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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

**EFFECT OF THE INITIAL POROSITY OF IRON-
GRAPHITE POWDER COMPACTS ON STRUCTURE AND
PROPERTIES AFTER DOUBLE PRESSING**

Specialization: 3312.01 – Materials Technology

Field of Science: Technical Sciences

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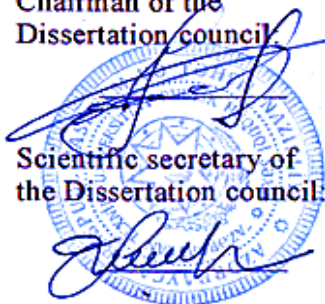
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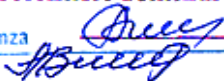
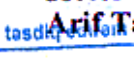
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GENERAL CHARACTERISTICS OF THE WORK

Relevance and degree of development of the topic. The intensive development of modern industry is closely connected with the achievements of materials science. In these fields, powder metallurgy plays a significant role in the development of new structural materials and the production of high-quality compacts and components based on them. Powder metallurgy methods allow for the production of compacts with the required composition and properties for various applications.

Due to the growing interest in powder metallurgy methods, many advanced technological processes have been developed and implemented in industry. The foundations of these processes include proper mixing of initial powder materials, cold compaction of the powder blend, and high-temperature treatment – sintering – of the pressed compact.

The subsequent improvement of the physical and mechanical properties of the compacts is ensured by additional alloying and heat treatment. It is known that iron-based structural materials obtained from various powders are widely used in many industrial sectors. Chromium, manganese, phosphorus, nickel, molybdenum, and boron are commonly added as alloying elements to such powders. It has been established that, after single cold compaction ($\sigma_m=380\text{--}780$ MPa) and sintering ($T = 1180\text{--}1200$ °C, $\tau_{\text{hold}}=3.5\text{--}7.0$ ks), the density of compacts produced from iron-graphite powder is $6.2\text{--}6.7$ g/cm³, and their porosity is 8–18%. The composition of such powder material contains 0.3–1.3% carbon, with 0.2–0.6% in the form of free graphite. Mechanical properties vary as follows: hardness 62–82 HRB, tensile strength $\sigma_m=140\text{--}240$ MPa, and compressive strength $\sigma_{\text{compr}}=780\text{--}880$ MPa.

When rational heat treatment regimes are applied, mechanical properties improve further: after quenching and tempering, the hardness reaches 48 HRC on the surface and about 23 HRC at the core. However, even with such properties, powder-based structural materials still do not fully meet industrial requirements. To further enhance these properties, double compaction and sintering methods

are employed. In this case, the density of the material increases to 7.2–7.6 g/cm³, hardness reaches HB 1600–2200 MPa, tensile strength σ_m increases to 520–620 MPa, and elongation ranges from 1.6–2.8%. These results lead to the conclusion that it is possible to obtain compacts with high physical and mechanical properties from unalloyed iron-graphite powder using double compaction and sintering processes.

It should be noted that, in many cases, advanced technological methods such as hot pressing, dynamic compaction, forging, and hot stamping are used to improve the most important characteristics of powder components. However, since these processes are performed at high temperatures, they reduce the durability of compaction equipment, require expensive and complex machinery, and significantly increase the labor intensity of production.

For the compaction of iron and non-ferrous metal powders - especially those with high plasticity - the cold compaction method is considered more efficient. However, structural powder components produced by single cold compaction and sintering cannot fully meet increasing industrial demands. Thus, the use of double compaction in sintering technology can be seen as a promising direction. Nevertheless, scientific-practical research and techno-economic justifications in this area are necessary.

One of the key issues is to investigate the changes in the density, structural-mechanical characteristics, composition, and properties of the material after the second compaction step.

The aim and objectives of the research. The main aim of the research is to develop the theoretical and technological foundations of the double compaction and sintering method for producing structural components from iron-graphite powder materials and to establish interrelations between the parameters of these processes.

To achieve this aim, the dissertation addresses the following **scientific and practical tasks**:

1. The main components of the iron-graphite powder blend were selected, and the rationale for the optimal blend composition was developed.

2. The parameters of the initial compaction and sintering processes were determined, and the dependencies between these parameters and the properties of the resulting compacts were established.

3. The optimal parameters and regimes of the second compaction and sintering processes were determined, and the structure and properties of the resulting iron-graphite material were investigated;

4. Scientifically grounded recommendations for the application of the research results in industrial settings were developed, and the economic efficiency of the process was substantiated.

Research methods. The objectives set forth in the dissertation were addressed through theoretical and experimental research conducted under both laboratory and production conditions. The mixing of the component materials, compaction of the powder blend, sintering of the green compact, and the subsequent second compaction and sintering operations were carried out using modern equipment, devices, and setups. The research operations, including detailed investigations such as microstructural analysis, were performed using innovative methods and advanced instrumentation.

Thus, the reliability of the results is validated by experimental studies conducted using contemporary instruments, measurement tools, devices, and accessories.

Scientific novelty of the research. Comprehensive investigations established that during the initial compaction stage, the densification capacity of the powder blend is determined by the relative apparent density of the powders. After the first compaction and sintering, the density coefficient of the compact shows a significant influence at lower final compaction pressures. At higher compaction pressures, however, the influence of the initial density of the pre-compacted green body on the densification process diminishes. This is due to the elimination of large pores under high compaction pressures and the relatively lower strength of the material matrix.

Interrelations between the main parameters of double compaction and sintering operations and the structure and properties of the powder material were established. It was found that, for effective gas evacuation from the powder blend during the initial compaction of iron-graphite materials, the die design must be optimized. Otherwise, under high initial compaction pressures and in the presence of a lubricant, the green body may undergo densification defects. In the second compaction, these defects are more effectively eliminated. Therefore, in order to facilitate the initial compaction process, it is recommended to use the maximum permissible amount of technological lubricant in the blend.

Theoretical and practical significance of the research. A technology for producing structural components from iron-graphite powder blends through double compaction and sintering was developed. The optimal chemical composition of the iron-graphite blend was determined. Based on the conducted research, the appropriate values for the pressure of the initial compaction and the temperature of the final sintering were established. It was determined that the initial compaction pressure of the iron-graphite blend should be 400 MPa, the tempering temperature should be 800–850 °C, the final compaction pressure should reach 1000 MPa, and the final sintering temperature should be 1200 °C. The second sintering step, involving the presence of a liquid phase, is of greater significance, leading to a more homogeneous structure in the sintered material compared to single - stage sintering.

The iron-graphite powder materials developed in this research, when economically alloyed with copper and nickel, can be successfully used in the production of structural components, including load-bearing parts. This is due to the fact that their strength characteristics are comparable to those of similar compacted powder materials.

The implementation of the proposed technology for the production of these materials and structural components can significantly improve the quality of the final products (strength, hermeticity, wear resistance), reduce metal consumption, lower the

costs of expensive equipment, and considerably decrease labor requirements.

Application of the research results. The results of this study can be implemented in oil machinery manufacturing and other related enterprises that produce structural components.

Approval and implementation. The main findings of the dissertation were presented and approved at the following conferences and seminars:

International Scientific-Technical and Scientific-Practical Conferences:

1. "Intelligent Technologies in Mechanical Engineering", International Scientific-Technical Conference, AzTU, 2016.

2. 2nd International Scientific-Technical Conference on "Problems of Metallurgy and Materials Science," Baku, AzTU, November 28–30, 2017.

3. Development of Education, Science and Business: Results 2020, abstracts of the international scientific-practical internet conference, December 3–4, 2020, Dnipro, Ukraine.

4. 18th International Scientific-Technical Conference on Problems of Water Transport, Baku, ADDA, May 4–5, 2023.

5. Machines, Units, and Processes: Design, Creation and Modernization, 8th International Scientific-Practical Conference, Saint Petersburg, January 28, 2025.

Republican Scientific-Technical Conferences:

1. 20th Republican Conference of Doctoral Students and Young Researchers, ADNSU, Baku, May 24–25, 2016.

2. Conference dedicated to the 80th anniversary of Prof. T.M. Panahov, AzMIU, June 10–11, 2016.

3. Republican Scientific-Technical Conference on "Youth and Scientific Innovations," Baku, AzTU, May 3–5, 2017.

4. Republican Scientific-Technical Conference dedicated to the 95th anniversary of Heydar Aliyev, "Youth and Scientific Innovations," AzTU, May 3–5, 2018.

5. Scientific seminars of the Departments of "Materials Technology" and "Metallurgy and Materials Technology" at AzTU, held between 2016 and 2023.

The total volume of the dissertation in characters, with the volume of the structural sections of the dissertation separately indicated. The dissertation consists of an introduction, four chapters, and is 132 pages in length (computer-typed), including 13 figures, 26 graphs, 12 tables, a list of 145 references, and an appendix. The structure of the dissertation work consists of the title page (501 characters), table of contents (2983 characters), introduction (11377 characters), Chapter I – (39480 characters), Chapter II – (19811 characters), Chapter III – (45280 characters), Chapter IV – (42186 characters), conclusion (4411 characters), list of used literature, appendices. Excluding figures, tables, graphs, and the reference list, the total character count of the dissertation is 166029 characters.

Publication of the Results. The main findings of the research have been published in 18 articles and conference abstracts.

MAIN CONTENT OF THE STUDY

In the introduction, the relevance of the topic is substantiated, and the objectives and tasks of the study are defined. The scientific innovations, as well as the scientific and practical significance of the research, are presented. Information regarding the approbation, publication, structure, and volume of the work is also provided .

In the first chapter, a comprehensive literature review was conducted. Based on the analyzed studies, it can be concluded that current research is primarily focused on the development of sintered structural steels through complex alloying. This approach aims to enhance the physical-mechanical and tribotechnical properties of these steels [3]¹.

The analysis of the literature review shows that the most straightforward and feasible method for producing structural powder components is the double pressing–sintering technology [8]².

¹ İkiqat presləməklə alınan dəmirqrafit ovuntu materialları. S.M.Rüstəmovə.

² Birqat presləməklə alınan dəmirqrafit ovuntu materialları. Doktorantların və gənc tədqiqatçıların XX Respublika konfransı. S.M.Rüstəmovə.

This is because both pressing and sintering operations can be carried out using the same equipment, meaning that only two types of machines are required for the four operations. The structure and strength characteristics of the material produced are comparable to those obtained by hot pressing and stamping methods. This is due to the high quality of the interparticle bonding process [4]³.

Based on the literature materials, it can be concluded that research on double pressing and sintering technology is very limited. This may be explained by researchers' unjustified focus on high-efficiency molding methods. The insufficient attention paid to cold pressing methods has considerably slowed down the development of this field [6]⁴.

In the second chapter, the selection of initial materials and the methodologies for conducting experimental studies are presented. The following materials were used in the research: restored iron powder ПЖ2М3 (GOST 9849–86), sprayed low-alloy iron powder ПЖПЖИ (Т-127-134-10), graphite powder of grade ГС (GOST 2022-96), and “У” grade zinc stearate (ТУ6–09–4473–97) used in the perfume and cosmetics industry.

Mixing of the powder blends was performed in a Y-shaped (3D) mixer under workshop conditions for 1 hour. The initial pressing of the blends was conducted both in laboratory and workshop conditions. Laboratory pressing was carried out using a GP-125 press, while workshop pressing was performed on an HPM-100S model hydraulic press at pressing pressures ranging from 400 to 1000 MPa.

The intermediate sintering of the pressed compacts was carried out in the laboratory using an MP-2UM muffle furnace at temperatures of 800–1000 °C in an endogas atmosphere. In workshop conditions, it was performed in a conveyor-type "Koyo Lindberg" furnace under the same temperature and atmosphere

³ Dəmirqrafit əsasında ovuntu materiallarından konstruksiya təyinatlı məmulatların alınmasında müasir istiqamətlər. S.M.Rüstəmov, N.R.Məmmədli.

⁴ Dəmir əsaslı ovuntu pəstahlarının alınması və xassələri. S.M.Rüstəmov.

conditions. The duration of intermediate sintering was 40–60 minutes.

The intermediate sintered compacts underwent second pressing on the HPM-100S press at 400–1000 MPa pressing pressure, followed by final sintering in the "Koyo Lindberg" furnace at temperatures of 1100–1150 °C in an endogas atmosphere for 1.0 hour.

The density and porosity of the pressed and sintered compacts were determined by standard methods based on Archimedes' principle. The hardness and strength characteristics of the sintered samples were studied using standard equipment.

The hardness of the compacts was measured using the TK-2M hardness testing device on the B and C scales. The tensile strength of the samples was determined using the P-5 testing machine according to GOST 1197-74, the bending strength using the P-10 testing machine according to GOST 18228-95, and the impact toughness using the KM-30 pendulum machine according to GOST 9594-98 [5]⁵.

The microstructure of the samples and powders was examined using both optical and electron microscopes. The optical microscopes used were the Japanese-made "Olympus" and the Neofot-21 (ADR), and the electron microscope was the Ukrainian-made REM-200 scanning electron microscope.

The microstructure and particle shapes of the powders were studied using the REM-200 microscope, while the microstructure of the sintered compacts was examined using the "Olympus" and Neofot-21 (ADR) metallographic microscopes. In addition, phase analysis of the samples was carried out using the DRON-2.0 X-ray diffraction device.

In order to reduce the scope of the experiments, mathematical planning of the experiments and error estimation were performed.

The optimization parameter was selected as the tensile strength of the sintered samples. Based on the results of a two-stage

⁵ İkiqat presləmə və bişirmədən sonra nümunələrin sıxlığı və mexaniki xassələri. S.M.Rüstəmovə.

full factorial experiment, the following regression equation was obtained for the first stage:

$$y = 318 + 3.875x_1 + 5.125x_2 + 7.375x_3$$

However, to obtain higher strength characteristics, it was found in the second stage of the experiment planning that the repressing pressure played a dominant role, and the final regression equation was:

$$y = 385.75 + 10x_3$$

In the third chapter, it was established that the density of the porous (crushed) medium being molded is a function of the stress tensor, it is not unambiguously related to the largest component of the latter, and the intensity of the briquette compaction process directly depends on the relative magnitude of the deviator component of the stress tensor.

Only through the application of highly efficient compaction methods – which include high-temperature processes and impulse compaction techniques – is it possible to achieve densities close to 100%. In such cases, the density of powder materials becomes comparable to that of dense (cast or forged) materials with similar composition and structure. However, in most cases, such high mechanical characteristics are not required for powder materials. This is because the methods of powder metallurgy allow the production of materials with superior strength and plasticity characteristics – exceeding those of the same composition wrought materials – due to the ability to obtain extremely fine particles and specially tailored structures [7]⁶. Therefore, by using the double cold pressing method, it is possible to produce structural powder materials that meet the necessary performance requirements [1]⁷.

In this chapter, the issue of determining the combined effect of factors influencing the course of the cold compaction process of the porous medium was also addressed. Specifically, the increase in the density of the green compact is inseparable from the fact that

⁶ Dəmir əsaslı məsaməli cisimlərin plastiklik hipotezinin eksperimental yoxlanması. A.T.Məmmədov, S.M.Rüstəмова.

⁷ İlkın soyuq presləmədə ovuntu materiallarının sıxlaşma qanunauyğunluqları. A.T.Məmmədov, S.M.Rüstəмова.

irreversible, i.e., non-plastic deformations occur in the compacted material. It is clear that a body with a certain current porosity is loaded in such a way that the strength of the material is insufficient to keep its deformation within the elastic range [15]⁸. Indeed, at any given moment of the compaction process, the arrangement of particles in the compacted material and the connections between them – characterized by composition, shape, etc. – form a porous space structure that is sufficient to bear the applied external loads, and naturally, the structure does not collapse. This situation allows the adoption of the following key assumptions:

- the porous (powder) material remains in a state of limit stress throughout the entire compaction process;
- the intensity of the compaction process not only depends on but is also determined by the deformation conditions of the material.

The latter is an interpretation of a well-known general fact for the compaction of porous media: it shows that the material's ability to resist loads is significantly influenced not so much by the magnitude of these loads, but rather by the manner in which they are applied.

The relationship between shear and normal stresses during powder mixture compaction can be expressed as follows:

$$[\tau_n] = \sigma_n \cdot tgS + K,$$

where k - is the coefficient of interparticle friction; s - is the internal friction angle of the powder relative to the die wall; the angle determines the proportionality between changes in τ_n and σ_n .

The direct measurement of the porosity variation in the deformed zone of the material was conducted using the «Kvantimetr-720» device. The cross-sectional polishing plane in the deformation direction was prepared by impregnating it under pressure with epoxy resin in a vacuum. The results processed for briquettes made from ПЖ2М3 powder with an initial average density of 70% showed that the material's compaction, as a function $\tau_n = f(\sigma_n)$ of the parameter beyond the fracture point, τ_n and σ_n accompanies its deformation

⁸ Dəmir əsaslı ovuntu materiallarına soyuq presləmə və bişirmə texnologiyasının tətbiqi. S.M.Rüstəmovə.

across all stress ratios. Thus, the earlier-mentioned conclusion was confirmed: the compaction of a porous medium does not directly depend on the parameter σ_n and this dependency is observed throughout the entire second region of the function, indicating that the dependency itself represents the transition threshold to a denser material.

It should be noted that in the range of density changes from ν 60% to 80%, the dependence of coefficients K and S on porosity is approximately linear for the studied materials. In this case, with sufficient accuracy for practical needs, it becomes possible to construct the interrelation of these parameters and the compaction curve, and to determine the function describing this curve in the mentioned porosity reduction range. In zones of lower or higher densities, as experiments show, K and S vary significantly and intensively, meaning that not only the coefficients in the compaction equation but also the very type of the dependency between pressure and density may change in rigid dies and hydrostatic conditions.

The analysis of experimental data and the selected compaction region of the porous material, where porosity may decrease along any trajectory (contrary to the previously assumed unambiguous pressure –density relationship), provides a solid justification for developing rational compaction schemes for powder materials.

Thus, our research shows that, in single pressing, the relative density of the green compact does not exceed 85–90% under any circumstances. The reasons, as noted earlier, include the friction forces between powder particles, the friction between particle surfaces and the die wall, the plasticity limit of the material, and so on. Therefore, after initial compaction, the porous preform must undergo sintering and then be re-compacted under new conditions. Hence, in the next section, the equations of plasticity theory were used to determine the stresses during the second compaction of the porous preform.

To describe the plastic behavior of a porous body, first and foremost, the yield condition or plasticity condition of the material must be adopted.

If the components of the deviatoric stress tensor are known, then using the equilibrium differential equations, σ_{ij} , $c=0$, and a series of boundary conditions, it is also possible to determine the components of the stress tensor.

The model of the plastic porous body examined in the dissertation was used to determine the stresses during the deformative tensile loading of compacts made from ПЖ2М3 iron powder. Tensile deformation is a steady-state process in powder materials processing because the stress-strain state at any point of the body depends only on its coordinates and not on time.

Preliminary testing of cylindrical powder specimens with dimensions $D \times H = 10 \times 10$ mm.

Preliminary compression tests were carried out on cylindrical powder specimens with dimensions $D \times H = 10 \times 10$ mm. Before testing, the relative density of the specimens was $\rho_0 \geq 0,68$.

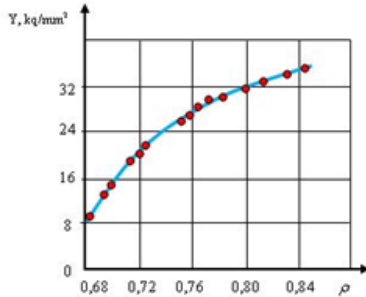
Compression tests were conducted on the sınaqlar ПП--250 machine. Fluoroplastic-based interface materials were used as lubricants to reduce friction at the contact surfaces. During testing, the diameter and height of the compressed specimen were measured. Based on the obtained results, the dependency $Y=f(s)$ was plotted (Graph.1).

The powder billets used in the tests had an initial outer diameter $D_0=23$ mm, an inner diameter $d_0=15$ mm, and a height $H_0=18$. The relative density was $s_0=0,68$. The billets were sectioned in the meridional plane. A coordinate grid with cell dimensions of 0.5×0.5 mm was drawn on the section plane using a corundum needle under a УИМ – 21 tool microscope.

The deformative drawing process was conducted on a УМП–10ТМ testing machine at a constant speed of $V_0=5$ mm/min. The diameter of the drawn hole in the billet reached up to $i_d=15,4$ mm, corresponding to a relative elongation of $i_{s0} ((d - d_0)/d_0 = 0,027)$. The cone angle of the transition section of the mandrel was $\alpha=4$, and the width of the calibrating belt was $b=1,5$ mm. The drawing process was continued until elongation of the billet occurred (Figure 1). After that, deformation was halted, the billet was removed from the bandage, and the coordinates of the deformed grid nodes were

measured using the УИМ-21 microscope. In Figure 1, the boundaries of the deformation zone under drawing conditions are indicated with dashed lines.

The stress values during the deformative drawing were computed using numerical methods, specifically by applying the finite difference method to the regular grid nodes while accounting for random perturbations. Numerical integration was performed using Simpson's rule.



Graph. 1. Dependence of the yield strength y on the relative density: the dependence of the Poinson's modulus on relative density is well expressed by the empirical dependence $\mu=0.5\rho^2$

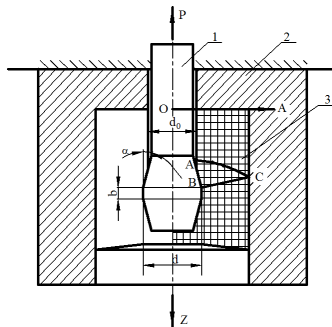
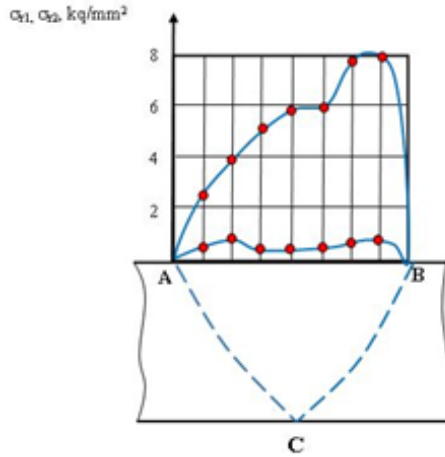


Figure 1. Diagram of the deformational tensile process of holes during powder compaction:

1 – mandrel; 2 – ring; 3 – die; ABC – zone of plastic deformations

The distributions (epures) of normal and shear stresses along the line $r=const$ in contact with the surface, are shown in graphic 2.

The normal stresses increase intensively along the z -axis and reach their maximum values at the exit of the deformation zone. Shear stresses also reach their peak at the outlet of the deformation zone, although their distribution exhibits a higher degree of uniformity.



Graph. 2. Plots of normal σ_r and tangential τ_{r2} stresses along the line $r = const$ tangent to the contact surface

Due to the small angle of σ , these stresses can be considered contact stresses in the first approximation. It is clear that there is no proportional relationship between the normal and tangential contact stresses. Therefore, in the calculation of the energy-force parameters of the process, preference should be given to the Zibel friction law rather than the Coulomb's law [2]⁹.

The proposed method for determining stresses can also be applied to other steady-state processes of powder material processing by pressure (such as drawing, extrusion, rolling, etc.).

To determine the velocity vector of dimensional changes, a method for calculating stresses in steady-state pressure processing of powder materials has been developed. This method is based on a

⁹Təzyiqlə emal proseslərində məsələli cisimə plastiklik nəzəriyyəsinin tənliklərinin tətbiqi. A.T.Məmmədov, S.M.Rüstəmov.

constructed coordinate grid and the plastic flow equations derived for porous materials. The method was applied to calculate the stresses arising during the deformational tensile process of the cavity in porous dies made from iron powder (type ПЖ2М3) by cold compaction followed by intermediate sintering [16]¹⁰.

It has been shown that the overall deformation of a sintered porous product depends on the type of stress state, the duration of loading, and the type of deviator. It is also a function of two invariants: C , the first invariant of the stress tensor, and C , the second invariant of the stress deviator.

The volumetric deformations are qualitatively described by all the considered models. However, for quantitative estimation of volume changes, preference should be given to the Martynov – Stern model.

In Chapter Four, it is noted that within the compaction pressure range of 400–1000 MPa, it is difficult to obtain hermetic and non-porous products by single-stage compaction and sintering using combustible, volatile, and evaporative plasticizers. This is because, during sintering of the compacted blanks, interconnected open porosity forms as a result of degassing, and solving this issue positively requires extensive specialized research and development efforts [14]¹¹.

In justified cases, for example, when it is necessary to avoid open porosity at a specified effective cross-section of pore channels, the compaction pressure should be increased to 1000 MPa or even higher, if possible [13]¹².

In addition to compaction pressure, an effective means of regulating porosity and pore channels is the optimized selection of the powder mixture components – primarily based on the shape of the particles and their granulometric composition.

¹⁰С.М.Пустамова. Применение уравнений теории пластичности на процессах обработки давлением пористого тела.

¹¹ Влияние температуры промежуточного спекания на свойства порошковых материалов. С.М.Пустамова.

¹² Dəmir əsəşli məsəməli materialların strukturuna aralıq bişirmə temperaturunun təsiri. S.M.Rüstəмова.

The formation of initial porosity during the compaction process of sintered materials continues during sintering due to the evaporation of the plasticizer and degassing of the compacted blanks, and ultimately completes at high temperatures. In this case, the heating rate of the compacted blanks can affect the density, chemical composition, hardness, and strength of the products [9]¹³.

The pre-reheating temperature before re-compaction significantly influences the continued formation of porosity, chemical composition, and microstructure, and this effect depends on the technological parameters of the initial materials and the compaction conditions of the products.

During the initial compaction and intermediate sintering processes, the chemical composition of the starting materials, the shape of the particles, and the degassing conditions – as well as the sintering temperature and heating rate during final sintering – significantly influence the magnitude of elastic after-effects in re-compaction and the shrinkage or growth of products during sintering.

Studies have shown that for both powder materials – ЖГр1 and ЖГр0.5D1.5H1.5 – the effective temperature range for annealing prior to re-compaction is around 900 °C [10]¹⁴.

When replacing parts made from compact materials with sintered materials, it is necessary to comprehensively justify the quantitative values of properties such as porosity, gas permeability, gas tightness, and other related characteristics.

The processes of mechanical property formation in re-compacted powders have been studied. The strength characteristics of porous materials based on ЖГр1 and ЖГр0.5D1.5H1.5 compositions are presented in Table 1 and Table 2. As seen, increasing the compaction pressure up to 700 MPa leads to an increase in both the tensile strength limit (σ_d), and the relative elongation (δ) of the powder compacts (Table 1). Further increase in

¹³ Aralıq bişirmə temperaturunun təkrar preslənmiş nümunələrin elastiki sonrakı təsirinin kəmiyyətinə və onların bişirmədə böyüməsinə (yığışmasına) təsiri. S.M.Rüstəмова.

¹⁴ Влияние промежуточной температуры спекания на свойства порошковых материалов. А.Т.Мамедов, С.М.Рустамова.

the compaction pressure initially continues to improve these properties, but beyond a certain point, they begin to decrease slightly.

Table 1

Physical and Mechanical Properties of ЖГр1-Grade Powder Material

Compaction Pressure, MPa	Specific Gravity of Compacts, g/cm ³	Tensile Strength, MPa	Relative Elongation, %	Hardness, HRB
380	6,28	172	6,60	22
520	6,48	192	7,24	28
620	6,78	206	8,16	34
720	6,82	230	8,78	41
780	6,76	226	8,42	39
910	6,74	206	7,32	39
400+600	7,02	324	15,12	73
400+700	7,16	336	16,92	74
400+800	7,22	352	20,02	75
400+900	7,28	360	20,52	77
700+600	7,16	352	20,04	72
700+700	7,26	380	24,22	76
700+800	7,32	384	24,02	80
700+900	7,34	390	24,42	77
900+600	7,12	338	18,12	84
900+700	7,18	350	18,43	86
900+800	7,22	350	20,24	92
900+900	7,26	368	20,83	93

According to the classical theoretical premise of powder metallurgy, this effect can be explained by the fact that compacts made from the ПЖ2М3 composition consist of powders with a large specific surface area, and as the compaction pressure increases, the drainage conditions of the powder mixture deteriorate [18]¹⁵.

This factor specifically causes a decrease in the strength of compacts after powder compaction. As a result, the physical and mechanical properties of the powder compacts decline. These observations are clearly illustrated in Table 2. Here, compact samples made from spray-dried powder with a less developed specific surface area exhibit a significant decrease in density after being compacted at 1000–1100 MPa.

¹⁵ Ovuntu dəmirqrafit nümunələrin sıxlığının və bərkliyinin təkrar presləmə təzyiqindən asılılığı. R.Q.Hüseynov, S.M.Rüstəmovə.

Table 2

Physical and Mechanical Properties of ЖГр0.5D1.5H1.5-Grade Powder Material

Compaction Pressure, MPa	Specific Gravity of Compacts, g/cm ³	Tensile Strength, MPa	Relative Elongation, %	Hardness, HRB
420	6,02	154	6,04	46
510	6,33	170	6,92	54
620	6,64	172	7,32	55
710	6,72	220	7,04	60
820	6,84	230	6,74	62
880	6,83	248	6,75	67
400+600	6,76	352	15,04	85
400+700	6,92	358	13,52	89
400+800	7,06	368	13,12	90
400+900	7,16	404	15,54	94
700+600	7,06	412	12,54	89
700+700	7,12	434	13,46	92
700+800	7,24	466	14,64	90
700+900	7,26	470	15,36	89
900+600	7,16	444	13,08	90
900+700	7,24	472	12,56	92
900+800	7,32	477	13,52	98
900+900	7,36	499	16,62	86

It has been established that for powder with the ПЖ2М3 composition, when the compaction pressure exceeds 700 MPa, the drainage conditions of the powder mixture deteriorate. This effect is especially pronounced when preparing compacts with thick walls [11]¹⁶.

When the powder material with composition ЖГр1 is re-compacted and sintered, a direct proportional relationship is observed between the compaction pressure and the mechanical properties of the compacts (Table 3). Compacts pressed under pressures of 700–900MPa exhibit higher properties ($\sigma_d=310\text{MPa}$ and $\delta=25\%$). The relatively lower values of compacts pressed at (900+600), (900+700), (900+800), and (900+900) MPa pressures are associated with the deterioration of gas drainage conditions during the initial

¹⁶ Ovuntu dəmirqrafit nümunələrin sıxlığının və bərkliyinin təkrar presləmə təzyiqindən asılılığı. R.Q.Hüseynov, S.M.Rüstəmov.

Table 3

Mechanical Properties of Materials

The brand of the material	Pressing pressure, MPa	Density, q/sm ³	Hardness after quenching and tempering, HRC	Radial compression strength, kN
Cast iron	–	–	42-47	32,15
ЖГp1	400	6,20	34-36	12,10
	500	6,45	37-39	15,23
	600	6,7	40-42	16,15
	700	6,8	40-44	20,00
	800	6,8	39-43	19,85
	900	6,79	44-46	17,27
	400+600	7,0	44-48	35,24
	400+700	7,15	46-49	38,15
	400+800	7,2	44-48	45,17
	400+900	7,25	42-44	45,85
	700+600	7,17	45-47	41,23
	700+700	7,27	44-48	46,33
	700+800	7,3	44-48	50,00
	700+900	7,35	45-49	52,17
	900+600	7,1	45-48	38,24
	900+700	7,15	45-49	40,15
	900+800	7,2	44-48	41,23
	900+900	7,25	43-49	43,18
ЖГp0,5D1,5H1,5	400	6,05	30-35	16,2
	500	6,35	34-37	18,32
	600	6,6	35-38	19,17
	700	6,7	36-38	19,85
	80	6,8	38-41	19,75
	900	6,85	39-42	20,04
	400+600	6,7	40-42	37,17
	400+700	6,9	41-43	40,21
	400+800	7,05	42-44	42,22
	400+900	7,15	43-45	46,17
	700+600	7,0	43-45	43,23
	700+700	7,1	42-46	47,75
	700+800	7,2	44-48	51,00
	700+900	7,25	44-46	52,84
	900+600	7,15	43-45	50,07
	900+700	7,2	45-47	53,03
	900+800	7,3	45-48	54,17
	900+900	7,35	46-48	62,25

compaction. Although these compacts demonstrate high hardness, this can be explained by decarburization occurring during the sintering process [12]¹⁷.

Compacts made from powder with composition ЖГр0.5D1.5H1.5.

The samples then exhibit high tensile strength. However, when the compaction pressure exceeds 700 MPa, the relative elongation of the compacts decreases somewhat, while hardness continues to increase significantly.

It has been established that, in all cases, double compaction significantly enhances both the tensile strength and relative elongation of the compacts. As the re-compaction pressure increases, the tensile strength and surface hardness of the compacts increase, whereas the relative elongation shows no significant change.

Radial compression strength tests were conducted on cast iron castings as well as on ring-shaped compacts made from ЖГр1 and ЖГр0.5D1.5H1.5 powders. It was determined that the radial compression strength of rings prepared by initial compaction and sintering is significantly lower compared to samples cut from cast iron castings. When re-compaction and sintering technology are applied, the strength of the compacts increases considerably, and these compacts demonstrate better strength compared to those obtained by initial compaction and sintering.

Although ring compacts made from gray cast iron have a homogeneous structure, they are inferior in mechanical properties compared to powder compacts produced by re-compaction and sintering technology. This issue can be explained by the lower density of the cast iron compacts.

GENERAL CONCLUSIONS

Thus, based on comprehensive studies on the changes in structure and properties of iron-graphite based materials subjected to re-compaction and sintering technology, the following conclusions were drawn:

¹⁷ İkiqat soyuq presləmənin dəmir-qrafitin struktur və xassələrinə təsiri. S.M.Rüstəmovə.

1. New theoretical and technological principles of pressing structural-design oriented powder materials have been proposed, systematized, and refined. Specific features of static and dynamic pressing of powder materials during the initial cold compaction of compacts were identified. It was determined that the density of the compacted porous material is not directly related to the largest eigenvalue of the stress tensor. The course of the compact pressing process depends on the relative value of the deviator component of the stress tensor.

2. A compaction diagram for powder materials based on iron and graphite mixtures was developed. It was established that during initial pressing in a closed setup, the compaction of powders is limited by the coordinates of normal and tangential stresses. The types of functions and corresponding coefficients expressing the correlation between pressing pressure and material density for conventional compaction processes were determined [12]¹⁸.

3. Classical equations of plasticity theory for porous compacts were applied in the technological processes of granular material compaction. A mathematical model based on Beltrami's hypothesis regarding the stress state of porous and plastic powder materials was developed. Correlation equations for parameters such as deformation stresses and velocities were derived based on the proposed model.

4. A method was proposed for determining stresses during pressure processing of porous powder materials in stationary and stabilized regimes. Using a coordinate grid, plastic flow equations of porous bodies were derived to determine the deformation rate field. These equations were used for the analytical determination of stresses arising during tensile deformation of particles in compacts made from porous powders.

5. It was established that the volumetric deformation value of high-temperature sintered porous powder materials in a closed setup depends on the stress state of the compact, loading conditions, and the type of deviator. These deformations were evaluated using the proposed mathematical models. For quantitative evaluation of

¹⁸ İkiqat soyuq presləmənin dəmir-qrafitin struktur və xassələrinə təsiri. S.M.Rüstəmov.

deformations during pressing of porous materials, it is advisable to prefer the Martynova–Stern model.

6. Rational technological regimes for initial and re-compaction and sintering processes were determined experimentally. It was shown that the quality of high-density iron-graphite based compacts is influenced by the drainage process of the powder mixture. As sintering temperature, pressing rate, and compact size increase, the role of gas removal from the closed setup becomes increasingly critical.

7. It was established that the formation of physical-mechanical properties of porous powder compacts depends on the shape and the dimensions have a significant impact. It has been shown that, in terms of the efficiency of densification of porous material during the pressing process, using powders obtained by the liquid metal atomization method is more appropriate.

8. It has been determined that the intermediate sintering temperature is the most important technological parameter in the double pressing-sintering process for producing various compacts from porous powder materials. It has been demonstrated that the intermediate sintering temperature defines the level of physical-mechanical properties and the formation of favorable structural parameters in the subsequent stages of compaction.

9. It has been found that the re-pressing of iron-graphite based powder materials almost doubles the physical-mechanical characteristics of the compacts compared to those compacted once. Thus, the properties of the re-pressed compacts approach those of hot-pressed powder materials. It has been confirmed that the cold re-pressing technology of porous powder materials is significantly more efficient compared to hot pressing or stamping. Therefore, the wider application of cold re-pressing technology in the production of construction-purpose porous powder compacts can provide substantial technical and economic benefits.

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1. A.T.Məmmədov, S.M.Rüstəmovə. İlkin soyuq presləmədə ovuntu materiallarının sıxlaşma qanunauyğunluqları. AzTU, Elmi əsərlər, Bakı, 2016, №3, c.81-88.

2. A.T.Məmmədov, S.M.Rüstəmov. Təzyiqlə emal proseslərində məsaməli cisimə plastiklik nəzəriyyəsinin tənlirlərinin tətbiqi. AzTU, Maşınşünaslıq, Bakı, 2016, №1, s. 66-70.

3. S.M.Rüstəmov. Birqat presləməklə alınan dəmirqrafit ovuntu materialları. Doktorantların və gənc tədqiqatçılarnın XX Respublika konfransı. ADNSU, Bakı, 24-25 may 2016, s. 349-351.

4. S.M.Rüstəmov, N.R.Məmmədli. Dəmirqrafit əsasında ovuntu materiallarından konstruksiya təyinatlı məmulatların alınmasında müasir istiqamətlər AzMİU, Prof. T.M.Pənahovun 80 illik yubileyinə həsr olunmuş Konfrans materialları, 2016, 10-11 iyun, s. 344-348.

5. S.M.Rüstəmov. İkiqat presləmə və bişirmədən sonra nümunələrin sıxlığı və mexaniki xassələri. «Maşınqayırmada intellektual texnologiyalar» Beynəlxalq elmi-texniki konfrans AzTU, 2016, s. 316-320.

6. S.M.Rüstəmov. Dəmir əsaslı ovuntu pəstahlarının alınması və xassələri. “Gənclər və elmi innovasiyalar” mövzusunda Respublika elmi-texniki konfransı. Bakı, AzTU, 3-5 may 2017, s.71-72.

7. A.T.Məmmədov, S.M.Rüstəmov. Dəmir əsaslı məsaməli cisimlərin plastiklik hipotezinin eksperimental yoxlanması. Bakı, Milli Aviasiya Akademiyası, Elmi məcmuələr, 2016, cild 18, №4, s.72-79.

8. S.M.Rüstəmov. İkiqat presləməklə alınan dəmirqrafit ovuntu materialları. ADDA, Elmi əsərlər, 2017, №1, s.57-60.

9. S.M.Rüstəmov. Aralıq bişirmə temperaturunun təkrar preslənməmiş nümunələrin elastiki sonrakı təsirinin kəmiyyətinə və onların bişirmədə böyüməsinə (yığışmasına) təsiri. “Metallurgiya və materialşünaslığın problemləri” mövzusunda 2-ci Beynəlxalq Elmi-Texniki konfrans., Bakı, AzTU, 28-30 noyabr 2017, s.299-301.

10. A.T.Мамедов, С.М.Рустамова. Влияние промежуточной температуры спекания на свойства порошковых материалов. Вестник машиностроения, Москва, 2018, № 2, с.48-51.

11. R.Q.Hüseynov, S.M.Rüstəmov. Ovuntu dəmirqrafit nümunələrin sıxlığının və bərkliyinin təkrar presləmə təzyiqindən asılılığı. AzTU, Elmi əsərlər, Bakı, 2018, №3, s.171-177.

12. S.M.Rüstəmov. İkiqat soyuq presləmənin dəmir-qrafitin struktur və xassələrinə təsiri. AzTU–H.Əliyevin anadan olmasının 95-ci ildönümünə həsr olunmuş “Gənclər və elmi innovasiyalar”

mövzusunda Respublika elmi-texniki konfransı. Bakı, AzTU, I hissə, 3-5 may, 2018, s. 223-224.

13. S.M.Rüstəmovə. Dəmir əsaslı məsaməli materialların strukturuna aralıq bişirmə temperaturunun təsiri. AzTU, Elmi əsərlər, Bakı, 2018, №1, s.143-148.

14. С.М.Рустамова. Влияние температуры промежуточного спекания на свойства порошковых материалов. Розвиток освіти, науки та бізнесу: результати 2020: тези доп. міжнародної науково-практичної інтернет-конференції, 3-4 грудня 2020 р. – Україна, Дніпро, 2020. Т.2. с. 344-348.

15. S.M.Rüstəmovə. Dəmir əsaslı ovuntu materiallarına soyuq presləmə və bişirmə texnologiyasının tətbiqi. AzMİU, “İnşaat” fakültəsinin 100 illiyinə həsr edilmiş “İnşaataın müasir problemləri” Beynəlxalq elmi-praktik konfransının materialı, Bakı, 2020, s.306-310.

16. С.М.Рустамова. Применение уравнений теории пластичности на процессах обработки давлением пористого тела. Вісник Приазовського державного технічного університету: зб. наук. праць. Вип. 40. – Маріуполь: ДВНЗ «Приазов. держ. техн. ун-т», 2021, с.106-112.

17. Dəmir-qrafit ovuntu materiallarından məmulatların alınması proseslərinin bəzi xüsusiyyətləri. Su nəqliyyatının problemləri XVIII Beynəlxalq elmi-texniki konf. Bakı, ADDA, 4-5 may 2023, s.58-64.

18. С.М.Рустамова. Разработка технологии двухкратного холодного прессования и спекания порошковой смеси на основе железа. Машины, агрегаты и процессы. Проектирование, создание и модернизация. VIII Международная научно - практическая конференция, Санкт-Петербург. № 8, 28 январь 2025, s.55-59.


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[1,2,4]–provided the idea, formulated the research problems, solved them, and obtained results;

[7,10]–participated in solving the problems and analyzing the results;

[11,16]–formulated the research problems, solved them, and obtained results;

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