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EFFECT OF THERMAL CYCLE OF TIG WELDING ON STRUCTURE AND PROPERTIES OF PSEUDO-β-TITANIUM ALLOYS

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The structural pseudo-β-titanium alloys have found a wide application in aircraft and rocket construction. However, while producing welded joints of pseudo-β-alloys applying method of fusion welding, the difficulties arise connected with change in the structure and formation of metastable phases in welded joint. In this paper, using the developed mathematical model of TIG process, the influence of welding thermal cycle on the weld shape, cooling rate and structure of welded joint metal of the pseudo-β-titanium alloy VT19 was investigated. Amount of phases in the weld metal, heat-affected zone and base metal was determined, phase composition and its effect on the mechanical properties of welded joints were predicted. 8 Ref., 4 Tables, 11 Figures.

Keywords: *TIG welding, high-strength titanium alloys, mathematical modeling*

Structural pseudo-β-titanium alloys have found wide application in products of aircraft and rocket construction. The alloys of this class can be efficiently hardened by heat treatment, consisting of hardening and aging and having 10–20 % higher strength than α-alloys. However, production of welded joints of pseudo-β-titanium alloys using fusion welding provokes difficulties caused by change of structure and formation of metastable phases in welded joint [1–3].

Selection of methods, modes and technology of fusion welding of titanium β-alloys depends on type of welded structure, its designation, operation conditions and nature of heat treatment before and after welding. The main criterion for selection of modes and technology of welding is the optimum interval of cooling rates in welding. It should be considered that quality of welded joints depends on structure and properties of a near-weld zone, which are determined by welding thermal cycle. Therefore, it is reasonable to compare various modes of TIG welding on their heat effect on the weld and near-weld zone [4, 5].

Aim of the present paper is an analytical investigation of thermal conditions in a welding zone using mathematical modeling method for TIG welding, determination of dependence of structure of welded joint areas and its mechanical properties on welding modes.

Work procedure. Investigation of effect of thermal cycle of TIG welding on structural transformations was carried out using the method of mathematical modeling of thermal processes in welding of pseudo-β-titanium alloy VT19. The base of the method is a heat-balance equation. A 3D mathematical model of thermal processes in titanium during welding with scanning heat source was built for calculation determination of effect of welding mode parameters on weld formation using the finite element method. It is based on differential equation of heat conductivity and states boundary conditions describing heat exchange of product with environment.

Received temperature field was used for determination of such thermal parameters as distribution of maximum temperatures and cooling rate in welded joint section.

Used finite element 3D model of welding thermal processes was proposed in work [6]. The calculation thermal fields in the deposited product were received taking into account given above initial and boundary conditions. Based on the calculation results the isothermal curves of maximum temperatures were plot-

Table 1. Welding modes, which were subjected to mathematical modeling

Number of mode	Welding current, A	Arc voltage, V	Welding rate, m/h	Penetration depth, mm
1	240	12	10	3.8
2	310	12	10	6.0
3	320	12	16	1.9
4	620	12	16	6.0

ted. They were used for determination of geometry and size of penetration zone, HAZ, zone of polymorphous transformation.

Effect of thermal cycle in TIG welding of VT19 alloy on cooling rates in welded joint. 4 modes of TIG welding with different rate and heat input were investigated (Table 1).

Figure 1 shows an example of calculation distribution of the maximum temperatures and microsection of received experimental welded joint, produced at mode No.2 (see Table 1). This joint was used for mathematical modeling of thermal processes of TIG welding of pseudo-β-titanium alloy VT19. The difference in width of deposited bead in calculation and experimental sample made 3.1 %, width of back bead 2.4 %. Such small values of error between calculation and experimental data prove the adequacy of the developed mathematical model.

Calculation results of mathematical modeling allowed determining the effect of heat input and welding rate on penetration depth, weld shape and distribution of the maximum temperatures in the welded joint section (Figure 2).

In order to determine the effect of thermal welding cycle on cooling rate and structure of welded joint metal the modes were selected, at which complete penetration of weld metal (No.2 and No.4) with lower and higher value of heat input are provided. For this modes the cooling rates in temperature range from 1600 to 100 °C were calculated. The analysis of received calculation data showed that in cooling from

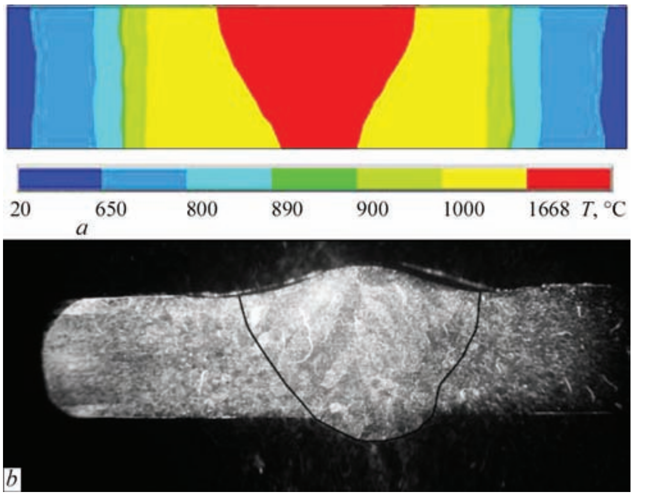

Figure 1. Result of calculation of penetration zone of base metal and HAZ shape, heat source: I = 310 A, U = 11 V, η = 0.43, v = = 10 m/h (*a*); microsection of TIG joint (I_w = 310 A, U_a = 11 V, v_w = 10 m/h) (*b*)

1667 to 890 °C the highest cooling rates are noted in the weld metal. In cooling from 1200 °C the cooling rate in the middle of weld at mode with lower welding rate reaches values of 228 °C (Figure 3, *a*) and the cooling rate in the fusion zone achieves 130 °C/s.

Increase of cooling rate and current does not result in noticeable changes in cooling rates in these ranges of temperatures and the maximum value of cooling rates is even somewhat lower, namely 217 °C/s.

When reaching the temperature interval of 1000–900 °C the maximum cooling rate in the weld center on the surface makes 177 °C/s, weld metal cools with

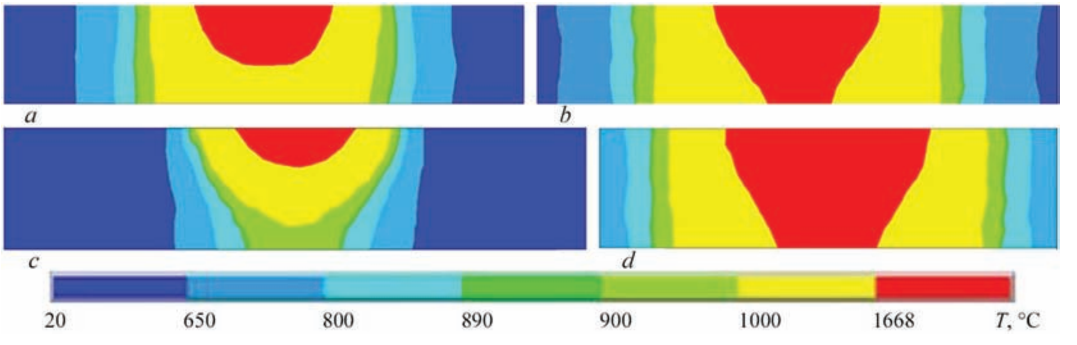

Figure 2. Effect of heat input and welding rate on penetration of titanium alloy VT19: *a* — mode No.1; *b* — 2; *c* — 3; *d* — 4

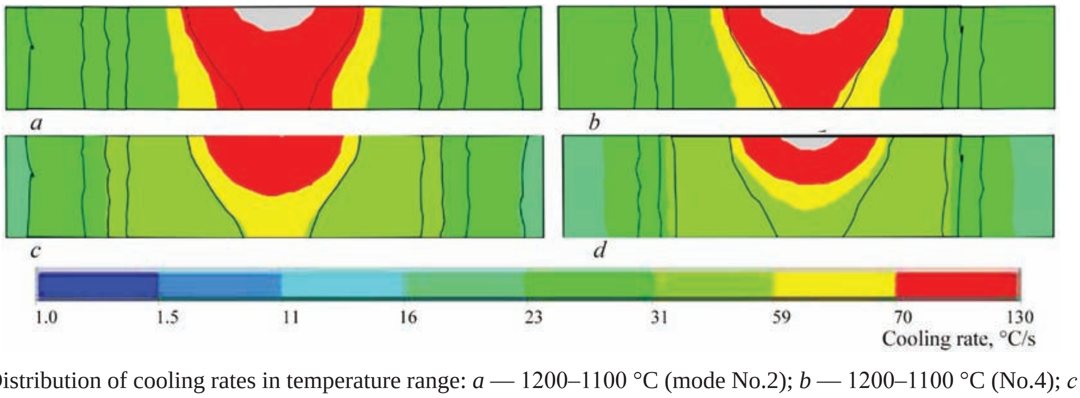

Figure 3. Distribution of cooling rates in temperature range: *a* — 1200–1100 °C (mode No.2); *b* — 1200–1100 °C (No.4); *c* — 1000–900 °C (No.2); *d* — 1000–900°C (No.4)

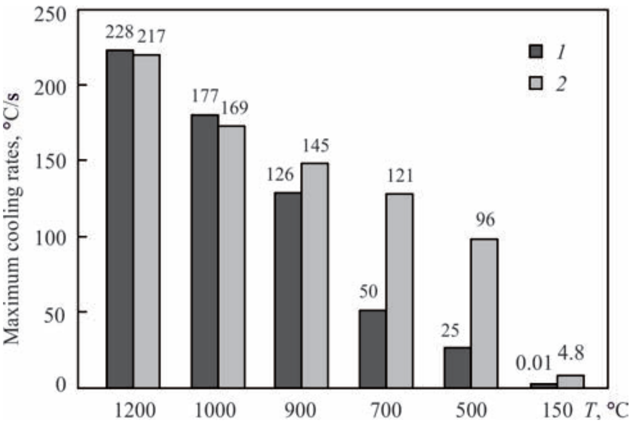

Figure 4. Values of maximum cooling rates at different temperatures: *1* — 310 A, 10 m/h; *2* — 620 A, 16 m/h

130–70 °C/s rate, and in HAZ the cooling rates lie in the limits from 59 to 23 °C/s (Figure 3, *c*). The cooling rates at mode with higher heat input has similar values, i.e. the maximum rate makes 169 °C/s, but area of the sample, in which such values are registered, is significantly larger (Figure 3, *d*). At that the cooling rate from the back side of the weld is smaller than in the sample at mode with lower welding rate.

In the temperature interval 900-800 °C the cooling rate of weld metal in the center on the area of 6.5 mm width and at 2.5 mm depth is still makes 130–70 °C/s. In the rest part of weld metal and HAZ the cooling rates becomes even and make 31–23 °C/s. In the sample welded with higher welding rate, the maximum cooling rates drop to 145 °C/s and area, at which cooling rates of 130–70 °C/s are registered, is more than in the sample with lower cooling rate. When reaching the temperature range corresponding to temperature of polymorphous transformation of alloy VT19, 800–700 °C (T_m = 780 °C) [7], the cooling rates reduce and in the fusion zone they are in the limits from 59-23 °C/s, and the maximum cooling rate 11 °C/s is registered in HAZ. At that, following the diagram, $\beta \rightarrow \alpha$ transformations are started to be registered in the HAZ areas distant from the weld center. In the sample with higher heat input the cooling rates high for such a temperature range are still observed , namely in the weld center they make 70–120 °C/s, in HAZ reach 59 °C/s. The cooling rate in the weld center of sample produced at mode with 10 m/h welding rate reach 16°C/s and that for HAZ is 11 °C/s in a temperature range 600–500 °C/s. The cooling rate values make less than 0.01 °C/s in the weld and HAZ of the sample produced at mode No.2 in temperature range

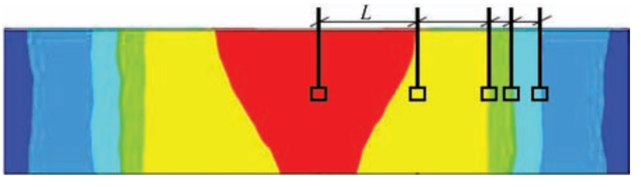

Figure 5. Scheme of determination of size of areas with maximum temperatures in welded joint (*L* — length of area)

200–100 °C/s. The cooling rates of 4.8 °C/s are registered in the weld of sample produced at mode with higher heat input in temperature range 50–150 °C.

Received results of the cooling rates allow concluding that the highest cooling rates at high temperatures (1000 °C and more) are registered at mode with low heat input. At temperature decrease (less than 1000 °C) the maximum rates of cooling are registered in the welded joint produced with higher heat input. At that a pace of change of cooling rates at this mode is also bigger (Figure 4).

Effect of TIG welding thermal cycle on amount of β-phase in the joints of pseudo-β-titanium alloys. Amount of forming β-phase in the weld and HAZ was determined for prediction of phase composition. For this modes Nos 2 and 4 were used in welding of experimental sample of pseudo-β-titanium alloy VT19 [8]. Cross-microsections of produced welded joint were used for determination of structure and amount of β-phase in different areas, for which the cooling rates in different temperature ranges (Figure 5) were received using the mathematical modeling.

Amount of β-phase was determined by computer processing of received microsections of the welded joint. Determination of microstructure is based on the fact that various phases has distinct etching and colouring. Thus, β-phase has light colour and α, α′, α′′are dark. As a result shape and size of separate grains can be determined and amount, shape and direction of grains, separate phases and structural constituents, change of internal structure of metals and alloys depending on conditions of their manufacture and treatment are stated.

The structure was examined in the middle of sample of 6 mm thickness. Distance *L* (see Figure 5) is the distance from the middle of weld to examined point on cross-microsection of welded joint.

The base metal of VT19 alloy of 6 mm thickness, at which TIG welding was carried out, has a grain diameter of 0.05–0.50 mm (Figure 6, *a*). In some grains of subsurface zone of BM there is nonuniform distribution of α-phase particles in grain (Figure 6, *b*). Disperse α-phase, size of α-phase particles makes 1–2 μm and less, is present in the base metal in large amount. Amount of β-phase in the base metal makes 31 %.

Weld metal of joint, produced by TIG welding at mode No.2 (see Table 1), consists of equiaxial and elongated in a direction of heat removal β-phase grains, hairlike boundaries of which appear at the background of dendrite structure (Figure 7, *a*). Amount of β-phase in this area makes 74 %.

Weld metal and HAZ of the joint, produced by TIG welding at mode No.4 (see Table 1) differing by parameters and configuration of zones, direction of crystallites growth, have microstructure, consisting of β-phase grains, identical to the joint performed by TIG welding at mode No.2 (Figure 7, *b*).

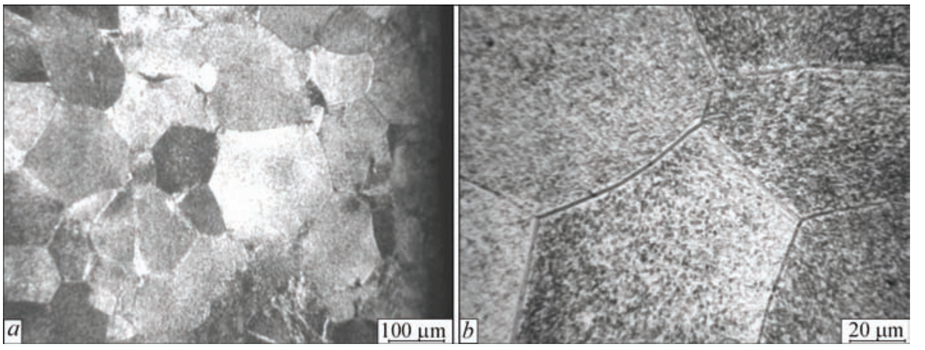

Figure 6. Microstructure of subsurface layer of base metal VT19

A fusion zone (Figure 8, *a*) is located at 5.4 mm distance from a weld axis. Weld grains at the background of dendrite structure are to the right on the photo and equiaxial β-grains of HAZ area close to the fusion zone are on the left. Amount of β-phase in this area makes 81 %. Partially fused grains belonging simultaneously to HAZ metal as well as base metal can be seen directly in the fusion zone.

HAZ area, where complete polymorphous transformation took place during welding, consists of equiaxial β-grains (Figure 8, *b*), has 4.75 mm width. Here amount of β-phase is on the level of 80 %.

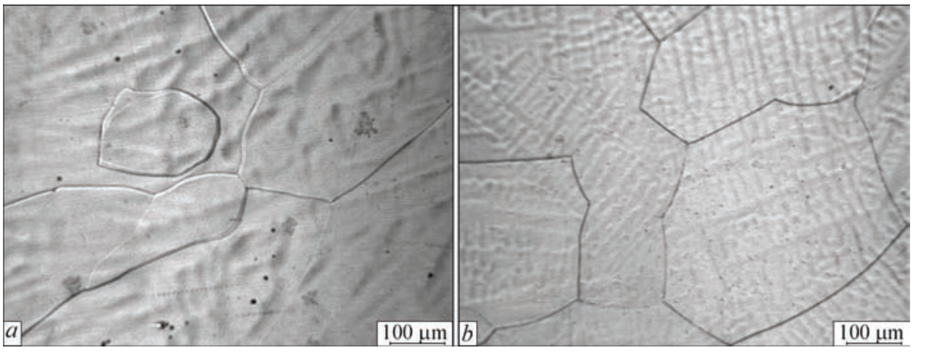

Figure 7. Microstructure of welded joint metal from pseudo-β-titanium alloy VT19, produced by TIG welding: *a* — mode No.2; *b* — No.4

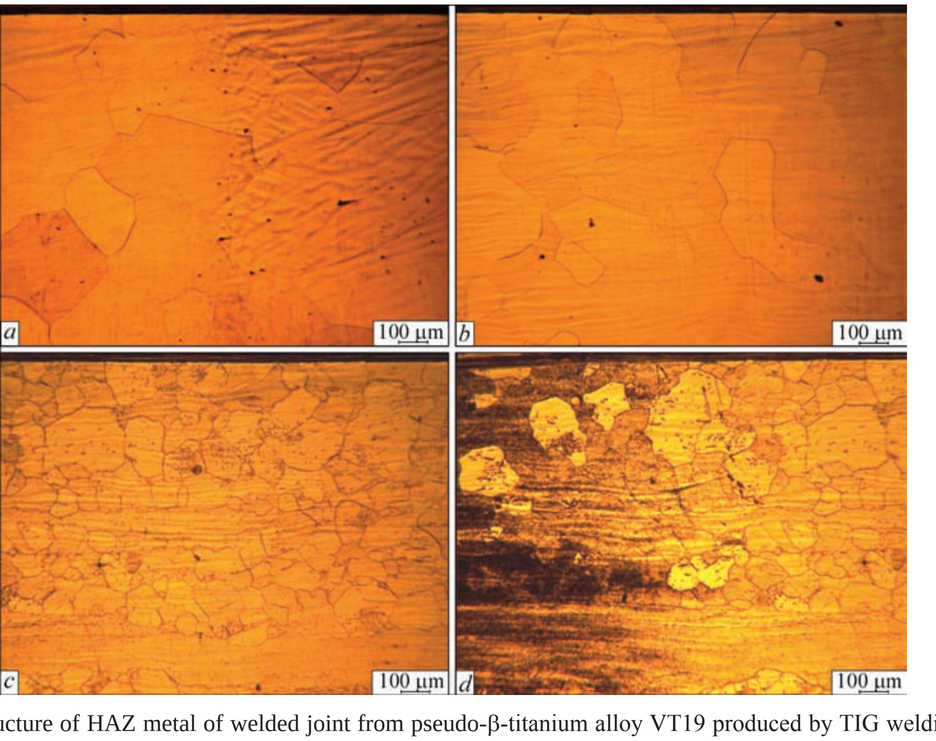

Figure 8. Microstructure of HAZ metal of welded joint from pseudo-β-titanium alloy VT19 produced by TIG welding without filler wire, mode No.1: *a* — fusion zone; *b* — area of complete polymorphous transformation; *c* — zone of incomplete polymorphous transformation; *d* — boundary between the zone of incomplete polymorphous transformation and base metal

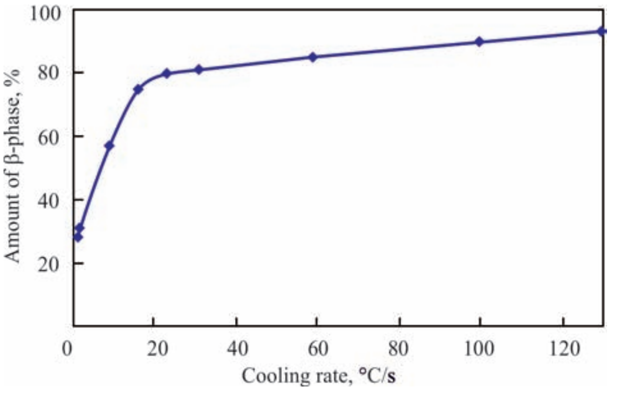

Figure 9. Dependence of amount of β-phase in metal of welded joint from pseudo-β-titanium alloy VT19 on maximum cooling rates at temperature of end of polymorphous transformation (800 °C)

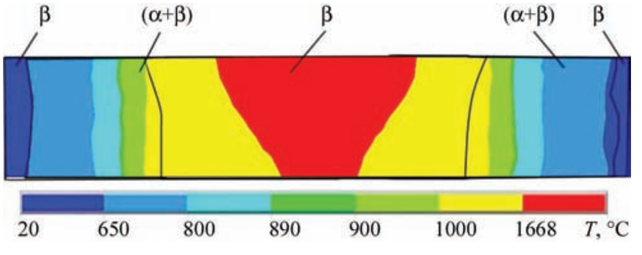

Figure 10. Distribution of phases in section of welded joint produced at the following mode: I = 310 A, v_w = 10 m/h

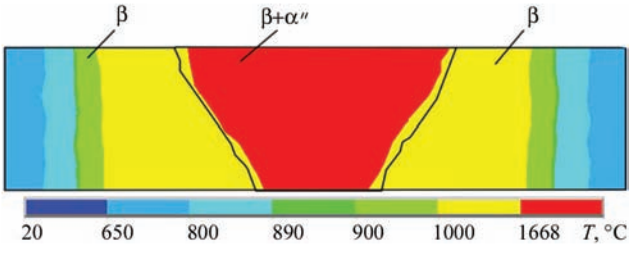

Figure 11. Result of calculation of penetration zone in welding (I = 620 A, v_w = 16 m/h)

HAZ area, where incomplete polymorphous transformation is observed, has 2.5 mm width (Figure 8, *c*). Here in β-grains there are the particles of other phases, which can be found in the base metal, in particular, α-phase. Amount of β-phase is 75 %.

Figure 8, *d* shows transfer from the area of incomplete polymorphous HAZ transformation to the base metal. Amount of β-phase makes 57 % at the boundary of transfer from the area of incomplete polymorphous transformation to the base metal. In the base metal amount of β-phase makes 31 %.

Obtained using mathematical modeling the calculation maximum cooling rates at temperatures of start of β→α polymorphous transformation (810 °C) were compared with the experimentally received data on content of β-phase in the considered areas of welded joint, made at mode No.1 (I_w = 310 A, v_w = 10 m/h) for the points at distance L from the weld center (Table 2).

Based on compared data a dependence of amount of β-phase on maximum cooling rate at temperature of start β→α polymorphous transformation (810 °C) in alloy VT19 was obtained (Figure 9).

Also, a distribution of phases in the cross-section of welded joint produced at mode No.2 (Figure 10) and No.4 (Figure 11) (see Table 1) was obtained comparing the received calculation data of shape of weld metal, HAZ and base metal, cooling rates, and experimental data of amount of β-phase in different areas of the welded joint.

As can be seen from obtained results, β-phase is mainly formed after welding at mode No.2 in the middle of weld. Metastable α′ and α′′-phases are absent in the welded joint. According to quantitative calculation of phase distribution in the welded joint section, an area of β-phase makes 78 mm², and α-phase is 58 mm² (Table 3).

In welding at mode No.4 β- and metastable α′′-phase (Figure 11) are observed in the weld center. β-phase prevails in HAZ and base metal. It is provoked by high gradient of cooling rates in different temperature ranges. Area of β-phase in welded joint section makes 113 mm². Area of metastable α′′-phase is 23 mm² (Table 3).

Effect of TIG welding thermal cycle on mechanical properties of welded joints from pseudo-β-titanium alloy VT19. Mechanical tests of base metal and welded joints from pseudo-β-titanium alloy VT19, produced at modes Nos 2 and 4, were carried out. Analysis of mechanical properties shows reduction of strength indices and impact toughness in the welded joint in comparison with the base metal (Table 4). It is explained

Table 2. Amount of β-phase and maximum values of cooling rates in different areas of welded joint

Parameter	Weld center	Fusion zone	Area of complete polymorphous transformation	Area of incomplete polymorphous transformation	Boundary between zone of incomplete polymorphous transformation and base metal	Base metal
Distance from weld middle L, mm	0	5.43	7.8	14.5	15.8	17
Amount of β-phase, %	74	81	80	75	57	31
Maximum cooling rates at T = 800 °C/s	59	31	23	16	9	1.5
Maximum cooling rates at T = 500 °C/s	16	11	11	1.5	1.5	1.5

Table 3. Area of precipitation of metastable phases in TIG welding of pseudo-β-titanium alloy VT19

Mode number	Mode parameters			Area of phase precipitation, mm^2		
	Welding current, A	Welding rate, m/h	Heat input, kJ/cm	β	α	α″
2	310	10	803	78	58	–
4	620	16	1004	113	–	23

Table 4. Amount of β-phase and mechanical properties of base metal and welded joint of pseudo-β-titanium alloy VT19

Area of examination, mode number	Amount of β-phase, %	Tensile strength σ_t, MPa	Yield limit σ_y, MPa	Relative elongation, δ_s, MPa	Reduction of area ψ, %	Impact toughness *KVC*, J/cm^2
BM	56	887	958	12	42	22
Weld, mode No.2	74	860	839	13,3	60	19
Weld, mode No.4	98	836	801	12	50	15

by high content of β-phase in the weld metal of welded joint. Metastable β-phase has low strength and high ductility, therefore, welded joints have low strength indices. Strength and impact toughness of the welded joint produced at mode No.4 have lower indices in comparison with the welded joint of mode No.2. It allows making a conclusion that increase of heat input and welding rate (Table 3) has negative effect on strength and impact toughness of the welded joints from pseudo-β-titanium alloy VT19, and only promotes increase of content of β-phase in the weld metal due to increase of weld metal cooling rates with sample cooling.

Thus, TIG-welded joints of titanium alloy VT19 are reasonable to be produced at modes with lower heat input and welding rate.

Conclusions

1. A 3D mathematical model was built for investigation of thermal processes of TIG welding of pseudo-β-titanium alloys using finite element method. It allowed getting thermal fields in the deposited product, determining distribution of the maximum temperatures and cooling rates in section of welded joints at different heat input.

2. It is determined that the highest cooling rates at high temperatures (1000 °C and more) were registered at mode with low heat input. At temperature decrease (less than 1000 °C) the maximum cooling rates are registered in the welded joint produced with higher heat input. At that, pace of variation of cooling rates at this mode is also large.

3. High cooling rates in a temperature range of start and end of polymorphous transformation determine content of β-phase in the weld metal of welded joint produced at mode No.2 at 90 % level. Reduction of cooling rates results in decrease of amount of β-phase in the weld metal and heat-affected zone.

4. Received dependence of amount of β-phase on cooling rates allows making a conclusion that the most intensive decay of β-phase takes place at the boundary of heat-affected zone and base metal that can lead to formation of metastable phases in this zone of the welded joint and deterioration of joint mechanical properties.

5. Mechanical properties of the welded joint produced at mode No.2 are lower than the similar indices for the base metal. It is explained by high content of β-phase in weld metal of the welded joint. Metastable β-phase has low strength, therefore, welded joints have low strength indices. The welded joint made on mode No.4 has lower mechanical properties in comparison with the base metal and joint of mode No.2 that is explained by increase of content of β-phase in the weld metal due to rise of metal cooling rates with sample cooling down.

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