DOI 10.1007/s11041-015-9789-2
Metal Science and Heat Treatment, Vol. 56, Nos. 9 – 10, January, 2015 (Russian Original Nos. 9 – 10, September – October, 2014)

UDC 669.2.017:620.18

FORMATION OF STRUCTURE, PHASE COMPOSITION AND PROPERTIES IN A TWO-PHASE TITANIUM ALLOY UPON VARIATION OF THE TEMPERATURE AND RATE PARAMETERS OF HEAT TREATMENT

A. G. Illarionov,[1] A. A. Popov,[1] M. O. Leder,[2] F. V. Vodolazskii,[1] and A. V. Zhloba[2]

Translated from *Metallovedenie i Termicheskaya Obrabotka Metallov*, No. 9, pp. 43 – 47, September, 2014.

The methods of light and scanning electron microscopy and x-ray diffraction phase analysis, measurements of hardness and tensile mechanical properties are used to analyze the effect of variation of the temperature and rate parameters of heat treatment on the occurrence of structural and phase transformations and variation of properties in sheets of a martensitic titanium alloy VST2. Phase and structural diagrams of the alloy are plotted for various treatment conditions as well as a diagram of variation of the volume fractions of phases in the alloy as a function of the quenching temperature. The set of the properties obtained is shown to be related to the special features of structure formation in cooling in different environments (water, air, furnace) from heating temperatures ranging within 790 – 990°C.

Key words: martensitic titanium alloys, heat treatment, quenching, cooling in air and with the furnace, phase composition, mechanical properties.

INTRODUCTION

To raise the competitiveness of titanium alloys with respect to steels, aluminum alloys and other structural metallic materials in various fields of engineering many producers strive to lower the production cost by introducing inexpensive alloying elements, like iron, without decrease in the level of mechanical properties [1]. The "VSMPO-AVISMA" Corporation has developed a novel ($\alpha + \beta$) martensitic titanium alloy VST2 with elevated iron content [2] for the production of sheet semiproducts. Production of semiproducts from this alloy requires knowledge of the processes occurring in the metal under heat treatment, in particular, upon variation of the heating temperature in a wide range and of the subsequent cooling rates, for example, by analogy with the research performed in [3, 4] for other double-phase alloys. The data should be useful for the development of the modes of quenching and annealing of the new alloy.

The aim of the present work was to study the formation of the structure, phase composition and mechanical properties of the alloy after a heat treatment in a wide temperature range and various variants of cooling of sheet semiproducts from VST2.

METHODS OF STUDY

We studied specimens cut from 9-mm-thick hot-rolled sheets of alloy VTS2 of the Ti – Al – V – Mo – Fe – Cr system produced by the commercial process employed by the "VSMPO-AVISMA" Corporation. When computing the aluminum and molybdenum equivalents of the alloy from the chemical composition in accordance with the data of [5] we obtained the following results: $[Al]_{eq} = 7.98\%$, $[Mo]_{eq} = 5.92\%$. The temperature of the polymorphic transformation (T_{pt}) determined by the method of test quenching [6] was 943 ± 3°C.

The microstructure was studied by the methods of light and scanning electron microscopy (SEM) using "OLYMPUS GX51" and "JSM-6490LV" devices, respectively. The x-ray diffraction phase analysis (XRDPA) was performed in copper K_α radiation with the help of a "Bruker D8 Advance" diffractometer. The Rockwell hardness was measured using a TK2 hardness meter at a load of 1.5 kN. The mechanical tests for uniaxial tension were performed in accordance with

[1] Ural Federal University after the First President of Russia B. N. Eltsyn, Ekaterinburg, Russia (e-mail: illarionovag@mail.ru, a.a.popov@ustu.ru).
[2] "VSMPO-AVISMA" Corporation, Verkhnyaya Salda, Sverdlovsk Region, Russia.

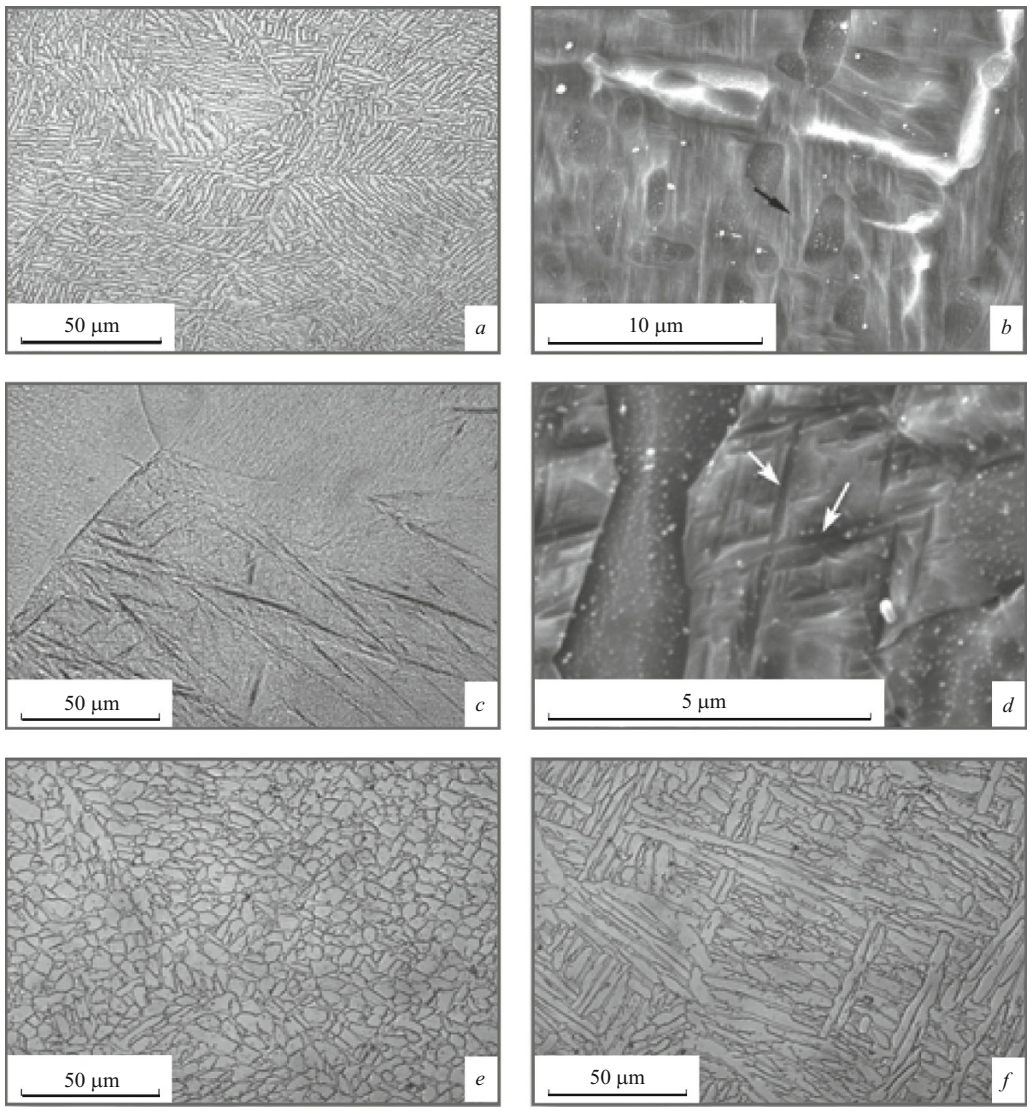

Fig. 1. Structure in a longitudinal section of a sheet of alloy VST2 in the initial condition (*a*), after water quenching from 865°C (*b*) and 990°C (*c*), after air cooling from 865°C (*d*), and after cooling in the furnace from 915°C (*e*) and 965°C (*f*).

the GOST 1497–89 Standard using a universal testing machine.

The heat treatment included heating in the range of 790 – 990°C at a step of 25°C, a 45-min hold at this temperature, and subsequent cooling in different environments (in water, in air, and with the furnace to 200°C and then in air).

RESULTS AND DISCUSSION

Figure 1 presents the structure of a sheet from alloy VST2 in different conditions. The structure of the hot-rolled sheet contains β-grains with a mean size of 290 ± 15 μm in the longitudinal direction and 160 ± 10 μm in the transverse direction, which are extended in the rolling direction. Inside the β-grains we observe primary α-plates with a thickness of up to 1 μm arranged in packets. The plates are bent, supposedly in the course of the final deformation in the (α + β) range (Fig. 1*a*). The grain-boundary α-phase on the boundaries of β-grains has been split partially due to the deformation. The mechanical properties in the longitudinal and transverse directions of the sheet are close ($\sigma_{0.2}$ = 970 – 1000 MPa, σ_r = 1020 – 1060 MPa, δ = 16 – 20%).

Analyzing the water-quenched specimens we established that when the heating temperature was increased, the volume fraction of the plates of the primary α-phase in the structure decreased. Quenching from 865°C and higher temperatures (up to T_{pt}) was accompanied by globularizing of the α-plates, and the matrix β-solid solution underwent a transformation yielding thin martensite plates (marked by the arrow in Fig. 1*b*), the size of which grew upon increase in the heating temperature, especially above T_{pt} (Fig. 1*c*). After quenching from a temperature close to and above T_{pt}

(940 – 990°C) the recrystallization processes developed in the structure produced equiaxed grains of a β-solid solution instead of the extended deformed ones.

When the cooling medium was changed from water to air, the tendency to lowering of the content of the primary α-phase upon growth in the heating temperature was preserved. However, in contrast to water quenching, air quenching from 865°C and higher temperatures (up to T_{pt}) caused formation of a secondary α-phase inside the β-matrix between plates of the primary α-phase instead of martensite (Fig. 1*d*; the plates of the secondary α-phase are marked with arrows). The content and the sizes of the plates of the secondary α-phase increases with the temperature from which the cooling is conducted. After air cooling from a temperature exceeding T_{pt} (965 – 990°C) the structure contains thin-plate precipitates of a secondary α-phase arranged in packets inside the recrystallized β-grains.

After cooling in the furnace from the temperature of up to T_{pt} the structure of the alloy is represented mostly by primary α-precipitates in β-grains. The plates of the primary α-phase acquire a progressively globular shape starting from the heating temperature of 815°C, and after cooling from 915°C the morphology of the α-phase is chiefly globular (Fig. 1*c*). After cooling in the furnace from the temperatures exceeding T_{pt} (965, 990°C) the α-phase acquires a coarse-plate packet morphology (Fig. 1*f*). This is connected with the fact that the primary α-phase dissolves completely due to heating above T_{pt}, and the matrix β-solid solution decomposes during the slow cooling with the furnace yielding packets of coarse α-plates, which is typical for double-phase titanium alloys [6].

We used the method of secants [7] to evaluate the size of the recrystallized β-grains formed at the temperature of 940 – 990°C. It turned out that increase in the heating temperature increased the grain size from 150 ± 10 μm (at $t_h = 940$°C) to 200 ± 10 μm (at $t_h = 990$°C)

The results of the x-ray diffraction studies of the alloy quenched in water from different temperatures show that after quenching from 780 – 865°C the diffraction patterns exhibit only lines of the α- and β-phases. After quenching from the temperature exceeding 865°C lines of α″-martensite appear. Lattice constant c of the α″-martensite remains virtually unchanged (ranges within 0.4645 ± 0.0002 nm), and the difference in the values of constant *a* and parameter $b/\sqrt{3}$ decreases upon growth of the temperature to T_{pt} (Fig. 2*a*), which is typical for alloys the class considered [3] and indicates weakening of the rhombic pattern of the martensite.

After cooling in air and in the furnace from all the studied temperatures the diffraction patterns exhibit only lines of the α- and β-phases. Comparative analysis of the lattice periods of the β-phase and of the parameter c/a computed from the diffraction patterns (Fig. 2*b* and *c*) shows that when the ambient is changed from an air one to the furnace one at the same heating temperature, the lattice constant of the β-solid solution is lower and the parameter c/a of the α-phase is mostly higher, which means that the processes of decomposition of the β-phase have developed completely and the condition of the alloy is more equilibrium when the cooling rate is decreased.

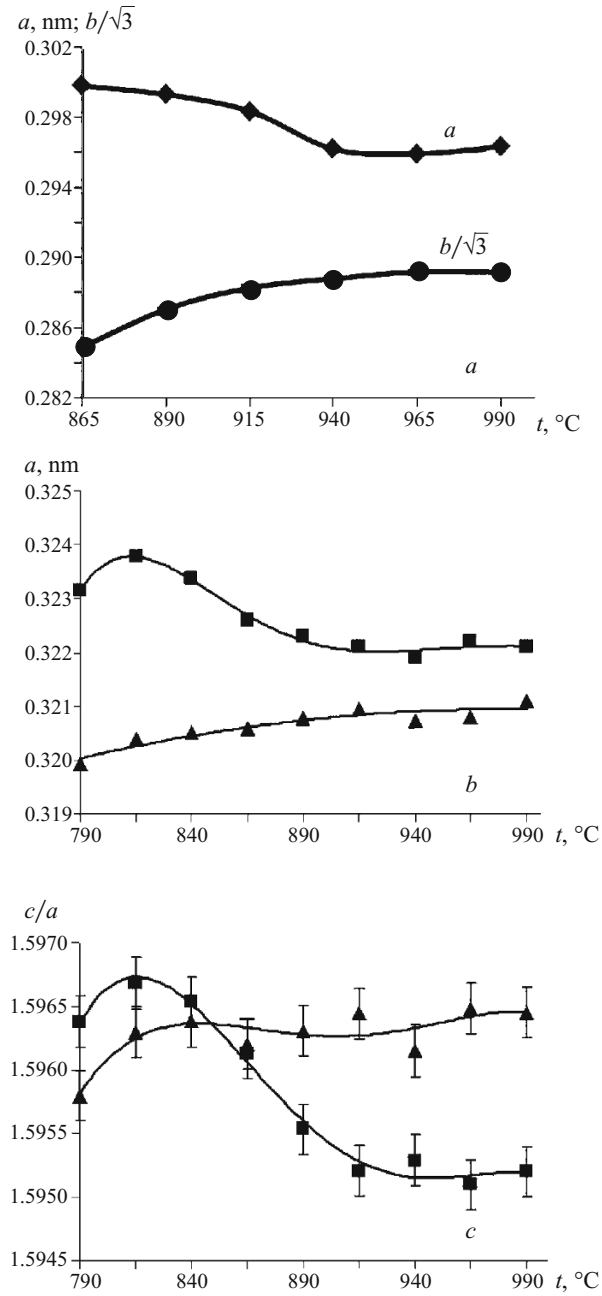

Fig. 2. Dependence of the lattice parameters of the α″-martensite (*a*), of the β-phase (*b*) and of the α-phase (*c*) on the temperatures of heating: ◆, ●) water cooling; ■) air cooling; ▲)cooling in the furnace.

We used the data of the structural and diffraction studies to plot a diagram of variation of the structure and of the phase condition of the alloy as a function of the heating tem-

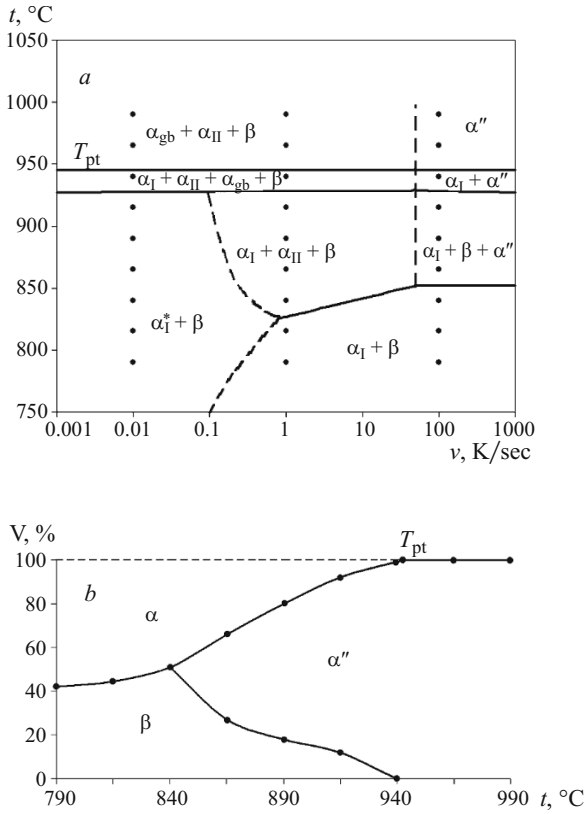

Fig. 3. Diagrams of alloy VST2: *a*) structure and phase diagram at different temperature and rate parameters of the treatment; *b*) diagram of variation of the phase composition due to water quenching.

perature and of the cooling rate and a diagram of variation of the phase composition in water quenching (Fig. 3).

It can be seen from the structure-and-phase diagram (Fig. 3*a*) that the phase composition of the alloy is represented by only α- and β-phases both in air cooling (v_{cool} ~ 1 K/sec) and in furnace cooling (v_{cool} ~ 0.01 K/sec). The type of the α-phase may differ depending on the conditions of its formation, namely, it may be an α_I-phase formed at the heating temperature; an α_I^*-phase, which may be termed conventionally a primary one being formed at the heating temperature and due to further coarsening as a result of deposition of the products of decomposition of the α-phase on it in slow cooling; an α_{II} secondary phase formed in cooling as a result of decomposition in the volumes of metastable β-solid solution; and an α_{gb} grain boundary phase formed in cooling over boundaries of β-grains. It follows from the diagram of Fig. 3*b* plotted for the water-quenched condition (v_{cool} ~ 100 K/sec) that the critical quenching temperature of the alloy, at which a martensitic $\beta \rightarrow \alpha''$ transformation is still absent, amounts to 840°C.

The dependence of the hardness, strength and ductility characteristics of the alloy on the temperature and rate conditions of the treatment is presented in Fig. 4. The hardness curves have a low minimum in the case of water quenching from 865°C, which is close to the critical temperature providing fixation of the maximum content of metastable β-phase in the structure (Fig. 3*b*). Subsequent growth of the quenching temperature to T_{pt} is accompanied by increase in the hardness, which seems to be a result of the increase in the volume fraction of α″-martensite and weakening of its rhombic morphology (Fig. 1*a*). The joint action of these two factors commonly results in growth in the hardness parameters of titanium alloys.

In air cooling the hardness is the highest after quenching from 865°C, when the β-solid solution decomposes yielding dispersed secondary α-particles (Fig. 1*d*). When the treatment temperature is increased, the hardness has a tendency to fall (by 2 – 4 *HRC*). In our opinion, this occurs due to growth in the size of the secondary precipitates.

When the specimens are cooled with the furnace, the hardness changes little, but has a tendency to decrease (by 1 – 2 *HRC*) upon growth of the heating temperature due to "coarsening" of the intragrain structure (Fig. 1*e* and *f*).

Analysis of the mechanical properties of the alloy after water quenching shows that they vary by a law typical for double-phase titanium alloys quenched for α″-martensite and considered in [8, 9]. The VST2 alloy studied in [8, 9] exhibited some growth in the rupture strength upon increase in the heating temperature to T_{pt} and decrease in the yield strength in the range of the quenching temperatures (815 – 865°C) (Fig. 4*b*), where the determined metastable β-solid solution was a mechanically unstable one and could undergo a strain-induced $\beta \rightarrow \alpha''$ martensitic transformation due to loading. M. M. Shteinberg has observed a close effect in metastable austenitic alloys [10]. The elongation decreased (from 10 to 5%) upon increase in the temperature of heating for quenching; the decrease was especially strong near and above T_{pt}, which seems to be explainable by disappearance of the primary α-phase from the structure and activation of the growth of β-grains (Fig. 1*c*).

In the case of air cooling the level of the strength properties varies through a maximum in the range of 840 – 890°C (Fig. 4*c*). This maximum corresponds to the range where, as it has been shown above, the β-solid solution starts to decompose yielding dispersed secondary α-particles (Fig. 1*d*). The level of the ductility parameters in the treatment close to and above T_{pt} is higher after air cooling than after water quenching due to the absence of martensitic component in the structure.

After cooling with the furnace the strength properties tend to decrease upon increase of the treatment temperature (Fig. 4*d*), which may be associated with coarsening of the products of the $\beta \rightarrow \alpha$ transformation (Fig. 1*e* and *f*). The elongation is quite high and remains virtually unchanged upon growth of the temperature keeping the level of 15%.

Analyzing the combination of the properties on the whole we may state that the strength (above 1000 MPa) and ductility ($\delta \geq 8\%$) characteristics of the studied sheets of al-

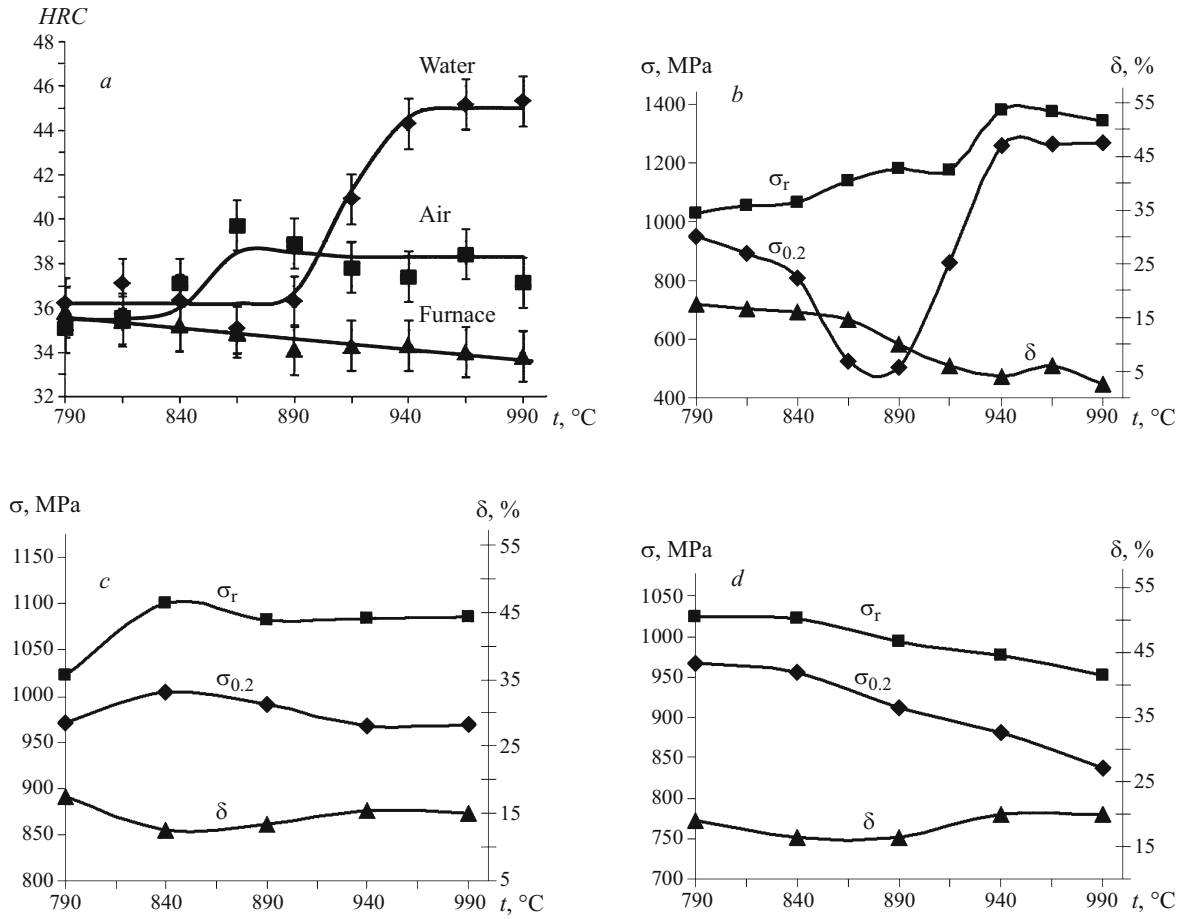

Fig. 4. Dependence of the hardness (*a*) and of the mechanical properties (*b* – *d*) of alloy VTS2 on the temperature of heating for quenching with water cooling (*b*), air cooling (*c*), and cooling in the furnace (*d*).

loy VST2 are satisfactory after air cooling from 840 – 890°C, namely, $\sigma_r \approx 1100 – 1200$ MPa, $\sigma_{0.2} \approx 1000 – 1050$ MPa, and $\delta \approx 8 – 12\%$.

CONCLUSIONS

1. After water quenching from a temperature of up to 865°C the β-metastable solid solution in the structure of titanium alloy VST2 and the α-phase are fixed; in the temperature range of 865 – 915°C we observe fixation of the α + β + α″ phases; at the temperatures exceeding 940°C the structure is represented by only α″-martensite. At quenching temperatures close to T_{pt} (940°C) and above T_{pt} (965 and 990°C) the disappearance of the primary α-phase causes development of recrystallization processes followed by growth of β-grains. Lowering of the cooling rate (air, furnace) from all the heating temperatures studied promotes fixation of a two-phase α + β condition.

2. We have plotted diagrams of variation of the structure and phase condition of the alloy at the chosen temperature and rate treatment parameters and a diagram of variation of the volume fraction of the phases during quenching.

3. We have obtained dependences of the properties of alloy VST2 on the heating temperature and on the cooling rate. The relation between the changes in the properties and the formed structural and phase condition has been determined. A balanced combination of strength and ductility parameters is formed when the alloy is cooled in air from 840 – 890°C, namely, $\sigma_r \approx 1100 – 1200$ MPa, $\sigma_{0.2} \approx 1000 – 1050$ MPa, and $\delta \approx 8 – 12\%$.

The work has been performed within Grant RFFI-Ukr_a No. 14-08-90411 and with support of the Program of Development of the UrFU.

REFERENCES

1. O. M. Ivasishin, P. E. Markovsky, Yu. V. Matviychuk, et al., "A comparative study of the mechanical properties of high-strength β-titanium alloys," *J. Alloys Comp.*, **457**(1 – 2), 296 – 309 (2008).
2. V. V. Tetyukhin, I. V. Levin, I. Yu. Puzakov, and N. Yu. Tarenkova, "A secondary titanium alloy and a method for its production, RF Patent No. 2425164," *Byull. Izobr. Polezn. Modeli*, No. 21, 1 – 12 (2011).

3. A. A. Popov, A. G. Illarionov, S. I. Stepanov, et al., "Effect of quenching temperature on the structure and properties of a titanium alloy: structure and phase composition," *Fiz. Met. Metalloved.*, **115**(5), 507 – 516 (2014).
4. A. G. Illarionov, M. S. Karabanalov, and S. I. Stepanov, "Formation of the structure, phase composition and properties under heat treatment of a biocompatible titanium alloy," *Metalloved. Term. Obrab. Met.*, No. 10, 28 – 32 (2010).
5. A. A. Il'in, B. A. Kolachev, and I. S. Pol'kin, *Titanium Alloys: Composition, Structure, Properties, A Reference Book* [in Russian], VILS – MATI, Moscow (2009), 520 p.
6. V. K. Aleksandrov, N. F. Anoshkin, A. P. Belozerov, et al., *Semiproducts from Titanium Alloys* [in Russian], VILS, Moscow (1996), 581 p.
7. *GOST 21073–75. Nonferrous Metals. Determination of Grain Size by Computation of Intersections of Grains* [in Russian].
8. A. A. Popov, A. G. Illarionov, S. I. Stepanov, and O. M. Ivasishin, "Effect of quenching temperature on the structure and properties of a titanium alloy: physicomechanical properties," *Fiz. Met. Metalloved.*, **115**(5), 517 – 522 (2014).
9. V. N. Moiseev, "Martensitic transformations in titanium alloys with metastable β-phase," *Metalloved. Term. Obrab. Met.*, No. 5, 18 – 23 (1972).
10. M. M. Shteinberg, L. G. Zhuravlev, Yu. B. Peisakhov, and O. P. Chernogorova, "Abnormal decrease in the yield strength near M_s in metastable austenitic alloys," in: *Aspects of Production and Treatment of Steel, Coll. Works* [in Russian], Chelyab. Polytekh. Inst., Chelyabinsk (1976), Issue 177, pp. 123 – 125.