








Improvement of Processes for Obtaining Titanium Alloys for Manufacturing Parts with Design Elements

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Abstract. The article presents a systematic block diagram for manufacturing TiAl titanium alloys. Based on the developed block diagram of TiAl components, the main already known stages of powder metallurgy manufacturing technology were improved. Based on the obtained chemical reaction of structurally inhomogeneous materials, the intermetallic phase relationship of titanium aluminides was revealed. It is studied that in the zone of interaction of the composition of titanium and aluminium components, a certain thickness of the transition layer is formed, which practically does not change with increasing exposure time. The crystallization process of inhomogeneous TiAl materials was studied in more detail using the constructed crystal lattice of titanium alloys. As a result, the formation of an atomic grid in space was observed. It should also be noted that the recognition of individual areas in microstructural images was carried out using the Smart-eye software package. The microscopic analysis allowed us to predict the main structural characteristics of TiAl components. In particular, to carry out more detailed control of the particles of TiAl components, their density, porosity, relationships with each other, the shape and size of Ti and Al powders. The structure of the interaction of TiAl materials and the interpolation dependence of the formed intermetallic layer are also presented. Based on the conducted research, the quality indicators of parts with structural elements, particularly gears, have been improved.

Keywords: TiAl components · Physical properties · Microstructure analysis · Morphological parameters · Inhomogeneous materials · Technology

1 Introduction

Titanium intermetallics and alloys based on them are attracting more and more attention in mechanical engineering, aviation, rocket science, and space products. It is essential that due to the unique combination of their physical and operational properties, it is possible to solve a number of modern mechanical engineering problems when designing new parts. It should be noted that an integral part of the development of modern mechanical engineering is the introduction and improvement of new highly efficient heterogeneous materials and technologies for their products based on design. It

is known that titanium and alloys based on it have a unique set of properties. The most important ones include low specific gravity, high corrosion resistance to many reagents, sufficient strength at room temperatures, and elevated temperatures. However, the use of TiAl components is limited due to the high cost compared to other structural materials. Therefore, the main task of modern mechanical engineering technology is to expand the scope of improving the processes of obtaining titanium alloys for parts with structural elements. Also, improving their use by developing new economic technologies reduces the cost of both structurally heterogeneous materials and finished products significantly. It is possible to significantly reduce the cost of titanium alloys and products made from them using classical powder metallurgy methods. The main technological operations of this method include pressing mixtures into the product of the required shape and sintering structurally inhomogeneous materials in a vacuum.

Since titanium alloys are structural materials, they are essential for them to achieve the necessary complex mechanical properties. In alloys manufactured using powder technologies, this is ensured by chemical and microstructural homogeneity, permissible impurity content, and achieving a high relative density close to 99% of the theoretical one. Unfortunately, the specific structure of such composites significantly limits the possibility of using traditional research methods to obtain them. When manufacturing such materials, it is necessary to control the structure parameters during the technology implementation at all its stages. Therefore, progress in creating parts with design elements requires a broader study, research, and prediction of the structural characteristics of these materials. Thus, the urgent task of modern mechanical engineering technology is to investigate the physical and mechanical properties of TiAl materials for manufacturing parts with design elements.

2 Literature Review

Analysis of titanium-aluminium powders is covered in [1]. The biggest problem with studying these materials is their high cost and manufacturing complexity [2]. In addition, the results show that different powder particle sizes and concentrations of hollow material particles lead to high porosity [3]. The disadvantage of these studies is that the authors study powder particles only of a round spherical shape [4]. In [5], various technologies for manufacturing titanium-aluminium powders are investigated and predicted and an increase in their use in the large-scale industry due to the correct percentage of raw materials selected. It was found that Ti-6Al-4V [6] raw materials strongly affect the load mode. In [7], the authors of the paper investigated the edge approach for analyzing inhomogeneous elastic materials. It should be noted that the results obtained are reduced to a system of particular boundary integral equations, which is solved by the numerical method of boundary elements. Research teams [8] investigated the interaction zone between titanium and aluminium in a composite obtained by immersion and exposure of titanium rods in an aluminium melt. It was [9] found that the heat treatment time and cooling conditions affect the thickness and structure of the transition layer formed as a result of the interaction. The results of [10] show the peculiarity of porosity and coordination number calculations. The results obtained make it possible to optimize the version of the charge composition, which

provides an increase in the oil permeability coefficient by 3%, which fully satisfied the technical operating conditions of the bushings. The authors of [11] investigated the production of titanium alloys based on titanium aluminides as a material for gas turbine engine parts. The disadvantages of these methods include high electrical energy costs, which leads to an increase in the cost of titanium alloys and a large chemical heterogeneity of the resulting material [12]. In [13], to establish the possibility of obtaining layered intermetallic composite materials, titanium-based liquid aluminium was aged for different times at different temperatures in the air atmosphere using flux and without it [14].

The authors [15] found that the use of flux based on this powder composition contributes to forming a thicker and denser layer of intermetallides due to high temperature. The peculiarity of works [16] is that this composition of titanium-aluminium powders is limited by their existence's physical and chemical conditions. In many cases, increased requirements are placed on the performance characteristics of parts with design elements that are made based on titanium alloys [17]. The leading quality indicators include physical and mechanical properties of TiAl materials, a wide operating temperature range, the holding time of titanium-based liquid aluminum, which affects the width and density of the intermetallic layer, high stability, and reliability [18]. Therefore, the solution to such a problem requires a more comprehensive approaches such as [19, 20], including new technologies and structures, new ideas, methods, and principles of building methods and technologies [21–23]. Changes in their chemical structure [24], therefore conducting fundamental and applied interdisciplinary research using the latest methods and technologies of production.

3 Researches Methodology

3.1 Titanium Alloy Manufacturing Technology

The study aims to investigate the physical and mechanical properties of TiAl materials for manufacturing parts with design elements, conduct research at the points of the interaction zone of TiAl materials, and construct an interpolation dependence of the intermetallic layer based on the results obtained.

Well-known initial structurally inhomogeneous materials (TiAl components) are commonly used in mass production. At the same time, the manufacturing process takes place with the help of ceramic molds in the form of castings, which will not be able to provide defect-free castings. It should be noted that with the help of developed and optimized technological processes and the technical task set, we produced experimental samples from TiAl components.

The technological scheme for manufacturing TiAl titanium alloys is shown in Fig. 1.

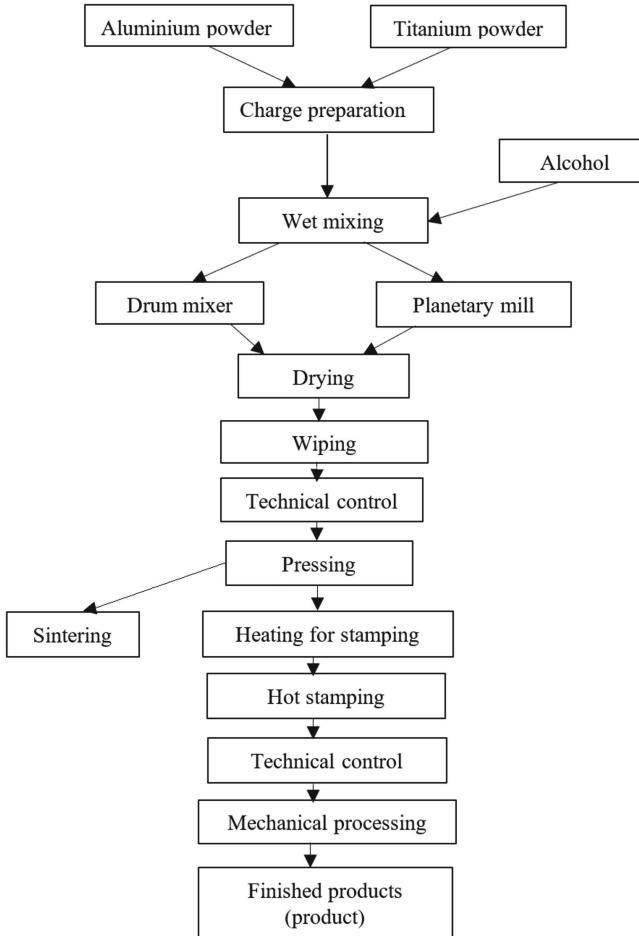


Fig. 1. Technological scheme for manufacturing TiAl alloys.

Before mixing, the powders structurally inhomogeneous materials were dried at a temperature of 70–120 °C for 3 h. Mixing of titanium and aluminium powders was carried out in steel ball mills for 2 h. The ratio of components was selected from stoichiometric calculations to obtain G-TiAl intermetallic phases. The mixed reaction mixture prepared in this way was weighed on an electronic scale of the CAS SW-II model and poured into the reactor. The temperature of the samples TiAl components during the synthesis process was controlled using a W-Mo thermocouple with an accuracy of $\pm 5\text{--}7$ °C. A PSU-125 hydraulic press was used to seal the powder mixture. The samples were formed in a cylindrical shape with a diameter of 25 mm and a height of 30 mm. An important role was played by the density of the samples TiAl components since the thermal auto-ignition mode was observed only for high-density samples at the level of 0,7–0,55 of the density of the starting materials. The porosity of TiAl materials was evaluated by hydrostatic weighing and microstructural analysis using

micrographs of sections and using the Smart-eye program. Hydrostatic weighing was performed for samples TiAl components without surface protection and protection, which made it possible to estimate the proportion of closed and open pores. The weighing was performed in distilled water at a temperature of 25–30 °C with an accuracy of 0,01. The water density was 0,997 kg/m³.

The structure of the TiAl samples was studied using the Smart-eye software package. The principle of operation of Smart-eye software is to connect an optical or electron-raster microscope that displays electrons on samples from TiAl components. Chemical microanalysis of the main structural components of the inhomogeneous material was performed on a raster electron microscope model Sarson MAGNI SCOPE MA-60. It should be noted that the study was carried out at an increased voltage of 19 kV, with a resolution of 1 Nm. It should also be noted that microanalysis was performed on the surface of an etched micro-grinder of structurally inhomogeneous materials and using the scanning method. A characteristic feature of X-ray radiation was studying certain chemical elements at specific points of interaction of raw materials, which was carried out along the studied trajectory.

3.2 Chemical Reaction and Crystallization Process of TiAl Materials

Aluminium and titanium powders with a dispersion of up to 100 μ were used to produce titanium alloys (TiAl). The ratio of components was selected from stoichiometric calculations to obtain the intermetallic phase γ -TiAl, in which the combustion temperature is lower than the melting point, $T_{\text{burning}} < T_{\text{melting}}$. As a result, a compound of titanium alloy TiAl is formed in Table 1.

Table 1. Chemical reaction TiAl.

Reaction $R_1 + R_2 \rightarrow P$	$T_{\text{mel}} (R_1), K$	$T_{\text{mel}} (R_2), K$	$T_{\text{mel}} (P), K$	T_{ad}
Ti + Al \rightarrow TiAl	1930	987	1730	1660

In order to study in more detail the crystallization process of structurally inhomogeneous materials, in particular TiAl components, we constructed a pinched hexagonal lattice (GSHG). In this scheme of the crystal lattice of titanium alloys, the atoms are located in the corners and the center of the bases of a hexagonal prism, and the three atoms are located between their bases. The total number of atoms is 17. It is also worth noting that the crystal structure of TiAl materials is characterized by a geometrically correct arrangement of atoms (ions) in space. Metal atoms are located at a certain distance between each other, at which the interaction energy of positively and negatively charged particles is minimal. In the plane, atoms form an atomic grid, and in space – an atomic-crystal lattice (lattice). In addition, the atoms oscillate around the equilibrium point at a high frequency.

The scheme of the crystal lattice of titanium alloys is shown in Fig. 2.

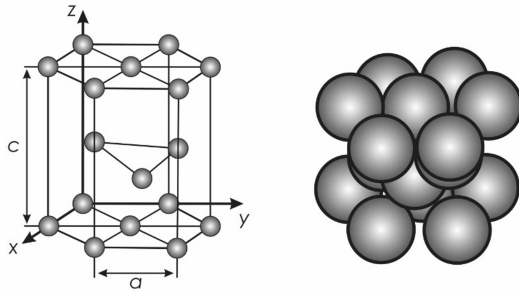


Fig. 2. Diagram of the crystal lattice of titanium alloys TiAl, where: a and c are the lattice period, $c/a = 1,633$.

It should also be noted that the crystallization procedure of TiAl components consists of two main components the formation of embryos, that is, it is the crystallization center. Moreover, the growth of crystals, which occurs in the center of the embryo. Each of these essential components must have individual velocities, which in turn determine the main parameters of the crystallization process as a whole. In particular, the first and main parameter of crystallization is the maximum rate of germ formation (c). The total amount of embryo formation is determined by the total amount of embryo formation, which has a ratio of one volume per unit time and is measured in $1/(\text{cm}^3 \cdot \text{s})$. The second crystallization parameter includes the linear crystal growth rate (a). This parameter is characterized by a rapid change in its linear dimensions (crystals) and is measured in centimeters per second (cm/s).

4 Results

4.1 Investigation of Titanium Alloys Based on Microstructural Analysis

During the manufacture of a blank part with design elements, it is necessary to apply the method of forming teeth by plastic deformation (rolling), which significantly increases mechanical parameters. In order to improve the quality indicators of gears and obtain a qualitative assessment of titanium alloy samples, it is necessary to determine and study the main morphological parameters of their microstructure using TiAl microanalysis. It should be noted that the focus was on the structure of titanium alloys in the solid-state after heat treatment and plastic deformation.

Notably, a sample of a micro-grinder of titanium alloys was examined in the part of the part that, in this case, was of the most significant interest—the destruction of the teeth of the gear wheel. After the technological process of obtaining titanium-aluminium composite materials was carried out, separate zones (red and blue regions) of interaction between structurally inhomogeneous materials during etching, which were close to destruction, were studied. It was found that there is a correlation between the original TiAl components and their properties. This allows us to state that the percentage of raw materials was correctly selected.

Figure 3 shows the structure of TiAl samples at a magnification of 800μ .

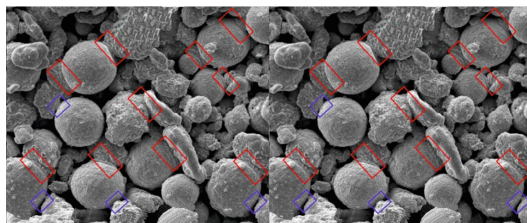


Fig. 3. Microstructure of TiAl titanium alloy samples at magnification $\times 800 \mu$.

Microstructure analysis (Fig. 3) at the selected points (red and blue regions) showed that the interface between titanium and aluminium allows distinguishing a transition layer of the intermetallic phase of titanium aluminides in the interaction zone of the titanium composite aged for different times. They also found that during the interaction between titanium and aluminium, the thickness of the transition layer practically does not change with increasing holding time and averages 6–8 μ (see Fig. 4). At the same time, the porosity was 16%, the total particle area 35478 mcm^2 , and the particle size ranged from 0,45 to 0,54 mcm . The structure of interaction between TiAl materials is shown in Fig. 4.

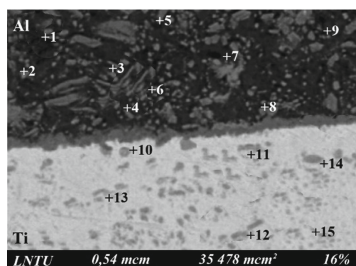


Fig. 4. Structure of interaction of TiAl materials.

From this Fig. 4, the thickness of the transition intermetallic layer, which is formed during the interaction of TiAl titanium alloys, is too small and allows us to obtain reliable results. It is also confirmed that in the considered binary system, both titanium and aluminum powders participate in the diffusion process, regardless of the temperature (above or below the melting point of aluminum).

4.2 Interpolation Dependence of the Intermetallic Layer

Due to significant differences between the molar volumes of titanium and its aluminides, an intermetallic layer was formed (Fig. 4). It is in a stressed state, which leads to its cracking and destruction. As a result, the separated fragments of the layer expose the surface of titanium, where a chemical reaction is restored between it and aluminum.

The consequence of this is the formation of a zone of interaction of the initial components of TiAl materials. Thus, the interpolation dependence is shown in Fig. 5 (Table 2).

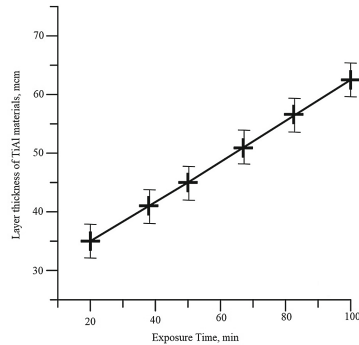


Fig. 5. Interpolation dependence of the intermetallic layer

Table 2. Analysis of the study at the points of the interaction zone of TiAl materials.

Materials	Exposure time, min	Layer thick-ness of TiAl materials, mcm
TiAl	20	35
	40	40
	45	45
	65	50
	80	55
	100	65

The interpolation dependence of an intermetallic layer with a thickness of 6–8 μ with increasing exposure times (20–100 min) shows a clear relationship between the initial components of TiAl materials. This is confirmed by the presence of an intermetallic phase of titanium aluminides in the interaction zone of the titanium composite.

4.3 Experimental and Industrial Justification of the Results Obtained

3D part modeling studies were performed in SolidWorks software. To build a 3D model of a gear wheel, the following main parameters were used: the diameter of the dividing circle d , the diameter of the circle of protrusions of the wheel teeth d_1 , and the circle of depressions d_2 , and the number of teeth z . From the above material and manufacturing technology of TiAl titanium alloys, we can present a complete 3D model of the gear wheel shown in Fig. 6.

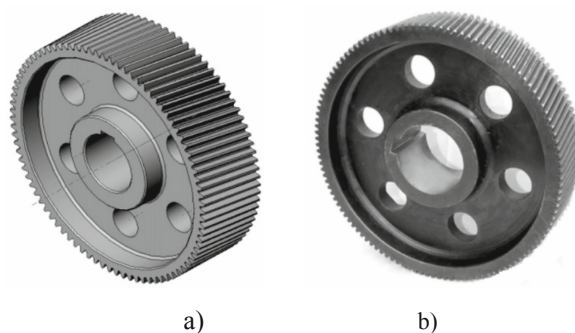


Fig. 6. 3D model of a gear wheel, where: a) in the SolidWorks software window; b) real view of the gear wheel.

Based on the calculations of the efficiency factor (performance factor), an analysis was performed at the points of the TiAl interaction zone of materials. Based on which calculations were made for the strength of a three-dimensional gear model. Using the SolidWorks software, the main recommendations for improving the quality of gears are formulated, which made it possible to optimize and predict the variant of the charge composition of the TiAl component, which provided an increase in the efficiency (performance factor) by 2–3%, which fully satisfied the technical conditions of operation of parts with design elements.

5 Conclusions

Using metallographic analysis, the authors of the article investigated the regularities of forming the TiAl structure of materials and established the dependence of the influence of the structure on mechanical, physical, and mechanical properties.

It was found that during the interaction between titanium and aluminium, the thickness of the transition layer practically does not change with increasing holding time and averages 6–8 μ , which makes it possible to obtain reliable research results.

Experimental and industrial justification of the results obtained showed that the proposed percentage of the TiAl charge composition variant of materials provides good antifriction properties, which is fully satisfied with the technical conditions of operation of structural parts.

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