Study of the Porosity Based on Structurally Inhomogeneous Materials Al-Ti

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Abstract. A technology for forming structurally inhomogeneous materials of Al-Ti samples has been developed. The components of the initial mixture were calculated based on the bulk of real powders, taking into account the mass, stoichiometric coefficients of the original components, the purity, and the bulk density. The microstructure of structurally inhomogeneous materials samples was studied using application programs. Besides, image recognition is performed at various magnifications before etching and after etching. The main properties of Al-Ti materials at different temperatures are obtained. An interpolation of the porosity dependence is constructed based on theoretical and experimental data. It is proved that the granulometric composition of structurally inhomogeneous materials has been improved based on the correct percentage of the initial mixture. The dependences of porosity on pressure and melting temperature for manufacturing structural parts are substantiated and constructed. Thus, there is reason to argue that improving the granulometric composition of Al-Ti based on a correctly selected percentage of the initial mixture, taking into account the further process of forming structurally inhomogeneous materials, allows to control such a parameter as porosity, as well as to study the physical and mechanical properties in the manufacture of various structural purposes parts to predict their structures.

Keywords: Technology of sample formation · Microstructure · Components of the initial mixture · Percentage ratio · Powder filling · Temperature · Pressing pressure · Physic-Mechanical properties · Particle size distribution

1 Introduction

One of the areas of materials science is the development of new materials using powder metallurgy technology. The development objective needs are caused by the need to create fundamentally new structural and functional materials that have a sufficient level of mechanical strength at high loads, increased wear resistance, heat resistance, and low density. Currently, when creating a number of parts and assemblies in mechanical engineering, shipbuilding, aviation and rocket and space technology, high-strength, lightweight composite materials are increasingly used, in particular, composites that combine components with a high young's modulus, and elements with significantly

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lower values of the elastic modulus. By combining the volume content of the components, it is possible to obtain structurally inhomogeneous materials with the required values of the main physical, mechanical, and functional properties.

In recent years, significant advances have been made in the design of such materials for various applications. However, the specific structure of such composites significantly limits the possibility of using traditional research methods to obtain them. During manufacturing, such materials with the necessary set of properties, it is necessary to control the parameters of their structure during the implementation of the technology at all its stages. This applies to the operation of pouring into the mould, which is accompanied by the correct percentage of the original mixture. It is well-known that a wide range of chemical, physical, and technological components leads to heterogeneity in the properties of materials inside, and does not allow obtaining structural characteristics at a qualitative level. Therefore, progress in creating new materials requires a broader study and prediction of the structural characteristics of these materials, as well as the traditional methods of studying the structure of labor intensity. Thus, an urgent task is to improve known and to develop new methods for predicting the structural and physical-mechanical characteristics of materials.

2 Literature Review

As described in the paper [1], powders from aluminium alloys were studied using the casting method. The initial mixture was diluted with various chemical compositions of the pore-forming agents. During the research, the materials of different porosity were obtained in different ways. Also, using various compositions of amorphous Ni-Ti alloys, the heterogeneous properties of the source materials were significantly enhanced. A considerable number of researchers were engaged in the study of the mechanical properties of powders at the time, among which it is important to note [2, 3]. The results obtained in these studies are provided by cleaning the starting materials in liquid, gas, and other states. In turn, these results put increased demands on the microstructure properties of structurally inhomogeneous materials. Considerable attention is paid to maximum insight, dirt and other operational properties. As discussed in [4], the Ti-6Al-4 V powder is investigated. The authors of the paper have applied heat treatment at a range of certain tensile temperatures of Ti-6Al-4 V samples produced by SLM. The obtained data show a significant loss of force due to an increase in the annealing temperature due to grain growth, while there was no noticeable tendency to deformation of the samples. According to [5], the authors of the paper have investigated a general edge approach for analyzing thermo-electroelastic structurally inhomogeneous materials containing a shell that allows permissive inclusions with specific boundary conditions. It should be noted that the results obtained are reduced to a system of singular boundary integral equations, which is solved numerically by the boundary element method. Besides, special attention is paid to modelling the functions of various forms of materials that explain this feature and allow to determine the age of the intensity coefficients accurately.

According to the paper [6], individual and combined addition of Ti to the processed Al-Si-Cu-Fe-Mn alloy was performed. The peculiarity of these works is that the microstructure and phases of these alloys were studied using an optical microscope and x-ray testing in combination with EDS. The morphology of these alloys was quantified using SDAS. In addition, the strengthening of these manufactured materials was due to grain purification for α-Al and modification for the coarse, secondary phase of the substance. However, such methods do not allow to fully realize the possibilities of dispersed hardening due to the unsatisfactory wettability of material particles due to the presence of oxide films on their surface. It is known that the process of forming blanks consists of compacting the powder under the action of a certain pressure to obtain blanks of a certain shape from it [7, 9]. For an increase in their strength, blanks formed from powders are sintered [8]. At the same time, the melting temperature parameters, pressure, and physical and chemical properties of powder materials do not reflect the results of real parameters that should be taken into account when obtaining laboratory (model) samples, more real industrial products [10–12]. However, despite the efforts of scientists, a number of problems in the field of materials science remain open. Therefore, it is essential to further study and improve them by strengthening the particles of structurally inhomogeneous materials that need to be introduced either by mechanical mixing with aluminium powder (using powder metallurgy methods) or by direct introduction into the aluminium melt. It should be noted that the solution to such problems would allow more control of such parameters like porosity, as well as to study the physical and mechanical properties in the manufacture of parts for various structural purposes to predict their structures.

3 Researches Methodology

3.1 Calculation of the Initial Components Mixture

The purpose of the research is to investigate the physical and mechanical properties in the manufacture of structural parts, and to construct interpolation dependences of porosity on the pressure and melting temperature, as well as on the distance to the walls of the hopper.

The calculation of the initial mixture components was carried out considering the mass and stoichiometric coefficients of the initial components, the purity, and bulk density of the initial charge. The data required for calculating the initial components are shown in Table 1.

The total mass of the initial components forms an aluminium alloy, which must be manufactured by using individual technological processes of powder and lapidary metallurgy. The mass of this mixture was calculated using the formula:

$$M_{comp} = \sum_{i=1}^{m} z_i M_i \tag{1}$$

where m – number of source components; M_i − the atomic or molecular weight of the original component (*mol*).

Table 1. Components of the initial Al-Ti mixture and their properties.

Component	Number of components, mol, z_i	Atomic or molecular weight, M_i	The density of matter, ρ, kg/m^3 (g/cm^3)
Al	1	26,9 g/mol	2,7 (g/cm^3)
Ti	2	10,6 g/mol	4,54 (g/cm^3)

The volume containing the components according to their theoretical (single-crystal) density is:

$$V_{comp} = \sum_{i=1}^{n} z_i \frac{M_i}{\rho_i} \quad (2)$$

where V_{comp} − the volume that is filled with the original components ($cм^3$); ρ_i − the density of the corresponding component ($g/cм^3$); z_i − a number of initial components (mol).

The theoretical density of the initial mixture is G_{theor}:

$$G_{theor} = \frac{M_{comp}}{V_{comp}} \quad (3)$$

The bulk density of the initial mixture G_{bd} is found from the expression:

$$G_{bd} = b \times G_{theor},\ M_{cm} = G_{bd} \times V_{cm} \quad (4)$$

Knowing the bulk density of the initial mixture and the volume, that is, the volume of the sample that was prepared for pressing and subsequent sintering, the authors of the paper find the theoretical mass of the initial mixture. In this case, the authors of the paper have used a cylindrical mould with dimensions: Ø = *30* mm, h = *60* mm, after which we can find the volume according to the following formula:

$$V_{cm} = \pi r_{sample}^2 \cdot h_{sample} \quad (5)$$

where r_{sample} – the radius of a cylindrical sample; h_{sample} – height of the cylindrical sample.

The calculated values of the mixture mass and the components are presented for the case of complete interaction of the components with the formation of a stable Al-Ti bond. However, in practical applications, it is necessary to ensure that the desired porosity, wear resistance, and density of parts are also obtained. This can be achieved by changing the percentage of components, as well as by adding pore-forming components. In this case, titanium and aluminium can interact, thus not fully forming a solid mixture (alloy).

3.2 Typical Fillings and Basic Properties of Structurally Inhomogeneous Materials

Thermal synthesis of powder mixtures Al-Ti was carried out according to the following technological scheme. The initial powder charge was mixed in a drum mixer for 15 min. The powder mixture was weighed (based on the volume of the working cavity of the mold and the bulk density of the powder), and weighed on a Radwag WLC 0.6/C/1 precision scale. The particle dispersion of the prepared mixture was controlled using sieve analysis. The criterion for evaluating the degree of grinding of a aluminium and titanium powders mixture was the presence of a large number of particles with an average size that varied from 0.5 μ to 1 μ. This powder mixture was etched with acetone and dried in the air, to obtain a clearer image of the grain boundaries of the micro-grinders. The mass of the initial components was pressed under pressure into cylindrical blanks with a diameter of Ø = 30 mm, h = 60 mm. The pressing pressure varied from 50 MPa to 90 MPa. Sintering was performed at temperatures of 200, 500, and 1000 °C. The cooling rate after sintering was about 0.2 deg/sec. The porosity of the obtained samples ranged from 14% to 25%. The main physical and mechanical properties of structurally inhomogeneous Al-Ti materials are presented in Table 2.

Table 2. Basic properties of Al-Ti materials at different temperatures.

Property	Temperature, 200 °C	Temperature, 500 °C	Temperature, 1000 °C
Volume content, %	99.7	98.9	98.1
Outer diameter, mm	24.10	24.00	24.00
Internal diameter, mm	17.71	17.87	17.84
Weight, g	3.870	3.439	3.042
Density, g/cm^3	6.78	6.57	6.40
Hardness, GPa	25	10	4.4
Porosity, %	14	18	25
The tensile strength in bending, MPa	240	200	137
The limit of compressive strength, GPA	1,7	–	–
Modulus of elasticity, GPA	81	79	71
Thermal conductivity, W/(m · K)	25.061	51	79.2

It should be noted that these raw materials Al-Ti have a low density, which reduces the weight of structural parts (piston) and, consequently, reduces the inertial load on the elements of the cylinder-piston group of materials. This also simplifies the problem of reducing the thermal resistance of parts elements, which in combination with good thermal conductivity, reduces the heat stress of the final products. It should also be noted that when titanium and aluminium components interact, the formation of four intermetallics is possible, particularly TiAl, $TiAl_2$, and $TiAl_3$ with a tetragonal structure, and Ti_3Al – with a hexagonal structure. Therefore, the main advantages of this selected percentage of raw materials include: small mass of the original components (at least 30%); high thermal conductivity (3–4 times higher); good anti-friction properties.

4 Results

4.1 Dependence of Porosity on Pressure and Melting Temperature for Manufacturing Structural Parts

In this section, the authors of the paper have observed the process of obtaining Al-Ti materials using a reaction between molten aluminium and a pre-made mixture of Ti powders. Particular attention was paid to the reaction temperature, which significantly affects the final processing of the product microstructure. It should be noted that the introduction of aluminium powder into the initial charge leads to the formation of thermal energy. As a result, the reaction between Al and Ti takes place, which further initiates the Ti reaction. After that, the aluminium melts, the melt envelops the titanium particles, so that a structurally inhomogeneous Al-Ti material is formed in the boundary zones. It was found that when the temperature reaches 1000 °C, the sample begins to glow, after which it self-ignites after 3–5 s. The use of a thermocouple installed inside the container, the self-ignition temperature of the samples was recorded, which is (1000 ± 10) °C and depends on the percentage of aluminium, the more aluminium, the lower the self-ignition temperature. The porosity is relatively small.

In Fig. 1, the dependencies of porosity on pressure and melting temperature for manufacturing structural parts are presented.

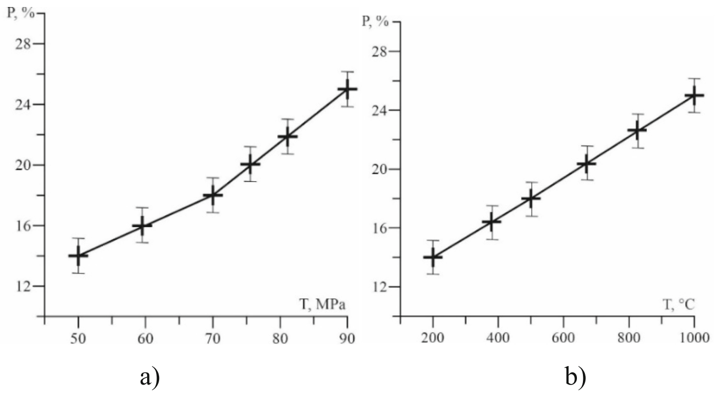


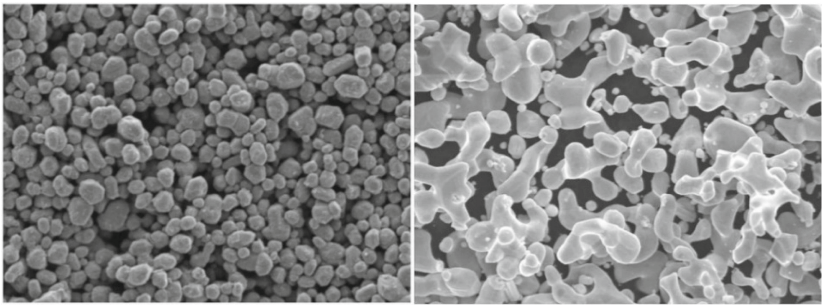
Fig. 1. The dependence of porosity on pressure and melting temperature: a – dependence of porosity on pressure; b – dependence of porosity on melting temperature

It should be noted that any method is chosen for obtaining structurally inhomogeneous materials (Al-Ti) provided a uniform distribution of components throughout the matrix volume, the formation of the maximum strong bond between the matrix and the reinforcing phase, the invariance of the structural-phase composition, and was also cost-effective and environmentally friendly. In addition, the advantage is that the pressing method allows us to quickly compact the powder body and get the workpiece with minimal residual porosity when sufficient low pressure (50–90 MPa).

4.2 The Microstructure of Structurally Inhomogeneous Al-Ti Materials Samples

For a complete and qualitative assessment of Al-Ti samples, it is necessary to determine and investigate the main morphological parameters of their microstructure, namely: 1 – determination the number of different sizes and shapes particles; 2 – determination of the sample structural defects; 3 – determination of the pore shape and particle shape; 4 – determination of the total pore distribution in the section and throughout the volume; 5 – determination the total distribution of certain particle shapes along the perimeter and volume.

In Fig. 2, the structure of Al-Ti samples at an increase of 800 μm (before and after etching) is presented.



a) b)

Fig. 2. The microstructure of samples of structurally inhomogeneous Al-Ti materials at an increase of × 800 μ, where: a - before etching; b - after etching.

There is a correlation between the original Al-Ti components and their properties. A structure that has dissolved to a greater depth has a dark color, and a structure that has dissolved less has a light color. This allows us to claim that the percentage of source materials is correctly selected. From the obtained graphic dependencies, it was found that the surfaces of structurally inhomogeneous materials micro shifts are inhomogeneous, and their morphology depends on digestion. After etching the surface of the cuts, their relief increased due to stronger etching of the edges around the pores that were worn during the grinding and polishing of the samples. At the same time, the pore sizes increased, which made it possible to record clearly the difference in the porosity of structurally inhomogeneous materials of different compositions. The etching duration was the same to ensure the same effect on the relief of the cuts.

4.3 Interpolation Dependence of the Porosity Based on Theoretical and Experimental Data

Based on the results obtained and the proposed numerical methods for calculating the components of the initial mixture, which was carried out taking into account the mass and stoichiometric coefficients of the initial components, the purity and bulk density of the initial charge, the porosity dependence on the distance to the mould wall was calculated using computer simulation models developed and based on experimental studies. The data obtained are shown in Table 3. The authors of the paper have also built an interpolation of the relationship (Fig. 3) porosity on the distance to the hopper walls, where 1 is at a distance of L_1 = 50 μ; 2 – at a distance of L_2 = 100 μ; 3 – at a distance of L_3 = 150 μ; 4 – at a distance of L_4 = 200 μ; 5 – at a distance of L_5 = 250 μ (at the bunker wall located at a distance of 280 μ). Solid line – theoretical data, the dash-dotted curve corresponds to the experiment.

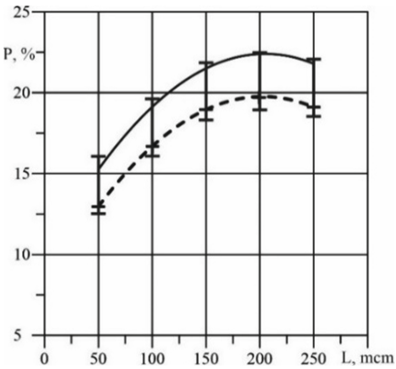


Fig. 3. Interpolation dependence of porosity on the distance to the hopper walls.

Table 3. Dependence of the porosity on the distance to walls of the silo.

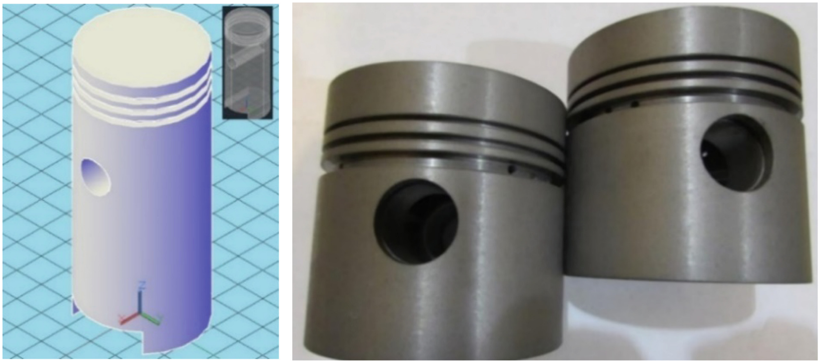
L, mcm	Porosity, %
L_1 = 50	14
L_2 = 100	16
L_3 = 150	18
L_4 = 200	19
L_5 = 250	24

The interpolation dependence of porosity on the distance to the hopper walls provides a visual representation of the particle size distribution, provided that the radius intervals in the fractions are the same. When calculating the n-number of particles in the range of radii from r_i to r_j belong to the average r_i, that is, it satisfies the condition $Q_n = \bar{h}(r)$, which characterizes the differential distribution of particles over the volume of the hopper.

4.4 Experimental and Industrial Justification of the Results Obtained

Structurally inhomogeneous materials based on aluminium alloy Al-Ti are characterized by a set of properties that open up wide opportunities for their application in various industries.

For Fig. 4, a general view of the structural part, in particular, the piston, is presented.



a) b)

Fig. 4. General view of the piston, where: a – in the COMPASS software window; b – photos of real cylindrical pistons

Based on the results of porosity calculations, as well as heat treatment modes, the economic effect of Al-Ti was calculated and determines the reliability and durability of the piston, in particular, power, mechanical and technological properties, its cost and scarcity. The results obtained make it possible to optimize the version of the charge composition, which provides a small mass of the initial components (at least 30%); high thermal conductivity (3–4 times higher); good anti-friction properties, which fully satisfies the technical conditions of operation of structural parts.

5 Conclusions

A method for evaluating the main parameters of the full-scale powder filling process has been developed. By using the metallographic analysis, the authors of the paper have investigated the regularities of structure formation and established the dependencies of the structure's influence on mechanical, physical, and mechanical properties, as well as porosity from the distance to the mould wall. It was found out that the results obtained provide a visual representation of the particle size distribution, provided that the radius intervals in the fractions are the same.

It should be noted that the results obtained allow to optimize the porosity of the resulting material for specific functional properties and technological requirements of specific products, as well as to predict the physical and mechanical properties of their structures. The calculations indicate that the porosity of the obtained samples of structurally inhomogeneous materials decreases with an increase in the width of the hopper.

Experimental and industrial justification of the results obtained showed that the proposed percentage ratio of the charge composition variant provides a small mass of the initial components (at least 30%); high thermal conductivity (3–4 times higher); good anti-friction properties, which fully satisfies the technical conditions of structural parts operation. Moreover, conduct the bulk of research without setting up expensive and time-consuming field experiments. This makes it possible to introduce virtually waste-free production of products for a wide range of purposes, save energy and materials, and reduce labor costs by reducing the number of technological operations and automating processes.

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