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HIGH TEMPERATURE TITANIUM ALLOY TIG WELDING USING ACTIVATING FLUXES

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ABSTRACT

High temperature titanium alloys are materials that can withstand high temperatures and maintain their mechanical properties under extreme heat load. The use of high temperature titanium alloys helps to increase the efficiency of engines and reduce the weight of structures, which in turn leads to reduced fuel consumption and increased overall equipment productivity. Welding of high temperature titanium alloys is complicated due to the presence of such impurities as aluminum, vanadium, molybdenum and other elements in their composition that increase their high temperature properties. Silicon is one of the elements that effectively increase the high temperature properties of titanium alloys. However, a significant defect of alloys with silicon is cold cracks in the welds, which occur at temperatures below 700 °C, when the material passes from a ductile to a brittle state. The brittleness of the weld in as-welded state, in turn, is determined by its structure and, with an increase in welding stresses during the cooling, it leads to the appearance of defects such as cold cracks, the source of which are microcracks, dislocations, etc. In this work, a study was conducted of the influence of the additional technological operations, such as flux welding and preheating before welding, on the structure and mechanical properties of welded joints of a high temperature titanium alloy of the Ti–6.5Al–5.3Zr–2.2Sn–0.6Mo–0.5Nb–0.75Si system.

KEYWORDS: high temperature titanium alloy, TIG welding, preheating, welding with fluxes

INTRODUCTION

High temperature titanium alloys are materials capable of withstanding high temperatures and preserving their mechanical properties under extreme heat load. These alloys have high strength, corrosion resistance and low density, making them ideal for application in the aerospace and automotive industry, as well as in the energy sector [1, 2].

Application of high temperature titanium alloys promotes an increase in the efficiency of engine operation and reduction in structure weight that, in its turn, leads to reduction in fuel consumption and increase in the overall productivity of the equipment. Despite their high cost and complex treatment, the advantages, which they offer, justify their application in critically important components, where the reliability and durability are the key factors [3].

Titanium alloys usually have impurities of aluminium, vanadium, molybdenum and other elements, which enhance their heat-resistance properties. They are used in production of the components of turbines, aircraft engines, car parts and in many other high-tech industries. Silicon (Si) is one of the elements, effectively enhancing the heat-resistance properties of the titanium alloys [4]. Silicon addition to the alloy promotes a strengthening of the material structure and increase of its stability at temperature gradients. This is achieved due to silicon forming solid solutions and dispersed particles in the titanium matrix, which prevents the movement of dislocations and reduces the deformation rate [5].

When producing the welded joints of the high temperature titanium alloys, containing silicon as the alloying element, their significant defect is cold cracks in the welds, initiating at temperatures below 700 °C, when the material goes from the ductile into the brittle state [6]. Brittleness of the weld in as-welded state, in its turn, is determined by its structure and at increase of the welding stresses during cooling it leads to initiation of defects of the type of cold cracks, the source of which are microcracks, dislocations, etc. Therefore, welding of such alloys requires application of additional technological operations such as local heat treatment and preheating [7, 8].

More over, these titanium alloys, compared to the conventional alloys, are more sensitive to such interstitial impurities as oxygen, nitrogen and carbon. Owing to the fact that silicon in the high temperature alloys is no longer an impurity, but an alloying element, increased silicon content may lead to development of chemical and physical heterogeneity in the cast metal and the HAZ, which may result in formation of brittle interlayers. The interstitial impurities lower the ductility and impact toughness of the weld metal, increase the brittle fracture susceptibility, and sensitivity to stress raisers. More over, in the high temperature alloys oxygen, nitrogen and carbon lower the thermal stability, which is associated with the fact that the above elements accelerate the processes of

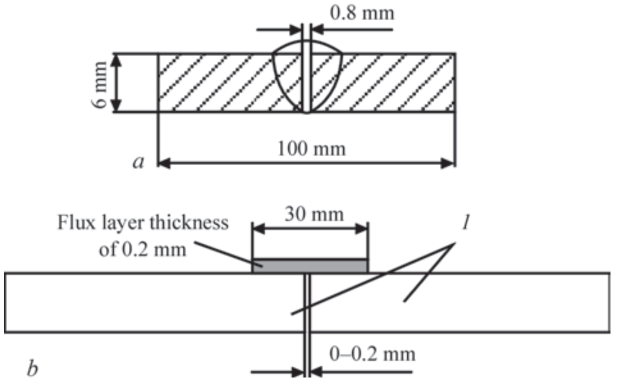

Figure 1. Schematic of sample assembly for welding: *a* — TIG welding with through penetration; *b* — TIG welding over a layer of flux

metastable phase decomposition. Oxygen, nitrogen and carbon impair the adaptability-to-fabrication of the high temperature alloys, in particular their weldability. Heat treatment — annealing is used to enhance the high temperature resistance of the titanium alloys [9, 10].

THE OBJECTIVE

of this work is investigation of the structure and properties of the high temperature titanium alloy after TIG welding, as well as determination of the influence of preheating on the structure and properties of welded joints.

MATERIALS AND PROCEDURE OF INVESTIGATION

Samples of the size of 200×100×6 mm were welded (Figure 1, *a*). Welding was conducted from one side. Welding modes were selected under the condition of ensuring complete penetration of the joints of 6 mm Ti–6.5Al–5.3Zr–2.2Sn–0.6Mo–0.5Nb–0.75Si alloy.

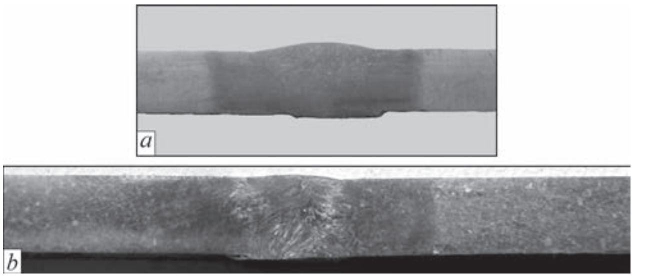

Figure 3. Transverse macrosection of a welded joint of high temperature titanium alloy Ti–6.5Al–5.3Zr–2.2Sn–0.6Mo–0.5Nb–0.75Si produced by: *a* — TIG welding; *b* — A-TIG welding

In addition to the standard argon-arc welding (TIG), also argon-arc welding over a layer of flux (A-TIG) with preheating was performed. This kind of welding is an effective means of influencing the penetrability of the arc, in which halogenides of alkali and alkali-earth metals are added to the arc atmosphere, leading to a change in the mode of weld metal penetration and weld formation due to arc constriction [11]. The flux promotes an increase in the penetration depth and change in the penetration shape. Owing to an increase in the arc penetrability, TIG welding with flux deposited on the surface of the edges being welded (Figure 1, *b*), allows welding in one pass the joints of titanium alloys up to 6 mm thick without edge preparation [12, 13].

The modes of TIG welding with through-penetration and over a layer of flux of the high temperature titanium alloy Ti–6.5Al–5.3Zr–2.2Sn–0.6Mo–0.5Nb–0.75Si from one side are given in Table 1.

Sample preparation for automatic TIG welding of titanium with through penetration is shown in Figure 1.

Before welding the 6 mm metal plates were subjected to vacuum annealing at the temperature of

Table 1. Mode of TIG welding with through-penetration of high temperature titanium alloy Ti–6.5Al–5.3Zr–2.2Sn–0.6Mo–0.5Nb–0.75Si from one side

Mode No.	Welding current, I_w	Arc voltage, U_a, V	Welding speed, V_w, m/h	Arc length, L_a, mm	Preheating temperature, T_{pr}, °C
1	330	12	8	2	–
2 (over flux)	400	12	16	1	200
3 (over flux)	330	12	16	1	400

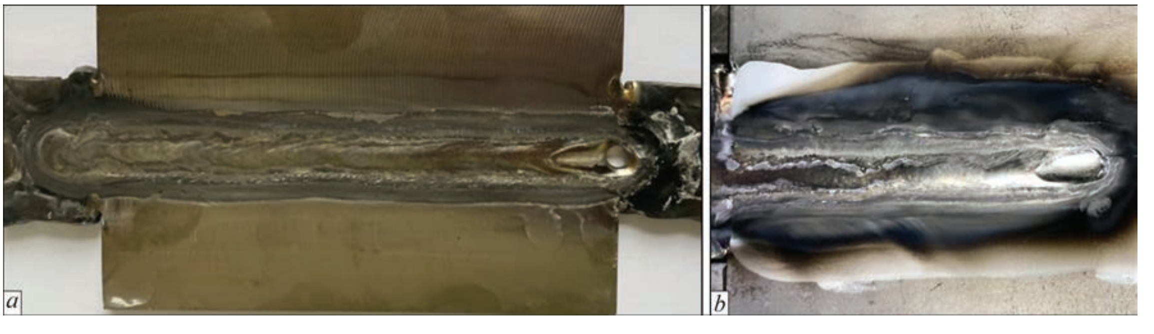

Figure 2. Example of an A-TIG welded joint of high temperature titanium alloy Ti–6.5Al–5.3Zr–2.2Sn–0.6Mo–0.5Nb–0.75Si: *a* — face side of the weld; *b* — sample in the furnace after welding

900 °C with cooling in the furnace. The appearance of welded joints of the produced weld is given in Figure 2. The microstructure of the welded joints is shown in Figure 3.

RESULTS AND THEIR DISCUSSION

MICROSTRUCTURAL STUDIES

Microstructure of the base metal (BM) of a welded joint made in mode No.1 (see Table 1), is shown in Figure 4. The base metal consists of equiaxed primary β-grains of 150–900 μm size with an intermittent interlayer of the α-phase along the grain boundaries. The intragranular structure is formed by colonies of α-plates of different size. The thickness of α-phase plates is equal to 1–3 μm.

The weld metal of the high temperature titanium alloy Ti–6.5Al–5.3Zr–2.2Sn–0.6Mo–0.5Nb–0.75Si consists of equiaxed primary β-grains elongated in the direction of the heat evolution, larger in the weld upper part (Figure 5, *a*, *b*) and finer in the middle and root parts. The equiaxed grains form predominantly along the weld axis. An interlayer of the α-phase is observed here and there along the grain boundaries. During rapid cooling of the weld metal from the temperatures in the β-region the β→α′ martensitic transformation occurs with formation of colonies of plates of 5–50 μm size. The fusion zone in the near-weld zone consists of equiaxed grains of 100–600 μm size. In the HAZ adjacent to the weld, where the metal was heated in welding to temperatures in the β-region, an α-phase with a lamellar morphology could form after cooling at a high rate (Figure 5, *c*, *d*). Plate thickness was 1–2 μm. In the HAZ region adjacent to the base metal, heated to temperatures in the (α+β)-region during welding, the α-, β- and α′-phase differing from the α-phase by another level of alloying, can be present (Figure 5, *e*, *f*).

The metal of the welded joint produced by A-TIG welding with application of preheating at 200 °C (mode No. 2), consists of equiaxed grains of 200–400 μm size with a lamellar intragranular structure (Figure 6, *a*, *b*), the width of α-plates being 1–4 μm. The metal microstructure in the fusion zone consists

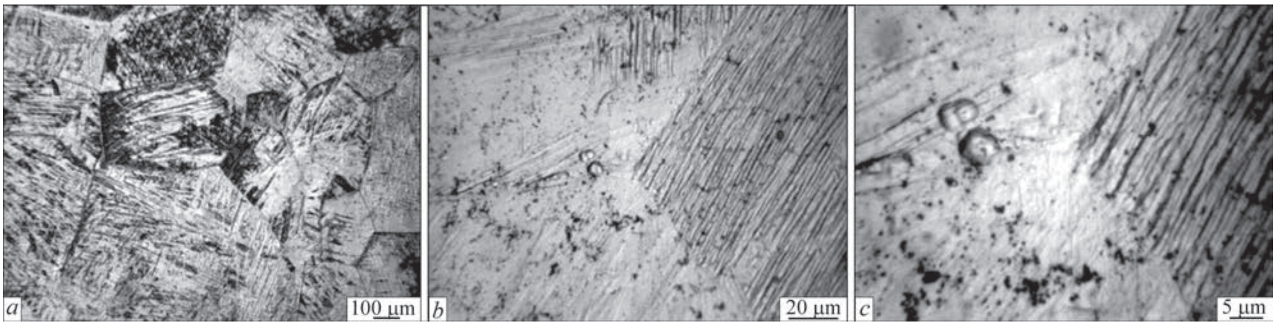

Figure 4. Microstructure of the base metal in a joint of high temperature titanium alloy Ti–6.5Al–5.3Zr–2.2Sn–0.6Mo–0.5Nb–0.75Si

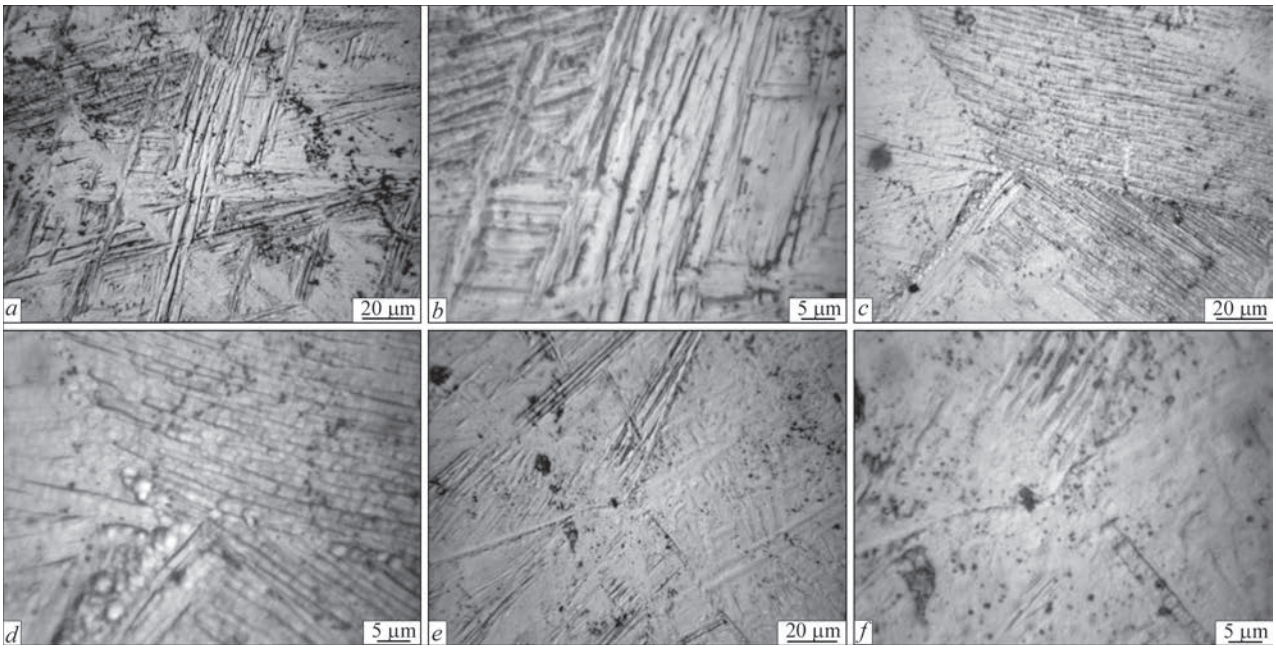

Figure 5. Microstructure of a joint of high temperature titanium alloy Ti–6.5Al–5.3Zr–2.2Sn–0.6Mo–0.5Nb–0.75Si welded in mode No. 1: *a*, *b* — weld metal; *c*, *d* — HAZ adjacent to the weld; *d*, *f* — HAZ adjacent to the base metal

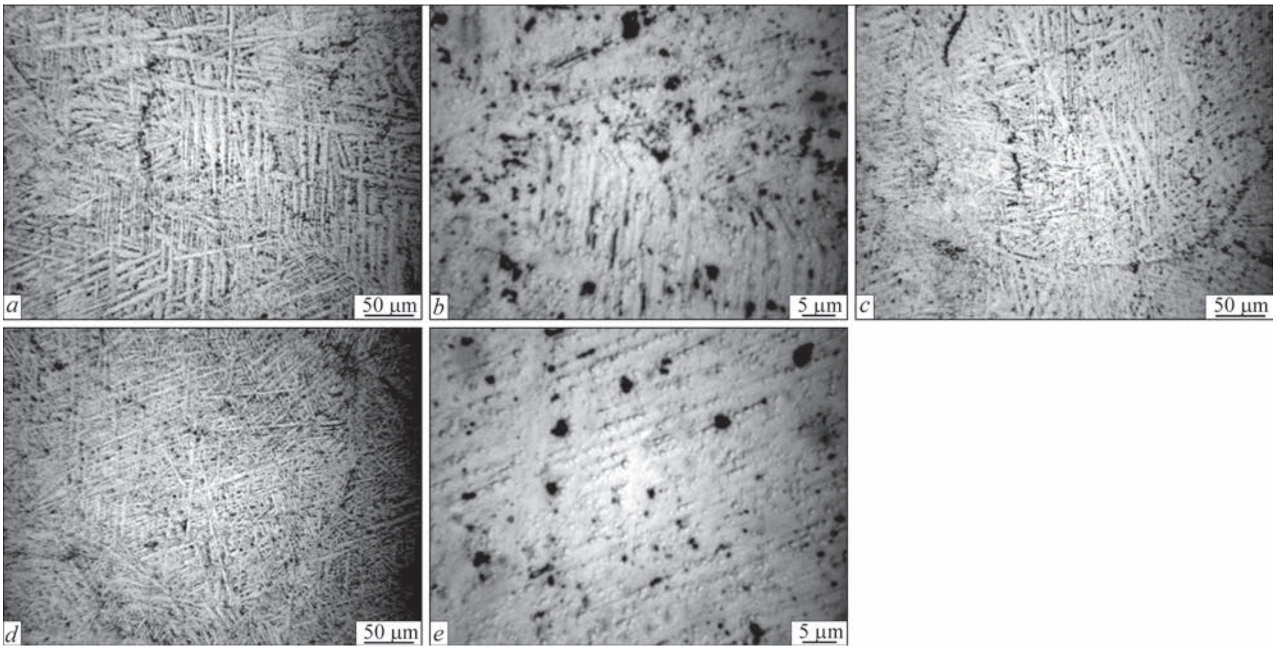

Figure 6. Microstructure of a joint of high temperature titanium alloy Ti–6.5Al–5.3Zr–2.2Sn–0.6Mo–0.5Nb–0.75Si welded in mode No. 2: *a*, *b* — weld metal; *c* — HAZ adjacent to the weld; *d*, *f* — HAZ adjacent to the base metal

of equiaxed grains of 100–600 μm size. Dispersed particles in the form of isolated precipitates and their clusters can be also present in the metal structure, their size being less that 1 μm (Figure 6, *c*). In the HAZ region adjacent to the base metal, which was heated to the temperatures in the (α+β)-region during welding, the α-, β- and α′-phase differing from the α-phase by another level of alloying, are present (Figure 6, *d*, *e*). The physical and mechanical properties of the α′-phase in pseudo-α alloys, however, are close to those for the α-phase, so that the presence of α′-phase in the welded joint will not impair its physical and mechanical properties. A lamellar structure is observed in the HAZ metal, similar to the weld metal, as well as the above-described dispersed particles.

The weld metal of the joint produced in mode No. 3, consists of grains of 100–500 μm dimensions (Figure 7, *a*, *b*) with a lamellar intragranular α-phase. Dispersed precipitates of two kinds are observed between the plates in the figures: light- and dark-coloured. The nature and arrangement of the dispersed particles are similar to those in the welded joint made in mode No. 2. In the fusion zone fine polyhedral equiaxed grains of 50–150 μm size are located between

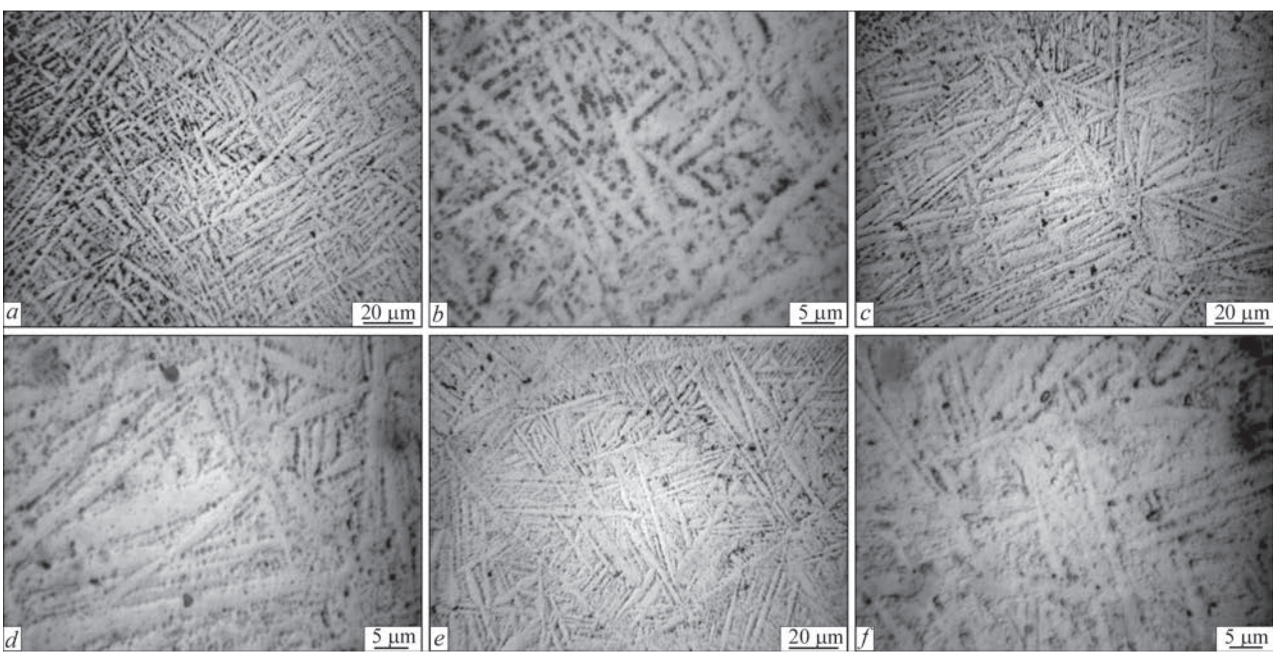

Figure 7. Microstructure of a joint of high temperature titanium alloy Ti–6.5Al–5.3Zr–2.2Sn–0.6Mo–0.5Nb–0.75Si welded in mode No. 3: *a*, *b* — weld metal; *c*, *d* — HAZ adjacent to the weld; *d*, *f* — HAZ adjacent to the base metal

Table 2. Mechanical properties of welded joints of high temperature titanium alloy Ti–6.5Al–5.3Zr–2.2Sn–0.6Mo–0.5Nb–0.75Si

Mode No.	T_{pr}, °C	σ_t < MPa	$\sigma_{0.2}$, MPa	δ_s, %	*KCV*, J/cm^2
As-rolled base metal	–	1044	975	4.5	12.7
TIG, mode No.1	–	969	80	11.2	8.9
A-TIG, mode No. 2	200	1007	929	–	9.7
A-TIG, mode No. 3	400	1091	988	6.8	9.0

the weld metal and HAZ grains elongated in the direction of heat removal (Figure 7, *c*, *d*), the width of the layer of such grains being 300–400 μm. Dispersed precipitates and α-, β- and α′-phases are present in the HAZ metal adjacent to the base metal which was heated in welding to temperatures in the (α+β)-region (Figure 7, *e*, *f*). In all the HAZ regions dispersed particles of the same size as those in other welded joint regions are present, being located along the boundaries of the grains and plates. Among such particles the most probable is the titanium silicide, as silicon concentration in the alloy significantly exceeds the limit of its solubility in α-titanium. Local presence of dispersed particles of the α_2- and β-phases in the HAZ metal is not excluded.

Thus, the conducted studies allowed us to conclude that the microstructure in different regions of the welded joints of high temperature titanium pseudo-α alloy is identical and similar with different methods and modes of welding. It can be assumed that the phase composition of the metal in different regions of the welded joints will not have any sharp differences. A change in the welding energy input makes a greater contribution to the joint structure. At application of the basic technological process — TIG with through penetration — coarsened packs of the size in the

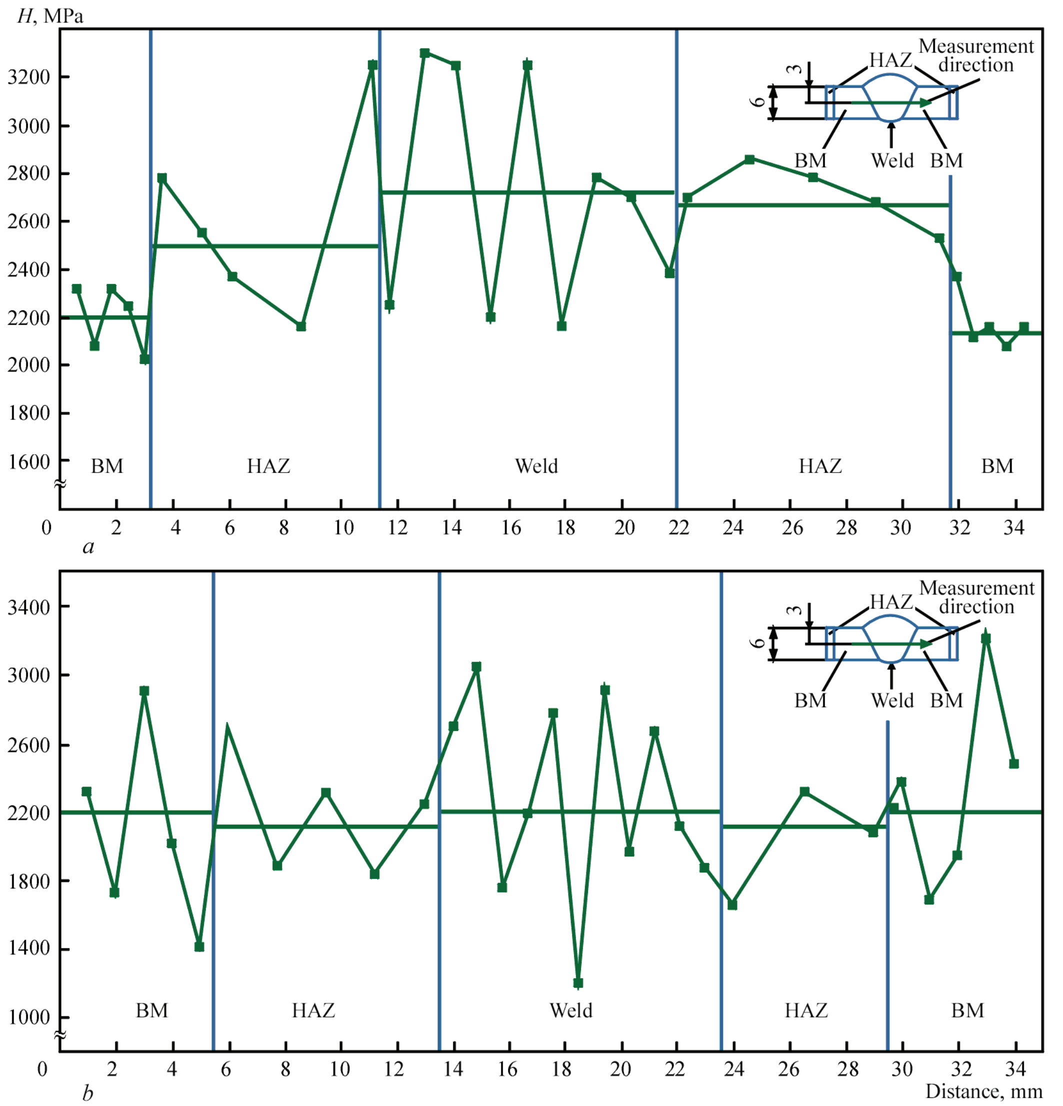

Figure 8. Microhardness distribution in the welded joint of high temperature titanium alloy Ti–6.5Al–5.3Zr–2.2Sn–0.6Mo–0.5N b–0.75Si: *a* — welding mode No. 1; *b* — mode No. 3

range of 10–30 μm (by the size of the largest plates) are formed. At lowering of the specific power during application of A-TIG welding a reduction in the pack dimensions and an increase in the microstructure homogeneity are observed, which should have a positive effect on the welded joint mechanical properties.

INVESTIGATION OF MECHANICAL PROPERTIES

Investigation of the welded joint mechanical properties showed that the joints produced by TIG welding with through penetration without preheating application in mode no.1 (Table 2) have the lowest strength values in as-welded condition (Table 2), equal to 969 MPa or 93 % of that of as-rolled base metal. Welded joints produced by TIG welding with application of preheating to 400 °C (mode No.3) have the highest strength values equal to 1091 MPa, which is at the level of the base metal strength. Welded joints made by TIG welding with application of preheating to 200 °C (mode No. 2) have medium strength values at the level of 1007 MPa or 96 % of base metal strength.

Distribution of metal microhardness in welded joints of high temperature titanium alloy Ti–6.5Al–5.3Zr–2.5Sn–0.6Mo–0.5–Nb–0.75Si, produced by TIG welding with preheating to 400 °C in as-welded state, showed that the microhardness level in the base metal remained unchanged, while in the metal of the weld and the HAZ the microhardness level decreased, has leveled out and is in the range of 1800–2800 MPa (Figure 8).

Thus, in A-TIG welding with reduced specific power a fine highly homogeneous structure is formed. Preheating to 400 °C leads to a certain coarsening of the structure; coarsened packs of the size in the range of 10–30 μm (by the size of the largest plates) form in the weld metal, and its application can be justified only by technological reasons, namely lowering the risk of cracking. With lowering of the specific power during application of A-TIG welding a reduction in the pack size is observed and an increase in the microstructure homogeneity, which will have a positive effect on the welded joint mechanical properties. That is why it is rational to perform TIG welding of the high temperature titanium pseudo-α alloy of Ti–6.5Al–5.3Zr–2.2Sn–0.6Mo–0.5Nb–0.75Si system with application of fluxes and preheating to the temperature of 400 °C, which provide the highest values of strength in as-welded state at the level of 1091 MPa.

CONCLUSIONS

1. The influence of preheating in TIG welding on the properties of welded joints of the high temperature titanium alloy Ti–6.5Al–5.3zr–2.2Sn–0.6Mo–0.5Nb–0.75Si was studied, and it was determined that application of preheating of the joints to 400 °C in A-TIG welding ensures formation in the welded joint of structures of α-phase plates 1–4 μm thick and dispersed particles of the α_2- and β-phase of average size of up to 1 μm.

2. Investigation of the mechanical properties of welded joints of the high temperature titanium alloy Ti–6.5Al–5.3Zr–2.2Sn–0.6Mo–0.5Nb–0.75Si showed that TIG welded joints produced with application of preheating to 400 °C have the highest strength values, which are equal to 1091 MPa for alloy Ti–6.5 Al–5.3Zr–2.2Sn–0.6Mo–0.5Nb–0.75Si and are at the level of 0.95–1.05 of base metal strength.

3. Determination of microhardness distribution in the TIG welded joint of the high temperature titanium alloy Ti–6.5Al–5.3Zr–2.2Sn–0.6Mo–0.5Nb–0.75Si allowed us to establish that application of preheating to 400 °C in TIG welding enables lowering the average microhardness level in the weld metal and the HAZ from 2700 to 2300 MPa, which corresponds to base metal microhardness.

4. A technological process of A-TIG welding of the high temperature titanium alloy Ti–6.5 Al–5.3Zr–2.2Sn–0.6Mo–0.5Nb–0.75Si was proposed, which envisages welding with energy input of 700–800 kJ/m over a layer of ANT25 flux and welded joint preheating to the temperature of 400 °C, which provides formation of a fine highly homogeneous microstructure in the joints and the strength values of as-welded joints at the level of not less than 0.95 of base metal strength.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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