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THERMOCYCLING TREATMENT OF TITANIUM ALLOYS BASED ON POLYMORPHIC TRANSFORMATION

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The structure and properties of welds of titanium alloys VT6ch and VT22 after thermocycling performed in various modes are studied. The structure of the welds is studied by the methods of metallographic and x-ray diffraction analysis. The mechanical characteristics of the welds are determined by testing them for tensile strength, impact toughness, and crack resistance.

INTRODUCTION

The polymorphic $Ti_\alpha \rightleftarrows Ti_\beta$ (hcp $\rightleftarrows$ bcc) transformation does not cause considerable volume effect in titanium in contrast to steels [1]. Therefore, heating of titanium alloys is not accompanied by primary recrystallization. However, in commercial titanium alloys volume effects and microstresses can be considerable depending on the chemical composition of the phases and on the heat treatment regimes. For example, it is shown in [2] that maximum microstresses appearing during heating in hardened alloys VT23 and VT22 amount to 320 and 430 MPa, respectively. Microstructural stresses due to thermal anisotropy are described in [3, 4] on boundaries of α-phase grains after heat cycling of titanium preforms. In addition, it is shown that the role of vacancies and other defects in the process of polymorphic $\alpha \rightleftarrows \beta$ transformation is substantial. In [5] thermocycling treatment (TT) of cast alloy VT9 with the use of rapid electric heating decreases the grain size from 2000 to 300 μm. It is noted that the process of recrystallization due to TT occurs less intensely and more uniformly than as a result of preliminary deformation and annealing, which requires strict control of the TT regime. The authors of [6] have managed to ensure grain refinement in cast and deformed alloys VT1-0, VT5, VT3-1, and VT16 by repeated rapid heating and subsequent heat treatment. However, more frequently, thermocycling of titanium alloys causes processes of cell formation and spheroidizing of phases, i.e., leads to changes in the intragrain structure of the alloys.

Our studies and analysis of published data allow us to distinguish internal and external factors [7] determining the state and the properties of titanium alloys after TT. The internal factors include differences in the specific volumes of the α- and β-phases, anisotropy of the linear expansion factors of the phases, differences in the diffusivities of the alloying elements, anisotropy of the elasticity moduli and of other properties of the phases, surface energy, amount of vacancies and dislocations, initial state (deformed, cast, annealed), etc. The external factors include the maximum heating temperature and the minimum cooling temperature, the time of the hold at these temperatures, the rates of heating and cooling, the number of heat cycles, the mode of final heat treatment, etc.

The aim of the present work consisted in studying the effect of thermocycling on the structure and properties of welds of titanium alloys VT6ch and VT22.

METHODS OF STUDY

We studied the effect of TT on the structure and properties of welds of titanium alloys VT6ch (Ti – 6% Al – 4% V) and VT22 (Ti – 5% Al – 5% Mo – 5% V – 1% Cr – 1% Fe). These were two-phase (α + β) alloys with different amounts of phases. The alloys were produced by a standard commercial process. Specimens 32 and 13 mm thick were welded by electron beam and argon-arc methods. During TT the welded specimens were heated in electric furnaces with air atmosphere. In addition, we performed local thermocycling treatment (LTT) in vacuum in the devices used for the welding (ÉLU-VM, Siaky, ÉLU-24Kh8).[2] Local heating by electron beam was applied to the weld and to the heat-affected zone, i.e., to the most dangerous zones of joints produced by elec-

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[2] The local heating by electron beam was performed by Yu. T. Lysenkov.

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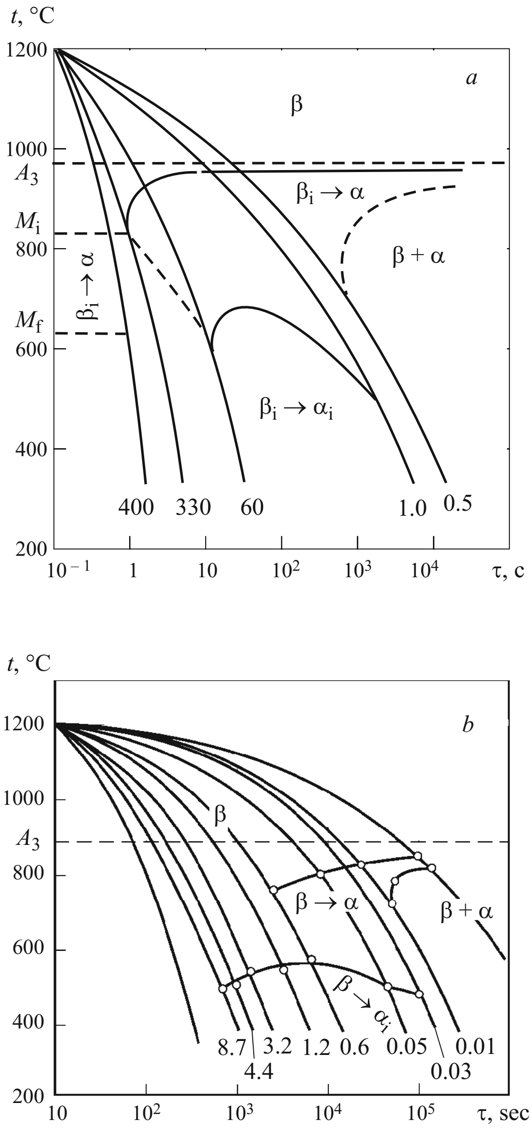

Fig. 1. Experimental diagrams of anisothermal transformations in alloys VT6ch (*a*) and VT22 (*b*). The figures at the curves present the cooling rates in K/sec.

tron-beam welding. The LTT was performed in the mode of heating of a fixed specimen by a stationary source. We used deflecting coils and a control unit to produce high-frequency oscillations of the electron beam in the longitudinal and transverse directions.

The temperature of the upper stage in TT and LTT was Ac_3 + 30°C, i.e., 1050°C for alloy VT6ch and 910°C for alloy VT22. The temperature of the lower stage was 700 and 500°C for VT6ch and 500°C for VT22. The number of heat cycles was varied from 1 to 15. In the case of furnace heating, cooling from the upper temperature stage to the lower stage was performed in air (about 1.5 K/sec) or with the furnace (0.1 K/sec). In the case of LTT, heating by electron beam was performed at a rate of 2.5 K/sec, and cooling in the temperature range Ac_3 – 500°C was conducted at a rate of

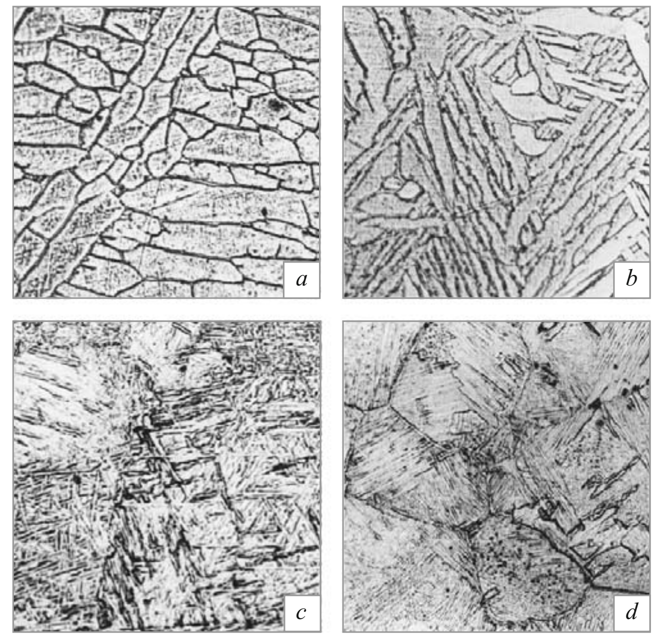

Fig. 2. Microstructure of a weld (electron-beam welding) of alloy VT6ch after different regimes of thermocycling (× 500): *a*, *b*) TT, 5 cycles, 1050 – 700°C [*a*) intermediate and final cooling with the furnace; *b*) intermediate cooling in air, final cooling with the furnace]; *c*) LTT and accelerated heating to 1100°C, 60 sec.

4 – 5 K/sec. In some cases the TT and LTT were followed by additional heat treatment.

We studied the structure and properties of different zones of welded joints with the help of metallographic (Neophot-30) and x-ray diffraction (DRON-3.0) analyses. The mechanical characteristics of the welds were determined by testing for tensile strength, impact toughness, and crack resistance.

RESULTS AND DISCUSSION

Thermocycling of alloy VT6ch with heating in the furnace was performed in the temperature ranges of 1050 – 700°C and 1050 – 500°C; the optimum number of heat cycles was 5. It follows from the diagram of anisothermal transformations (Fig. 1*a*) that a high-temperature α-phase segregates in the range of Ac_3 – 700°C both for air cooling and for cooling with the furnace. The difference in the volumes of the α- and β-phases does not cause microstresses sufficient for recrystallization but promotes the process of spheroidizing of the α-phase [8].

After TT with intermediate and final cooling with the furnace the structure contains wide (b_α ~ 10 μm) α-plates and large α-globules between which a small amount of α-phase is detectable (Fig. 2*a*). In the case of such structure the welds have the highest plasticity and reduced strength (regime *1* in Table 1).

TABLE 1. Mechanical Properties of Welded Joints (EBW) of Alloy VT6ch after TT (5 cycles) and LTT (15 cycles)

Regime of heat treatment	Weld		HAZ
	σ_r, MPa	*KCU*, MJ/m^2	*KCU*, MJ/m^2
1) TT at 1050°C (0.1 K/sec) ⇄ 700°C (0.1 K/sec)	920	0.60	0.63
2) TT at 1050°C (1.5 K/sec) ⇄ 700°C (1.5 K/sec)	1000	0.53	0.54
3) TT at 1050°C (1.5 K/sec) ⇄ 700°C (0.1 K/sec)	960	0.65	0.67
4) LTT at 950°C ⇄ 550°C + heating to 1100°C, 60 sec + aging at 550°C, 4 h	1070	0.56	0.57

Note. The rate of cooling after heating to the appropriate temperature is presented in parentheses.

The best set of mechanical properties was observed after the TT modes combining intermediate cooling in air and final cooling with the furnace. Such thermocycling promoted formation of a structure with colonies of α-plates from 130 μm (weld) to 90 μm (matrix metal) in size at a mean thickness of α-plates $b_\alpha \sim 4$ μm (Fig. 2*b*). After thermocycling in the range of 1050 – 700°C with intermediate cooling in air and final cooling with the furnace, welded joints of alloy VT6ch had the highest impact toughness both in the weld and in the heat-affected zone (regime *3* in Table 1). In this case the joints had high strength and good elasticity. It is just the formation of a structure with colonies of α-plates over the boundaries of which a crack branches under impact loads, which ensures high impact toughness and crack resistance of welded joints.

Welds of alloy VT6ch were subjected to LTT with heating by electron beam in temperature ranges of 1050 – 550°C and 950 – 550°C. In accordance with the diagram of anisothermal transformations for alloy VT6ch (Fig. 1*a*), cooling at a rate exceeding 4 K/sec is accompanied by segregation of high- and low-temperature α-phase. This ensures more considerable phase hardening as compared to the studied modes of TT with furnace treatment. Indeed, LTT in the range of 950 – 550°C for 15 cycles ensured formation of a substructure with fine colonies of α-plates in the weld and in the heat-affected zone (Fig. 2*c*).

Specimens of welded joints of alloy VT6ch after LTT were subjected to accelerated heating (in the same device) to 1100°C, to a short-term hold at this temperature (60 sec), and then to cooling. The short-term heating caused recrystallization of the β-phase (Fig. 2*d*), which resulted in refinement of β-grains in the weld, i.e., its mean size decreased by about a factor of 7 with respect to the initial value (after welding). An electron microscope study showed that in the process of LTT conducted at 950 – 550°C (without transition to the β-region) the formed dislocation pattern was the most complex. Under these treatment conditions considerable phase stresses arose due to anisotropy of the thermal expansion factors of the α- and β-phases, difference in the physical properties of the phases, and difference in the specific volumes of the β-phase and the high-temperature and low-temperature α-phases. In the stage of final heating in the β-region (1100°C, 60 sec) the defects of the structure of the α-phase were inherited by the β-phase, which promoted formation of recrystallization centers and growth of crystals from these centers. In order to remove the stresses and stabilize the structure, specimens of alloy VT6ch were subjected to aging by a standard regime (550°C, 4 h). After such heat treatment, welded joints of alloy VT6ch had elevated strength and good values of impact toughness (regime *4* in Table 1).

After LTT in the range of 1050 – 550°C and subsequent heat treatment, recrystallization of β-phase did not occur, but a thin-plate structure formed inside large grains of transformed β-phase. The absence of recrystallization of β-phase after LTT and the transition to the β-region was caused by some redistribution of defects of crystal structure and partial relaxation of phase stresses.

Thermocycling treatment of welded joints of alloy VT22 was performed with heating in the furnace in the range of 920 – 500°C. The optimum number of cycles was 5 [9]. At a rate of intermediate and final cooling equal to 1.5 K/sec a low-temperature α-phase segregated in grains of β-phase over boundaries and inside subgrains (Fig. 3*a*). These subgrains formed as a result of formation of cells during TT. The mechanical properties of alloy VT22 with such structure turned out to be unsatisfactory ($\sigma_r \le 900$ MPa, $KCU \le 0.1$ MJ/m^2) due to the presence of nonequilibrium α- and β-phases. For this reason the welds of alloy VT22 after TT were subjected go additional heat treatment. The best properties were obtained after TT in the range of 920 – 500°C and subsequent heat treatment including heating at 840°C for 3 h, cooling with the furnace to 750°C, holding for 2 h, cooling in air to room temperature, and aging at 600°C for 4 h. As a result of heating at 840°C for 3 h the structure with cells underwent recrystallization. Quite coarse α-globules and α-plates ($b_\alpha \sim 2.5$ μm) with a minimum content of defects and thinner α-plates ($b_\alpha \le 1$ μm) with elevated density of atomic and crystal structure defects segregated in the recrystallized β-grains ($D_\beta \sim 60 – 80$ μm) (Fig. 3*b*). The values of the impact toughness of the matrix metal and of the heat-affected zone became almost equal ($KCU \sim 0.58$ MJ/m^2) and the strength of the matrix metal was preserved at a quite high level.

TABLE 2. Mechanical Properties of Welded Joints (EBW) of Alloy VT22 after LTT and Heat Treatment

Regimes of heat treatment	Weld		HAZ
	σ_r, MPa	*KCU*, MJ/m^2	*KCU*, MJ/m^2
LTT at 920 ⇄ 500°C, 5 cycles + stage cooling in the mode: 820°C, 0.15 h → 750°C, 0.15 h → 630°C, 0.3 h	1070	0.58	0.59
LTT at 920 ⇄ 500°C, 15 cycles + annealing in the furnace at 810°C, 3 h	1150	0.46	0.48

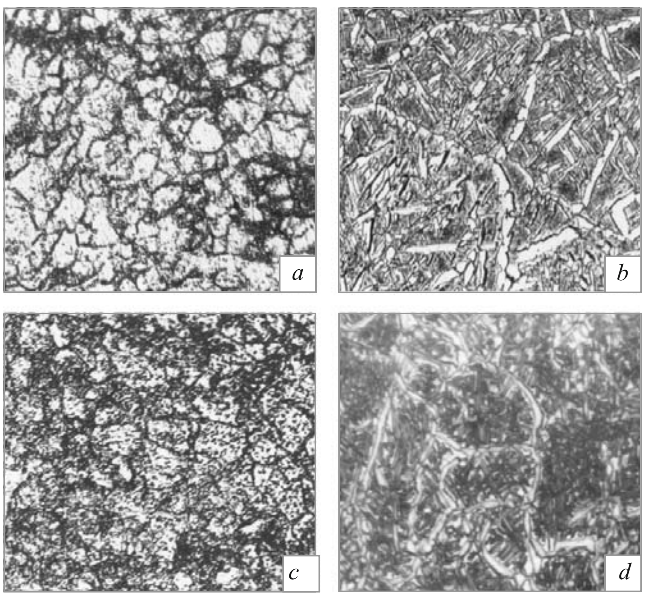

Fig. 3. Microstructure of a weld (electron-beam welding) of alloy VT22 after different regimes of treatment (× 500): *a*) TT, 5 cycles, 920 – 500°C (furnace heating), intermediate and final cooling in air; *b*) the same as (*a*) plus heat treatment in the mode 840°C, 3 h, cooling with the furnace to 700°C, 2 h, cooling in air, and aging at 400°C, 4 h; *c*) LTT, 15 cycles, 920 – 500°C; *d*) the same as (*c*) plus annealing in the furnace at 800°C.

Welded joints (EBW) of alloy VT22 were subjected to LTT with heating by electron beam at a rate of 2.5 K/sec in the temperature range of 920 – 500°C for 5 cycles; cooling occurred due to heat removal into cold regions of the metal (about 5 K/sec). At such rates of heating and cooling, alloy VT22 underwent only inconsiderable polymorphic β ⇄ α transformation, which did not cause a volume effect sufficient for development of recrystallization [10, 11].

In the last cycle we used stage cooling with short holds, i.e., 820°C, 0.15 h → 750°C, 0.15 h → 630°C, 0.3 h, then in air. This treatment resulted in decomposition of the β-phase and segregation of an α-phase, which ensured strength properties at the level of annealed alloy (σ_r = 1070 MPa); the impact toughness of the weld and of the heat-affected zone increased (Table 2).

We also performed LTT of alloy VT22 for 15 cycles with intermediate and final cooling at a rate of 5 and 10 K/sec (due to additional copper faceplates). The structure of the alloy after this treatment is presented in Fig. 3*c*. With allowance for the diagram of anisothermal transformations (Fig. 1*b*), alloy VT22 after cooling at a rate of 10 K/sec contains only a β-metastable phase; after cooling at a rate of 5 K/sec a low-temperature α-phase segregated from the β-phase. Thermocycling for 15 cycles with cooling rate of 5 K/sec and subsequent annealing at 810°C for 3 h caused recrystallization of the β-phase (Fig. 3*d*) in the weld and in the heat-affected zone; the size of the β-grains decreased by a factor of 6. However, it should be noted that LTT (15 cycles) and subsequent heat treatment caused nonuniform occurrence of the recrystallization process.

Thermocycling based on segregation and dissolution of low-temperature α-phase causes considerable volume effects. When combined with thermal stresses this gives rise to phase hardening responsible for recrystallization. Thermocycling with cooling rate of 10 K/sec causes only the appearance of thermal stresses, which are insufficient for recrystallization. This ensures good strength processes of the weld and close values of the impact toughness of the weld and of the heat-affected zone.

CONCLUSIONS

1. Thermocycling treatment (TT) with furnace heating causes spheroidizing of the α-phase and changes the intragrain structure of welded joints of alloy VT6ch from a lamellar one to an almost globular one.

2. TT with furnace heating in the range of 920 – 500°C (intermediate and final cooling in air) and subsequent heat treatment (840°C, 3 h) of welded joints of alloy VT22 promote refinement of grains of the β-phase due to the occurrence of primary recrystallization.

3. Local thermocycling treatment (LTT) with heating by electron beam in an optimum mode for 15 cycles and subsequent heat treatment cause recrystallization of the β-phase in welded joints of alloys VT6ch and VT22, but the recrystallization occurs nonuniformly.

REFERENCES

1. V. D. Sadovskii, G. N. Bogacheva, L. V. Smirnov, et al., “A study of phase recrystallization in titanium,” *Fiz. Met. Metalloved.*, **10**(3), 397 (1969).

2. A. A. Il'in, M. Yu. Kolerov, and V. M. Maistrov, "Volume changes in titanium alloys due to polymorphic transformation," *Metalloved. Term. Obrab. Met.*, No. 1, 5 – 56 (1986).
3. M. A. Skotnikova, "Nature of decomposition of vacancy-supersaturated bcc titanium crystals," in: *Structural Fundamentals of Modification of Materials by Nontraditional Technologies* [in Russian], OIAÉ, Obninsk (1977).
4. M. A. Skotnikova, "Microstructural stresses due to thermal anisotropy in titanium alloys," *Instrument*, No. 5, 26 (1996).
5. L. A. Elagina, A. I. Gordienko, M. Ya. Brun, and V. V. Ivashko, "Possibilities of the use of rapid heating for raising mechanical properties of titanium alloys," *Metalloved. Term. Obrab. Met.*, No. 1, 32 – 36 (1984).
6. V. P. Anufriev and Yu. G. Veksler, "Thermocycling treatment of articles from titanium alloys," in: *Thermocycling Treatment of Metallic Materials* [in Russian], Leningrad (1980).
7. V. S. Lyasotskaya, N. Yu. Ravdonikas, and I. A. Lebedev, "Special features of thermocycling of titanium alloys," *Metalloved. Term. Obrab. Met.*, No. 1, 41 – 45 (1985).
8. V. S. Lyasotskaya, Yu. T. Lysenkov, and E. K. Feoktistova, "Thermocycling treatment of welds from alloy VT6ch," *Tekhnol. Legk. Splavov*, No. 1, 18 – 8 (1989).
9. V. S. Lyasotskaya, I. V. Lyasotskii, E. K. Feoktistova, and N. V. Maleeva, "Structure and properties of alloy VT22 after thermocycling and annealing," *Metalloved. Term. Obrab. Met.*, No. 11, 54 – 55 (1983).
10. V. S. Lyasotskaya and S. I. Knyazeva, "Polymorphic transformation: a base for thermocycling treatment of titanium alloys," *Metalloved. Term. Obrab. Met.*, No. 4, 20 – 3 (2000).
11. V. S. Lyasotskaya, *Heat Treatment of Welded Joints of Titanium Alloys* [in Russian], Ékomet, Moscow (2003).