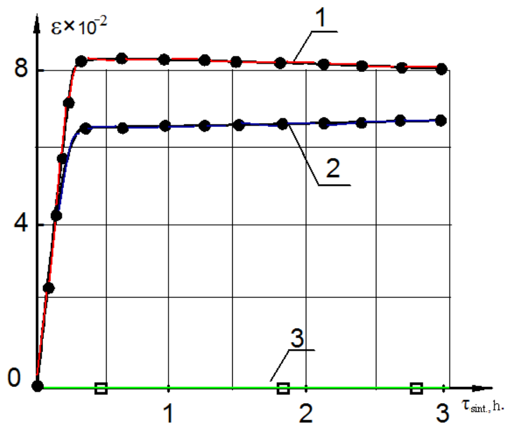


Figure 28. The dependence of the relative shrinkage of iron-glass presses on the initial dimensions of the copper cast iron powder:

r = 50 mkm (1), 100 mkm (2) and 160 mkm (3)

Promising areas of application of research results in various fields of industry of the Republic of Azerbaijan have been identified. It is shown that the developed materials of the "iron-cast iron-glass" type can be used in friction units of the country's oilfield equipment.

However, to expand the scope of application of such powder products, it is considered more promising to manufacture them from simple structures, and then to obtain a complex shape, these structures can be connected by soldering, adhesive and welding. The most reliable method of joining powder structures is welding. Details of oilfield equipment, as a rule, have a complex configuration. When converting them to the powder version, it is necessary to apply the technology of dismemberment during pressing, and then joining simple sintered parts by various welding methods, for example, furnace welding.

GENERAL CONCLUSIONS

1. Mathematical models of the shape of change of porous materials consisting of an elastic-plastic medium have been developed. It is shown that with excessively large radial compressions of the pressing, its porosity practically almost does not change. Therefore, the process of compaction of a sintered porous body made of "iron-cast iron-glass" is proposed to divide into two stages: the stage of shape and volume change and the stage of some shape change. At the first stage of formation, the ratio of volumetric and radial deformations is essential.
2. Linguistic models of the relationship between the composition of the "iron-cast iron-glass" material and its properties are constructed in the form of fuzzy "IF-THEN" rules obtained by applying the method of fuzzy clustering of C-means to experimental data. Based on the model, a material with the specified characteristics is synthesized (the composition of the material at which the specified characteristics can be achieved is determined). Similarly, fuzzy "IF-THEN" rules describing the relationship between technological parameters and mechanical properties of the material are developed.

Based on the model, the values of technological parameters at which the specified characteristics can be achieved are determined.
3. The assessment of the compressibility of porous "iron-cast-iron-glass" in conditions of limited passive deformation with the use of a tool with rigid walls is given, which is the most energetically advantageous process. With free precipitation of sintered porous material, the greatest energy costs are required. It is determined that only in the case of radial compression of a porous sleeve made of "iron-cast-iron-glass" in a rigid mandrel; its density is evenly distributed along the radius.
4. Methods of microstructural analysis and hardness testing were used for experimental evaluation of porous bodies made of "iron-cast iron-glass". By the finite element method using microstructural analysis, an idea of the porosity distribution of the material, grain deformation and their relationship is obtained. Hardness values are used to determine the mechanical properties and components of the stress-strain state of materials.
5. A unified mathematical model of the processes of compaction of powder charges and porous blanks made of "iron-cast iron-glass" has been developed. It is shown that in plastic flow, along with the general tensor relations, there is a scalar relation connecting the components of the stress tensor. Scalar properties of a compacted porous body are described by equations expressing the dependences of hydrostatic pressure and the intensity of tangential stresses on the porosity and initial states of powders and porous body. At the same time, hydrostatic pressure has an effect on shear deformations, and tangential conjugations have changes in the volume of the body.
6. By the finite element method, the problem of an unsteady pressing process of a cylindrical porous workpiece through a conical matrix is solved. In addition, the stress-strain state during the double-sided compaction of porous blanks made of "iron-cast-iron-glass" in rigid cylindrical matrices using the finite element method has been studied. An assessment of the nature of the components of the composition and kinematic parameters during plastic deformation of "iron-cast-iron-glass" porous blanks showed that, despite the finite values of the compaction pressures of the material equal to the yield

strength of the material, it is possible to obtain a non-porous material during precipitation.

7. The mathematical modeling of the sintering process of multicomponent systems of the "iron-cast iron-glass" type has been verified. An attempt is made to describe the kinetics of sintering of powder materials of solid-phase sintering and sintering with the participation of the liquid phase. An analytical description of the self-diffusion of iron and carbon diffusion with the participation of the liquid phase of glass is given. It is established that the diffusion pair (bipar) consists of two semi-infinite samples *A* and *B* connected by a flat boundary through which diffusion is carried out from one sample with an initial concentration of diffusiant C_2 to another sample with an initial concentration of diffusiant C_1 ($C_1<C_2$).

8. The advantages of using glass in powder materials of the "iron-cast iron-glass" type during sintering of the composition are shown. It is defined that in order to intensify the sintering process of the multicomponent iron-cast iron-glass system, the components of the system must be coated with well-wetting substances, for example, it is advisable to metallize cast iron and glass powders. In this regard, the most effective process can be considered chemical copper plating of cast iron and glass powders. Copper plating of solid powders of cast iron and glass can also lead to a significant improvement in the compressibility of compressions, and further intensify the sintering process due to the presence of liquid phases of copper and glass in the system.

9. The pre-exponential multiplier of the diffusion coefficient of the components of the "iron-cast iron-glass" system is determined. The correlation between the logarithmic value of the diffusion coefficient and the activation energy is established. However, this correlation is approximate (not exact) for amorphous alloys, such as glass. The diffusion coefficients are calculated from the experimental data of various annealing processes. The hetero-diffusion coefficient $\breve{D}$ of a binary system consisting of components *A* and *B*, which is expressed in terms of partial diffusion coefficients of these components, is determined.

10. The results of experimental studies of powder materials from "iron-cast iron-glass" are presented. The contribution of solid lubricants (graphite, copper inclusions) and solid inclusions (cast iron, glass) in copper powder compositions "iron-cast iron-glass" in the formation of antifriction properties of sintered materials is determined. It is shown that in order to prevent a decrease in the antifriction properties of the compositions, the amount of solid lubricants in them should not exceed more than 10%.

11. It was determined that in order to increase the load capacity of sintered "iron-cast-iron-glass" compositions for operation in dry friction conditions, they must be compacted, the kinematics of the process of compacting sintered workpieces in a conical matrix (extrusion) was investigated. Qualitative and quantitative assessment of the kinematics of the extrusion process and the deformation characteristics of the sintered workpieces were carried out. It was found that the speeds of movement along the X and Y-axes of the powder material, respectively, are 8 and 12% lower than cast, which is explained by the compaction of the porous workpiece due to the reduction of pores.

12. It is shown that when using metallized powders of cast iron and glass, as well as compaction of sintered "iron-cast iron-glass" under extrusion conditions, the density of the workpiece and the load capacity of the material significantly increases under dry friction conditions. Under dry friction conditions, the load capacity of "iron-cast iron-glass" reaches up to 6-8 MPa, which is a very positive effect.

An attempt is made to establish the relationship between the compositions – porosity property of sintered materials. It is established that the quantitative description of the properties of sintered bodies is very difficult, it requires the accumulation of many experimental data and with the use of ICT it is possible to solve this problem.

13. The influence of the type of iron powder on the formation of strength characteristics of sintered compositions of "iron-cast iron-glass" is investigated. It is shown that the best properties are achieved in the case of using reduced iron powder compared to

sprayed powder. An important degree of sponginess and development of the surface of the reduced powder accelerates the diffusion of alloying elements into the iron matrix. This is due to the greatest destruction of the iron lattice in the case of obtaining a reducing powder in the annealing and granulation processes.

14. The features of sintering of "iron-cast iron-glass" compositions are investigated. It is established that sintering of such materials takes place in two stages: the initial one, which corresponds to “active” shrinkage and the final one – passive shrinkage. It is noted that the size of the powders has a significant influence on the intensity of sintering, that is, the smaller the powder, the faster sintering goes.

15. Special areas of application of research results at industrial enterprises of the Republic of Azerbaijan are analyzed. The analysis of the characteristics of the developed materials and the specific of the industry allows us to recommend these materials for calculations in the friction angles of various machines and equipment.

The results of the research are the basis for the technology of obtaining parts 8ТЛ.210.005 "Bushing". The implementation of cold pressing technology at a pressure of 1000 MPa and sintering at a temperature of 11500C lasting 2 hours, as well as additional compaction of sintered "iron-cast iron-glass" under extrusion conditions, allows to increase the fatigue life of the powder composite material by 20 – 70% and by 25 – 35% the maintenance period of operation. The introduction of the technology with a production volume of 1000 parts per year will provide an economic effect in the amount of 345,600 manats for 8ТЛ.210.005 "Bushing" parts.

THE MAIN RESULTS OF THE DISSERTATION ARE PUBLISHED IN THE FOLLOWING WORKS:

1. Jabbarov, T.G., Imanov, X.И. Wear resistance of powder composite materials "iron-cast-iron-glass" during friction without lubrication. // AzTU, Scientific notes. Baku, 1993, No. 4, pp. 30-32.

2. Jabbarov, T.G., Sadigov, V.B. The influence of the amount of glass abrasive on the mechanical and tribotechnical properties of the "iron-cast-iron-glass" system corrosion-resistant abrasive composite material. // Azerbaijan State Naval Academy, Scientific notes. Baku, 2004, No. 2, pp. 51-53.
3. Jabbarov, T.Q. Methods of reducing the elastic response of iron-cast-glass composite material in radial compression. // Proceedings of Azerbaijan Higher Technical Schools. Baku, 2020. Volume 22, No. 4, pp. 56-59.
4. Jabbarov, T.G. Radial compression of porous bushings from iron-blade-glass, strengthened in a rigid mandrel. // Proceedings of higher technical educational institutions of Azerbaijan. E-ISSN: 2674-5224. Baku, 2021, pp. 29-35. DOI: 10. 36962/PAHTEI
5. Jabbarov, T.G. Compaction of porous powder body consisting of the elastic-plastic medium. // Eastern-European Journal of enterprise technologies. ISSN1729-37746/7(96). – Charkov, 2018, 6/7(96). – pp.44-48.
6. Jabbarov, T.G., Dyshin, O.A., Babanli, M.B., Abbasov I.I. Mathematical Modelling of the Sintering Process of Iron Based Metal-Glass Materials. // Proqress in physics of metals. ISSN 1608-1021. – Kiyev, 2019. – Vol.20, № 4, – pp.584-619.
7. Jabbarov, T.G., Aslanov, J.N., Shahmarova, R.S. Saturation of glass particles with meal during sintering of a composite material of the iron-glass system. // «EUREKA: Physics and Engineering». ISSN 2461-4254. – Tallin, 2021. – Vol.32, – pp.106-112.
8. Jabbarov, T.G., Dyshin, O.A., Babanli, M.B., Abbasov, I.I. Numerical simulation of the sintering process of multicomponent composite materials based on iron and glass. // STS “Institute for Single Cristals”. Functional Materials. – 2021, 28, №1, – p0p.158-169. ISSN 1027-5495 doi:https//doi.org /10.15407/fm28.01.158.
9. Jabbarov, T.G. Compaction of metal-to-glasporous bodies under conditions of limited passive deformation. // News of Azerbaijan high technical educational institutions. ISSN-1609-1620. – Baku, 2021. – Vol.23, Issue 2(130), – pp.35-41.

10. Jabbarov, T.G. Development of mathematical models of the process of cold pressing of porous bodies in elastic-plastic medium. // Azerbaijan high technical educational institutions. ISSN 1609-1620.– Baku, 2022. – Vol.24, issue 2(136), – pp.58-65.
11. Jabbarov, T.Q., Sharifov, Z.Z Effect of pressing pressure on the mechanical properties of nickel-alloyed abrasive steels. // Scientific notes of Azerbaijan State Maritime Academy. Baku, 2005, No. 3, pp. 84-85.
12. Jabbarov, T.Q., Sharifov, Z.Z Effect of thermal processing on the mechanical properties of chrome-molybdenum abrasive steels// Scientific notes of Azerbaijan State Maritime Academy. Baku, 2006, No. 4, pp. 84-85.
13. Jabbarov, T.G., Sharifov, Z.Z., Orujov F.S. Effect of firing temperature on mechanical properties of nickel-alloyed abrasive steels. // Scientific notes of Azerbaijan State Maritime Academy. Baku, 2007, No. 5, pp. 40-41.
14. Jabbarov, T.G., Sharifov, Z.Z., Orujov F.S. Effect of pressing pressure on mechanical properties of manganese alloyed abrasive steels. // Scientific notes of Azerbaijan State Maritime Academy. Baku, 2008, No. 7, pp. 76-77.
15. Jabbarov, T.Q., Sharifov, Z.Z. Effect of cooking time on mechanical properties of manganese alloyed abrasive steels. // Scientific notes of Azerbaijan State Maritime Academy. Baku, 2009, No. 1, pp. 42-43.
16. Jabbarov, T.G., Sharifov, Z.Z., Orujov F.S. Effect of cooking temperature duration on mechanical properties of nickel-alloyed abrasive steels. // Scientific notes of Azerbaijan State Maritime Academy. Baku, 2010, No. 1, pp. 10-11.
17. Jabbarov, T.G. Synthesis of "iron-cast iron-glass" obsolete powder composite materials using fuzzy logic and big data base concepts. // 10th International Conference on Theory and Application of Soft Computing, Computing with Words and Perceptions Prague. – Czech Republic, 2019, – pp.866-871.
18. Jabbarov, T.G., Gurbanov, N.A. Synthesis of Optimal Technological Parameters of "iron-cast-glass" Grinding Composite Materials

Using Fuzzy Logic and Big Data Concepts. // 4th International Conference on Theory and Application of Fuzzy Systems and Soft Computing – ICAFS-2020Budva. eBook – Montenegro, August 27-28. – Vol.1306. – pp.254-260. ISBN 978-3-030-64058-3, https://www.springer. com/gp/book/97830306 40576.

19. Jabbarov, T.G. Analysis of the Influence of the Shape of the Matrix on the Compaction of Porous Powder Bodies of "Iron-Cast Iron-Glass". // 11th World Conference "Intelligent System for Industrial Automation" (WCIS-2020), AISC1323, – pp.316-321. ISBN 978-3-030-68004-6, https://doi.org/10.1007/978-3-030-68004-6_41.
20. Jabbarov, T.G. Compaction scenario for powder elastoplastic medium of "Iron-cast-iron-glass" type. // Tenth World Conference "Intelligent Systems for Industrial Automation" WCIS-2018, 25-26 October 2018. – Tashkent, Uzbekistan, – pp.189-193.
21. Jabbarov, T.G. Evaluation of Force and Kinematic Parameters during Plastic Deformation of Sintered Porous Billets Made Of Iron-Cast Iron-Glass-International Conference on Research in Natural and Engineering Sciences (ICRNES 2020). – Konya. Turkey, – pp-235-246. https://756d243f-9742-4892987f8834db07019e.filesusr. com/ugd/ e42d97_cf2.
22. Jabbarov, T.G. The choice of powder charges and properties of the powder composite material "iron-cast iron-glass". // Fifth International Iron-Steel Symposium. April 1-3, – Karabuk, Turkey.pp.210-216
23. Jabbarov, T.G., Babaev, A.I. The influence of sintering regimes of powder-coated oxidized blanks on their mechanical properties. Contemporary problems in the physics of metals. // Materials of the International Scientific and Practical Conference. Baku: Elm, 2007, pp. 145-146.
24. Jabbarov, T.G., Ibrahimli, A.M. Effect of pressing pressure on the structure and properties of ЖЧ50СТ6 composite material. // Materials of the Republican scientific and technical conference of students and young researchers on "Youth and scientific innovations", AzTU. Baku, 2017, pp. 120-121.
25. Babanli, M.B., Jabbarov, T.Q. Selection of chromium alloying

additions for structural abrasive steels. Modern problems of the physics of metals. // V International scientific-practical conference. Baku, 2016, pp. 122-125.
26. Sabbarov, T.G. Effect of pressing pressure on the structure and properties of ЖЧ50СТ6 composite materials. // Theses of the Republican conference of young scientists and graduate students. Baku, 1997, pp. 64-65.
27. Jabbarov, T.G., Soltanov, A.B. Effect of oxidation parameters on the mechanical properties of ЖЧ50СТ6 composite material. // Scientific and technical conference of graduate students and young researchers of AzTU. Baku, 2002, pp. 143-144.
28. Jabbarov, T.G., Soltanov, A.B. Effect of cooking temperature on tribotechnical properties of oxidized ЖЧ50СТ6 composite material. // 46th Student scientific and technical conference. AzTU. Baku, 2003, p. 46.
29. Jabbarov, T.G., Soltanov, A.B. Effect of cooking temperature duration on tribotechnical properties of oxidized "iron-cast-glass" system abrasive composite material. // Scientific and technical conference of graduate students and young researchers, AzTU. Baku, 2003, p. 181-184.
30. Jabbarov, T.G., Soltanov, A.B. The effect of pressing pressure on the physical and mechanical properties of the oxidized "iron-slag-glass" composite material. //XIX Republican scientific conference of higher school students, AzUAC. Baku, 2003, pp. 120-121.
31. Jabbarov, T.Q. Corrosion resistance of the coating formed by electromagnetic surface-welding.//International scientific-practical conference on Intellectual Technologies in Machinery Construction. AzTU, Baku, 2016, - p. 399-400
32. Jabbarov, T.Q. , Gafarova G.M. Effect of processing methods on the technological properties of sawdust obtained from Х15Р5Д2Т sawdust // 2nd International Scientific and Technical Conference on Problems of Metallurgy and Materials Science. AzTU, Baku, 2017, 305-306.
33. Jabbarov, T.G. Development of mathematical models of the of cold pressing of porous bodies in an elastic-plastic medium Second International Scientific-Practical Conference", Modern

Information, measurement and Control Systems: Problems and Perspectives, 2020" (MIMCS-2020) dedicated to the: 100th anniversary of ASOIU, December 07-08. – Baku, Azerbaijan, 2020, – pp.314-315. E-ISBN: 978-9916-9639-4-4.
34. Jabbarov, T.G., Babanli, M.B., Ismayilova, K.H. Method of decrease of elastic counteract to the quality of powder materials pressed in closed press-casts. // Thermophysical properties for technical thermodynamics. International Conference "Thermophysical and mechanical properties of advanced materials" and 4th Rostocker international symposium, AzTU, 17-18 September. – Baku, 2015, – pp.80-81.
35. Jabbarov, T.Q. Effect of cooking temperature and duration on tribotechnical properties of "iron-cast-iron-glass" composite material. // XVIII International scientific and technical conference on Problems of Water Transport. Azerbaijan State Maritime Academy, Baku, 2023, p. 14-16.
36. Jabbarov, T.G., Mamedov, A.T., Imanov, H.I., Heydarov, V.A. Charge for obtaining a wear-resistant sintered material based on iron. // Author's certificate №1752508, April 8, 1992.

Personal contribution made by the applicant in the works published in co-authorship:

1. Works [3,5,8-10,17,18,20-23,31,34,35] the author performed independently;
2. [1,2,4-7,11-16,19,24-30,32,33,36] the formulation of tasks, conducting experiments were carried out by the applicant, and the processing of research results was carried out jointly with co-authors.

The dissertation defense will take place « 30 » ___05__ 2024__- th year in _13.00__ at the meeting of the Dissertation Council ED2.02 operating on the basis of the Azerbaijan State University of Petroleum and Industry Address: Baku, Azadlig Avenue, 34

The dissertation is available in the library of the Azerbaijan State University of Petroleum and Industry.

The electronic version of the dissertation and the abstract is available on the official website www.adnsu.edu.az

The abstract has been sent to the appropriate addresses «23.04»2024_- th year.

Signed to the press: __19__04_2024
(date, month, year)
Paper size: __A5___
Volume: ___81472______
(number of characters)
Circulation: ____100_______