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STUDY OF THE TEMPERATURES OF PHASE TRANSFORMATION IN HEAT-RESISTANT TITANIUM ALLOY OF Ti–Al–Zr–Si–Mo–Nb–Sn ALLOYING SYSTEM

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ABSTRACT

Calculated continuous-cooling-transformation diagram (CCT-diagram) was derived for titanium alloy of Ti–Al–Zr–Si–Mo–Nb–Sn system to determine the phase transformation kinetics. The structures and microhardness of samples of heat-resistant titanium alloy of Ti–Al–Zr–Si–Mo–Nb–Sn alloying system, quenched from different temperatures, were studied. It was proved that application of computational methods of modeling the structure-phase transformations for heat-resistant titanium alloys allows obtaining results close to the experimental values.

KEYWORDS: heat-resistant titanium alloy, thermodynamic modeling, phase transformation, deformation processing, temperature, structure, phase, microhardness

INTRODUCTION

Thermodeformational treatment (TDT) is an effective method to improve the complex of physical and mechanical properties of semi-finished products and products from titanium alloys, together with alloying and heat treatment. It is known that titanium alloys deformed in the β-region, have a lamellar microstructure and demonstrate a higher resistance to high-temperature creep and impact toughness. This advantage, however, is achieved due to lower ductility and thermal stability, leading to β-brittleness and structural heredity. During (α+β) deformation the material is usually heated and processed at the temperature 30–50 °C lower than that of β-transition [1, 2]. That is why, during selection of the optimal thermomechanical deformation mode it is necessary to determine the average values of permissible degrees of one-time deformation of the cast billets at different temperatures for the main structural components of the material. The objective of determination of the optimal thermomechanical parameters of the deformation process consists in selection of the initial and final temperature and establishing the maximal permissible degree of deformation in the specified temperature range. It is extremely important, however, to know the temperature of polymorphous transformation of α↔β-titanium, which in multicomponent titanium alloys varies, depending on the composition and concentration of the alloying elements [3].

MATERIALS AND EXPERIMENTAL PROCEDURE

Electron beam melted (EBM) ingots 110 mm in diameter [4] were used in the experiments. Their composition is given in the Table 1.

Experimental cast alloy of Ti–Al–Zr–Si–Mo–Nb–Sn alloying system is a pseudo-α-alloy, the main structural components of which are a lamellar α-phase and a small amount of residual β-phase [4]. However, the final structure of titanium pseudo-α-alloys forms during hot deformation processing, and the structure type does not undergo any significant changes during subsequent heat treatment.

To obtain the values of physical characteristics of the new titanium alloy, it is possible to use computer models for calculation of thermal-physical and physical properties of multicomponent alloys at solidification and cooling. One of the main methods to produce

Table 1. Chemical composition of the alloy of Ti–Al–Zr–Si–Mo–Nb–Sn alloying system, wt.%

Al	Zr	Si	Mo	Nb	Sn	Ti
6.2–6.9	5.0–5.5	0.5–0.85	0.5–0.8	0.5–0.8	1.5–2.5	Base

such data is thermodynamic modeling by CALPHAD procedure, based on the theory of multicomponent alloys [55].

CALPHAD (Calculation of Phase Diagrams) is the procedure and approach in the field of materials science, used for modeling, prediction and understanding of the material phase diagrams. The main objective of CALPHAD consists in solving complex problems of phase equilibriums and phase transitions, which helps to solve the question of design and optimization of materials. The main CALPHAD aspects include [6]: thermodynamic models — CALPHAD uses thermodynamic models to describe the energy of various phases and phase transitions in materials. These models are based on experimental data and theoretical calculations; phase diagrams — CALPHAD allows plotting phase diagrams of materials, representing the phases, present with different combinations of temperature, pressure and composition; data bases — CALPHAD uses thermodynamic data bases, containing information on standard thermodynamic values of different phases and phase transitions; prediction of material properties — CALPHAD allows predicting such material properties as hardness, heat conductivity, magnetic properties, etc. based on phase diagrams and thermodynamic models; application in metallurgy — CALPHAD is widely used in metallurgy for development of new alloys and optimization of the alloying processes; application in materials science — CALPHAD is used for investigation and development of new materials with certain properties; systems with many components — CALPHAD allows developing phase diagrams for multicomponent systems, which is particularly important for complex materials; further investigations — CALPHAD is continuously developing and new methods and data bases are added constantly to improve the prediction of phase diagrams and properties of materials.

SG model was used with application of CALPHAD method for nonequilibrium processes, which yields good results for multicomponent alloys forming during solidification, and which allows deriving the dependence of many parameters on their composition and temperature.

Properties of individual phases in multicomponent systems, such as molar volume, heat conductivity, and density, are expressed by functions, similar to those used for modeling the thermodynamic functions in excess multicomponent alloys. Having determined the properties of individual phases, the property of the final alloy is calculated using well-established mixture models [7]. Such models were first developed for two-phase systems, which were extended to multicomponent structures. Large data bases of the respective parameters are now available for the majority of the main steels and alloys, aluminium and titanium alloys [8].

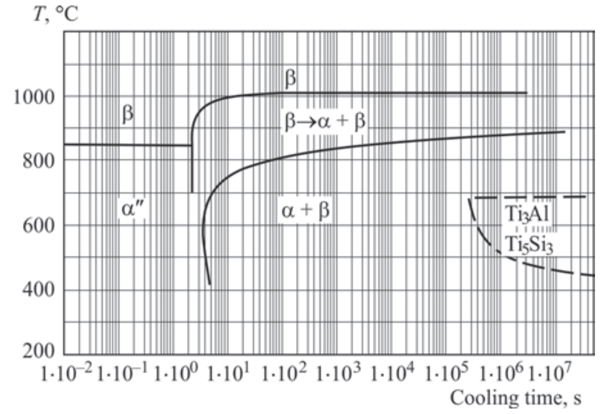

Figure 1. Calculated CCT-diagram of heat-resistant titanium alloy of Ti–Al–Zr–Si–Mo–Nb–Sn alloying system

During work performance, computer simulation of phase transformations of the heat-resistant titanium alloy of Ti–Al–Zr–Si–Mo–Nb–Sn alloying system was carried out [9]. To assess the change in the probable phase composition of the metal, computational CCT-diagram was plotted for this alloy (Figure 1).

The temperatures of the start of β→α transformation (~1015 °C) for cooling rates of 100–10 °C/s and end of β→α transformation (820–750 °C) for the same rates are marked in the diagram (Figure 1).

To confirm the calculated temperature of polymorphous transformation of a heat-resistant titanium alloy of Ti–Al–Zr–Si–Mo–Nb–Sn alloying system, a study of solid-phase transformations was performed with application of differential scanning calorimeter DSC 404 F3 Pegasus, operating in DTA mode (Figure 3). Samples were heated and cooled at the rate of 20 K/min up to the temperature of 1200 °C. To further refine the transformation temperatures, sample quenching was also performed with their further metallographic analysis. A series of samples were heated up to the temperatures from 800 to 1075 °C with 25 °C step,

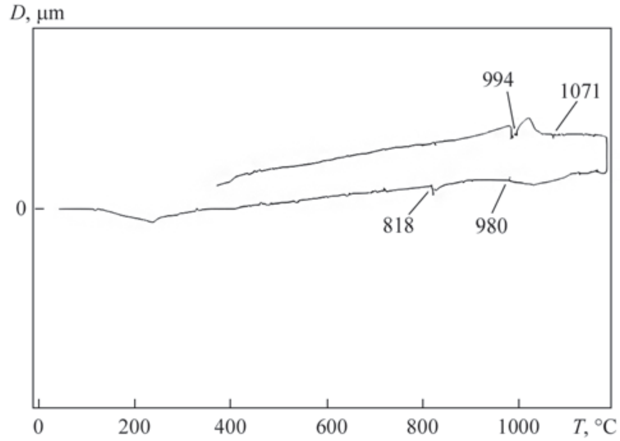

Figure 2. Dilatogram of an alloy of Ti–Al–Zr–Si–Mo–Nb–Sn alloying system

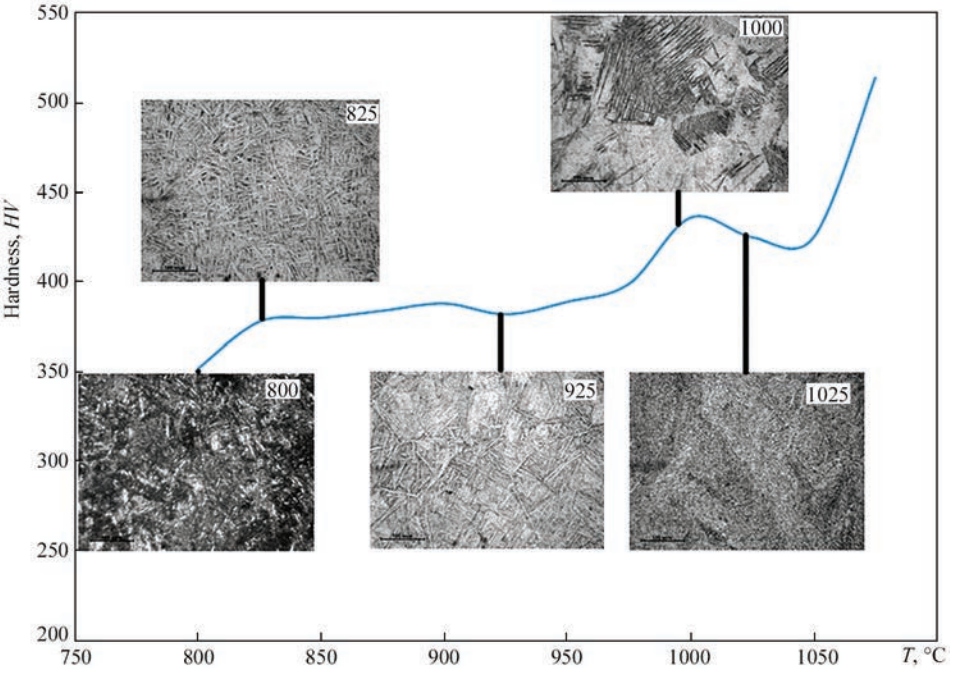

Figure 3. Microhardness of the samples and produced structures after quenching from different temperatures for an alloy of Ti–Al–Zr–Si–Mo–Nb–Sn alloying system

held in the furnace up to completion of the diffusion processes and quenched in water to record the phase composition. Change in the structure morphology and phase composition of the sample (Figure 2), allowed establishing the approximate temperature of polymorphous transformation of the material. Microhardness measurement was additionally performed on the quenched samples in LECO-M-400 instrument with 0.1 kg load. Change in material hardness also indirectly proves the change in its structure and phase composition (Figure 3).

The microstructure formed during quenching from the temperatures of the two-phase (α+β)-region consists of primary α-phase with lamellar morphology and α′-martensite. It is possible that presence of dispersion hardening due to dispersed α′-martensite results in a certain increase in material hardness in the temperature range of 825–1000 °C. Quenching from the single-phase region, leads to formation of α′-martensite and a small amount of the residual β-phase. Increase in hardness after the temperature of 1000 °C, is attributable to dissolution of the intermetallic α-phase and its further precipitation during quenching. A significant increase in material hardness in samples quenched from the temperature higher than 1050 °C, is explained by dissolution of silicides in the β-phase at these temperatures (Figure 4, *a*) [10], and during rapid cooling — by silicide precipitation in the entire sample volume (Figure 4, *b*).

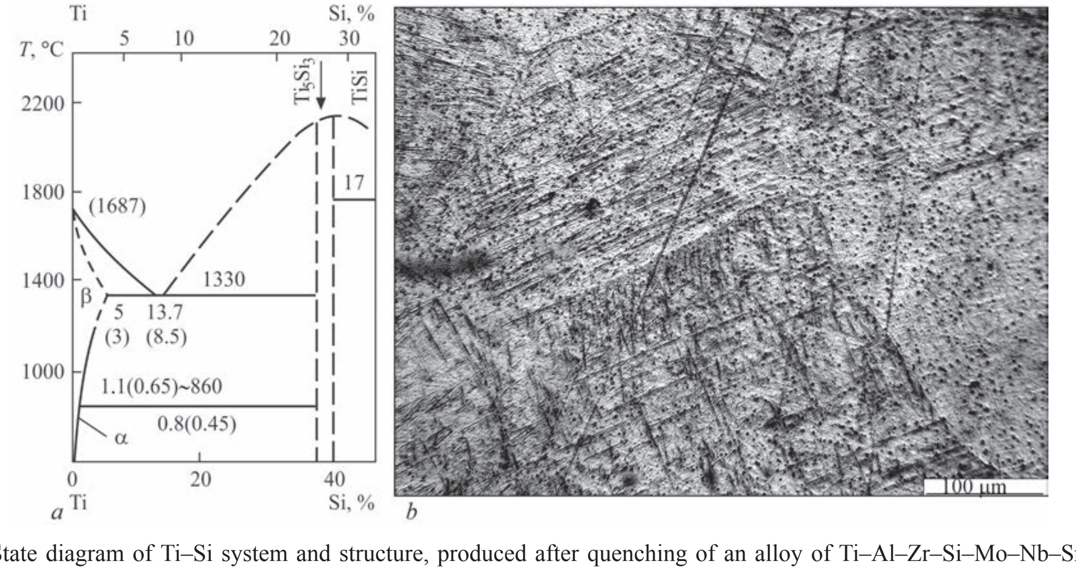

Figure 4. State diagram of Ti–Si system and structure, produced after quenching of an alloy of Ti–Al–Zr–Si–Mo–Nb–Sn alloying system from the temperature of 1050 °C

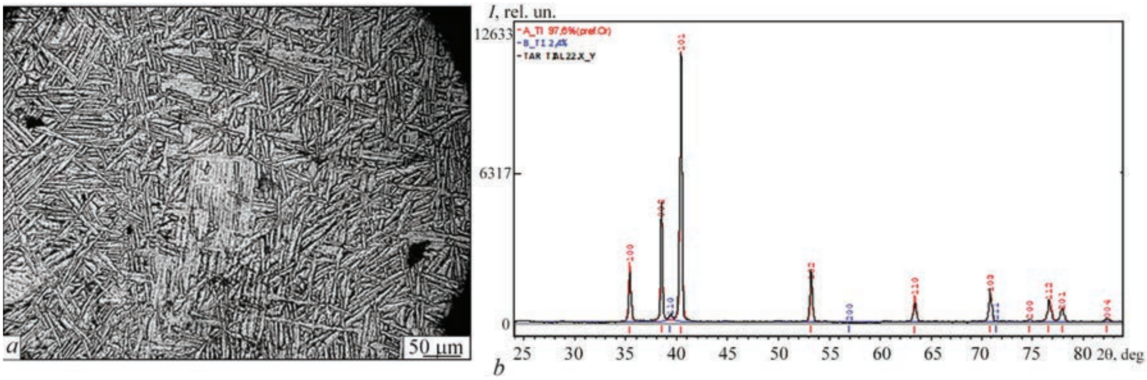

Figure 5. Microstructure (*a*) and roentgenogram (*b*) of initial metal of heat-resistant pseudo-β-titanium alloy of Ti–Al–Zr–Si–Mo–Nb–Sn alloying system

Comparison of computational diagram (Figure 1) and conducted experiments showed quite a slight discrepancy in the transformation temperatures. According to the diagram, in the range of the cooling rates of 10–100 °C/s, the calculated start of transformation begins at the temperatures of 780–850 °C, and ends at the temperature of 1015 °C, which is close to the experimental data. Dylatometric analysis demonstrates the temperature of transition from α- into (α+β)-region at about 818 °C, which is confirmed by the change in the structure in the quenched samples in the temperature range of 800–825 °C. The (α+β)→β transformation occurs in the temperature range of 994–1025 °C, which is also confirmed by the change in the structure morphology in the range of 1000–1025 °C. Thus, application of the computational methods of modeling the structural-phase transformation for heat-resistant titanium alloys yields results close enough to the experimental ones, which allows eliminating the operations of DTA and trial quenching and optimizing their structural-phase composition and improving their mechanical properties.

In keeping with the data obtained from the computational CCT-diagram of heat-resistant titanium alloy of Ti–Al–Zr–Si–Mo–Nb-Sn alloying system, and proved experimentally, hot deformation processing of EBM ingot with 50 % degree of deformation was performed from the temperature of β-phase region (~1050 °C) [11]. Deformed semi-finished products were produced in the form of rods 55 mm in diameter, the microstructure and phase composition of which are shown in Figure 5.

The microstructure of a sample from a deformed rod resembles the type of basket weave from α-plate packets (Figure 5, *a*). Silicide interlayers in the form of intermittent bands are located between the α-plates. Average grain size is equal to 50–70 µm. Investigations conducted by X-ray structural analysis confirmed that the pseudo-α-heat-resistant titanium alloy is a two-phase alloy and it consists of titanium β-phase (β-Ti) in the amount of 2.4 % (lattice parameters: a = 2.9400, c = 4.670), titanium α-phase (α-Ti) in the amount of 97.6 % (lattice parameters: a = 3.2225) (Figure 5, *b*).

CONCLUSIONS

1. A computational CCT-diagram was constructed for heat-resistant titanium alloy of Ti–Al–Zr–Si–Mo–Nb–Sn alloying system, which allowed determination of the temperature of α↔β-phase transformation in order to conduct further deformation processing.

2. Experimental quenching from different temperatures of a series of samples of heat-resistant titanium alloy of Ti–Al–Zr–Si–Mo–Nb–Sn alloying system was performed, which proves that application of computational methods of modeling the structure-phase transformations for heat-resistant titanium alloys yields results close to the experimental ones.

3. A dependence of metal microhardness on sample quenching temperature was established. Microhardness of metal of samples quenched from the (α+β)-region is higher than microhardness of samples quenched from the α-region, due to increase in the amount of the dispersed α′-phase, having a high strength and low ductility. Microhardness of metal of samples quenched from the β-region is ~10 % higher due to dissolution of silicides and their further precipitation at quenching.

4. Hot deformation processing of EBM ingot 110 mm in diameter from the temperature of β-phase region was performed, and deformed semi-finished products in the form of rods 55 mm in diameter were produced. Its microstructure and phase composition were studied. The deformed rod microstructure resembles the basket weave type from α-plate packets, and the silicide interlayers are located between the α-plates. Residual β-phase in the amount of 2.4 % is present in the structure.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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