EFFECT OF FRICTION WELDING PARAMETERS ON STRUCTURE AND MECHANICAL PROPERTIES OF JOINTS ON TITANIUM ALLOY VT3-1

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The study presents investigation results on formation of joints in friction welding (FW) of titanium alloy VT3-1, which is used in structure of axial-flow compressors of aircraft gas turbine engines (GTE). The purpose of the study was to optimise parameters of FW of alloy VT3-1, based on the possibility of its implementation by using modern equipment for linear friction welding (LFW) in order to manufacture and repair GTE monowheels, i.e. the so-called blisks. Optimal values of the FW parameters were determined on the basis of results of mechanical tensile tests, metallographic examinations and measurements of microhardness of the welded joints produced by FW in air and in shielding gas atmosphere (argon). It was established that in FW of alloy VT3-1 the sound (defect-free) joints can be produced over a wide range of variations in the process parameters, providing that the specified value of the total length loss in welding in ensured. Strength values of the joints exceed those of the base metal of alloy VT3-1. As a result of intensive thermomechanical deformation at temperatures above the β-transus temperature of alloy VT3-1 and rapid cooling after FW, the joining zone metal has a dynamically recrystallised fine-grained structure and increased hardness. Based on the results obtained, the FW parameters were optimised for alloy VT3-1 at a comparatively low linear velocity of relative motion of the billets, which is feasible in LFW of titanium alloys by using the existing equipment. 22 Ref., 1 Table, 6 Figures.

Keywords: *friction welding, titanium alloys, mechanical properties, full strength, welding parameters*

Titanium alloys are widely applied in aircraft engine construction, in particular for manufacture of components of axial-flow compressors of gas turbine engines (GTE). Modern machining methods allow manufacturing complex components, having a relatively high cost. However, the more complicated the machining process, the higher the probability of formation of defects.

Repair operations are most often performed by welding and cladding. However, it is extremely difficult to produce the full-strength joints in repair of parts made from multi-component alloys, and from titanium alloys in particular, while this is especially important for repair of actuated parts, e.g. blades of GTE blisks. Because of high reactivity of titanium with respect to atmospheric gases (oxygen, nitrogen, hydrogen), in fusion welding (FW) of titanium the welded joint metal becomes saturated with these gases. This leads to decrease in mechanical properties and embrittlement of the welded joints, thus negatively affecting the level of reliability of a repaired part. Shielding of the welding zone with oxygen-free fluxes, pure argon, helium or their mixtures provides the welded joints with a strength factor of no more than 0.9 [1].

Also, during the welding process it is necessary to provide the minimal distortions of workpieces, as they will determine the values of allowances and, hence, the scope of subsequent machining. Postweld heat treatment of a weldment is undesirable either (in a number of cases it is unfeasible). The above reasons limit the application of the known FW methods for titanium and its alloys.

The said drawbacks can be minimised by using pressure welding methods, and FW in particular. Joining of metals by this method occurs in the viscous-plastic state without melting of the faying surfaces. Owing to this fact, properties of metal of the joining zone (JZ) and heat-affected

*The study was performed with participation of A.I. Petrik.

zone (HAZ) change but insignificantly, while welding stresses and strains are usually much lower than in FW [2].

The issues of the use of different technologies for FW of titanium alloys are covered in a number of domestic and foreign publications [3–18]. Study [3] shows that conventional FW allows producing the sound joints on titanium alloy OT4, the mechanical properties of which are at a level of the base metal (BM). The FW parameters were set at a level of those for low-alloy steels [2] (heating pressure P_h and forge pressure P_f = 60 and 100 MPa, respectively; total length loss Δ_w = 6 mm).

Studies [4, 5] investigated the effect of ambient and shielding atmospheres (welding in air and in argon), as well as parameters of conventional FW on formation of structure and mechanical properties of the welded joints on titanium (99.7 %) and titanium alloys of the Ti–6Al–4V and Ti–6Al–2Sn–4Cr–2Mo systems. For all of the investigated alloys the presence of the shielding atmosphere was found to exert no effect on formation of structure of the JZ metal. Parameters of FW in [4] were characterised by comparatively low values of heating pressure P_h, forge pressure P_f (25.5 and 31.1 MPa, respectively) and relative motion linear velocity v = = 2.2 m/s.

Study [6] investigated peculiarities of formation of structure and mechanical properties of the welded joints on different titanium alloys in inertia FW of aircraft GTE compressor rotor disks. Weldability of different titanium alloys, such as Ti–6Al–4V, Ti–6Al–4V–2Sn, Ti–8Al–1V–1Mo, Ti–6Al–2Sn–4Cr–2Mo and Ti–6Al–2Sn–4Cr–6Mo, were investigated. As established on the basis of comprehensive mechanical tests and metallographic examinations, inertia FW provides the welded joints that meet specification requirements. The values of strength of the welded joints are higher, and the values of ductility and fatigue are lower than those of BM. Of notice is a very high value of the initial linear velocity of a relative motion in inertia FW of titanium alloys: v_{init} = 35 m/s (rotation frequency of 1130 min^{-1}, outside diameter of cylindrical billets of 584 mm).

Study [7] gives results of investigation of structural changes and associated welding stresses in inertia FW of two-phase ($\alpha + \beta$)-alloy Ti–6Al–2Sn–4Cr–6Mo. It was found that structural changes of metal in FW cause a substantial increase in hardness values of the JZ metal. At the same time, the maximal level of residual welding stresses is fixed at the HAZ–BM interface, and this leads to the necessity to subject the welded joints to heat treatment.

Study [8] gives an example of commercial application of inertia FW in manufacture of helicopter rotor components made from alloy of the Ti–6Al–4V system. It is noted that the JZ metal is of a high quality and free from defects, this providing correspondence of mechanical properties to specification requirements.

Therefore, FW by rotation of titanium alloys can produce sound welded joints over a wide range of process parameters: P_h = 25.5–350 MPa, Δ_w = 2–18 mm, and v = 2.2–35 m/s, provided that the specified upsetting is ensured. Other modifications of FW are also employed to join parts of titanium and its alloys. For instance, it is proposed to use friction stir welding (FSW) to manufacture complex-configuration tubular parts [9].

Linear friction welding (LFW) holds promise for manufacture and repair of GTE blisks [10]. A number of foreign publications considered the prospects of using LFW for manufacture of blisks [11, 12], studied structures and mechanical properties of LF welded titanium alloys [13, 14], described models of thermomechanical processes occurring in LFW [15, 16], and presented designs and specifications of the welding equipment [10, 17].

Analysis of the available publications shows that it is possible to produce the sound welded joints on titanium alloys by using LFW, provided that the sufficient thermal power is generated during the heating process for rapid softening and certain deformation of the JZ metal. The value of the thermal power in LFW is determined to a greater degree by the frequency and amplitude of a relative oscillatory motion, and to a lesser degree — by the heating pressure [15, 16].

Designing of a prototype of the machine for LFW of GTE blisks manufactured by OJSC «Motor Sich» involved a problem associated with optimisation of its technical characteristics. This was related to selection of optimal parameters for LFW of domestic high-strength titanium alloys. It is difficult to identify the optimal parameters of LFW for specific dimension types of billets for the GTE blisks by using the available data on rotational (conventional, inertia) FW. These data can be used only partially, as weldability was investigated mostly on foreign titanium alloys, and the majority of studies recommended using comparatively high values of the linear velocity of a relative motion of billets (v = = 2.2–35 m/s).

The fundamental difference of LFW of metals consists in complexity of technical implementa-

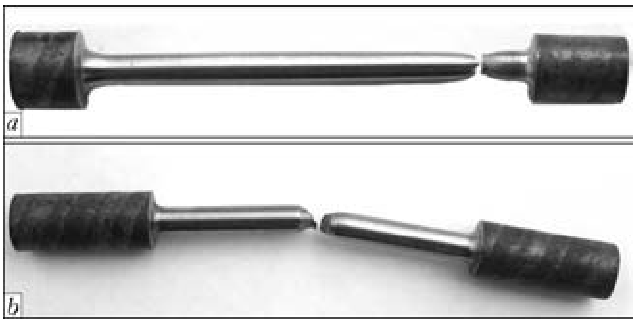

Figure 1. Standard (*a*) and special (*b*) specimens of welded joints on alloy VT3-1 after tensile tests

tion of the required process parameters. Modern welding machines for LFW are capable of working over wide ranges of oscillation frequencies (10–250 Hz) and amplitudes (1–7 mm) [10]. This allows setting, e.g. in joining of thermoplastics, the required combination of the oscillation frequency and amplitude, and applying LFW under industrial conditions. However, at comparatively high values of the axial thrust (LFW of high-strength alloys) it is hard to technically realise a combination of the high values of oscillation frequency and amplitude. Therefore, usually $v \leq 1$ m/s in LFW [10], and it is this value that predetermines peculiarities of formation of the welded joints, compared to conventional FW.

For this reason, when optimising parameters of LFW of domestic titanium alloys it is important to define permissible limits of variations in process parameters, heating pressure P_h and heating time t_h at comparatively low values of the linear velocity determined by a specific character of the process and technical characteristics of the LFW equipment. To study technical feasibility of formation of the sound (defect-free) joints on high-strength titanium alloy VT3-1 in manufacture of GTE blisks, and to evaluate their mechanical properties, the experiments were carried out on rotational FW, as the thermal deformation cycle of this modification of FW is identical to that of LFW [2].

The purpose of the present study was to optimise parameters of FW of high-strength titanium alloy VT3-1 at a comparatively low specified value of the linear velocity of a relative motion, which is technically feasible with LFW by using the existing equipment.

Preliminary experiments on investigation of formation of structure of the welded joints in FW of VT3-1 alloy specimens with a diameter of 10–30 mm were carried out by using machine ST120, which allows adjusting the values of rotation frequency, axial thrust and time of deceleration of rotation over wide ranges [18]. Welding of the 10 mm diameter billets of alloy VT3-1 to conduct mechanical tests and metallographic examinations was performed by using upgraded machine MST-2 providing the FW cycle at a constant rotation frequency of 1430 min^{-1} and at $P_f = P_h$. FW of the specimens was carried out both in air and in argon atmosphere. Alloy VT3-1 has the following chemical composition, wt.%: 0.2–0.7 Fe, up to 0.1 C, 0.15–0.4 Si, 0.8–2.3 Cr, 2–3 Mo, up to 0.05 N, 5.5–7 Al, up to 0.5 Zr, up to 0.18 O, up to 0.015 H, up to 0.3 — impurities, and titanium is the base [19].

Mechanical properties of alloy VT3-1 are as follows: σ_t = 1000–1250 MPa, δ = 12 %, ψ = 32–35 %, *KCU* = 300 kJ/m^2, and hardness (after quenching + tempering) *HRC* = 38–42 [20].

Tensile strength of the resulting welded joints was investigated by using tensile testing machine IR-100. Both standard specimens and special specimens with a notch in the JZ (Figure 1) were tested, which made it possible to determine the strength values of metal in this zone. Microhardness of the JZ metal was measured by using microhardness meter PMT-3. The main criterion of formation of a sound welded joint was reaching the maximal strength values of the joints at the minimal value of upsetting. To optimise the FW parameters the technological process parameters were varied within the following ranges: P_h = $= P_f$ = 10–30 MPa, and t_h = 1.8–8.0 s. At a ro-

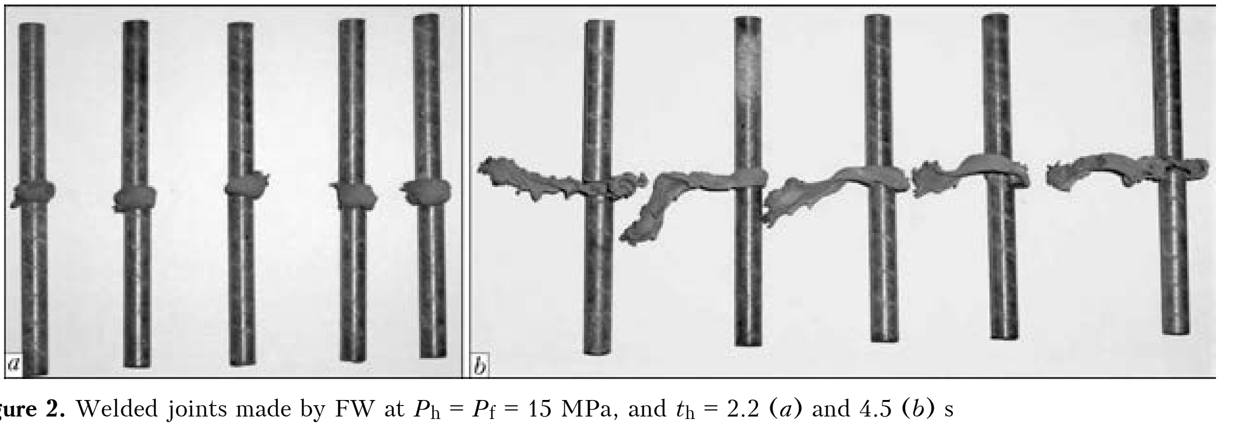

Figure 2. Welded joints made by FW at $P_h = P_f$ = 15 MPa, and t_h = 2.2 (*a*) and 4.5 (*b*) s

tation frequency of 1430 min^{-1} and billet diameter of 10 mm, v = 0.75 m/s, this corresponding to the values achievable in LFW of high-strength alloys by using the existing welding equipment [10].

As seen from Figure 2, the shape of reinforcement (flash) at v = 0.75 m/s approximately corresponds to the shape of flash in LFW of titanium alloy of the Ti–6Al–4V system (Figure 3). The shape of the flash changes with increase in t_h from 2.2 to 4.5 s, this proving advantages of the FW parameters with minimal t_h (see Figure 2).

Characteristics of strength of the FW joints are shown in Figure 4.

As shown by analysis of the results, in FW of alloy VT3-1 the strength values of the welded joints are not lower than those of the BM at all of the above values of P_h: 10, 15 and 27 MPa. However, t_h differs substantially for different values of P_h. For example, at P_h = 10 MPa, t_h should be not lower than 5.3 s, at P_h = 15 MPa it should be not lower than 2.2 s, and at P_h = 27 MPa the sound joints were produced at t_h = 2 s.

Increasing the heating time leads to growth of the total length loss of specimens at an insignificant increase in strength of a welded joint. For instance, at P_h = 10 MPa the strength of the joints exceeds that of the BM at $t_h \geq 5.3$ s. However, in this case the total length loss of the specimens considerably grows to 24 mm, compared to Δ_w = 7 mm at P_h = 15 MPa and t_h = = 2.2 s. The results obtained evidence that under industrial conditions P_h should be set within 15–27 MPa to minimise allowances for upsetting and machining.

Similar results obtained in investigation of the effect of the total length loss in FW of alloy of the Ti–6Al–4V system on the quality of the welded joints are given in study [4]. It was established that at v = 2.2 m/s, P_h = 25.5 MPa and P_f = 31.1 MPa the total length loss in welding can be decreased from 12.7 to 3.2 mm without prejudice to the quality of the joints. Similar results were obtained also in study [5], however at much higher values of v, P_h and P_f.

As noted above, titanium is characterised by a high reactivity with respect to gases contained in the atmosphere at a temperature higher than 350 °C. The effect of probable saturation of the weld metal with gases was checked on the specimens made by FW in air and in the atmosphere of a gas inert with respect to titanium and its alloys. Argon was used to shield the JZ in FW. As established, increase in metal hardness on the specimen surfaces in the HAZ metal to a depth of 0.5 mm was observed in FW performed in air. Moreover, the weld reinforcement forming during upsetting has a high hardness resulting from interaction of the softened metal pressed out from the joint by oxygen and nitrogen present in air.

Results of mechanical tests of the joints on standard VT3-1 alloy specimens with a diameter of 10 mm welded in the argon atmosphere are given in the Table. Fracture of the standard specimens was found to occur in the BM outside JZ and HAZ (see Figure 1, *a*). No substantial effect of the ambient atmosphere on strength values of the joints at the optimal values of heating pressure and time was revealed.

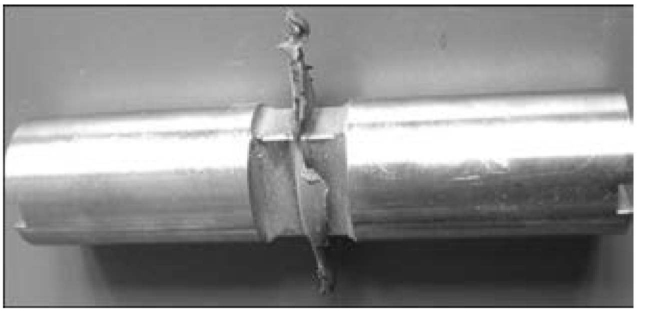

Figure 3. LF welded joint on titanium alloy (specimen is supplied by The Welding Institute, Great Britain)

Results of mechanical tests of welded joints on VT3-1 alloy specimens to tensile strength (t_h = 2.2 s, P_h = 15 MPa)

Specimen No.	Δ_w, mm	σ_t, MPa
1	6	1321
2	7	1446
3	6	1326
4	8	1258

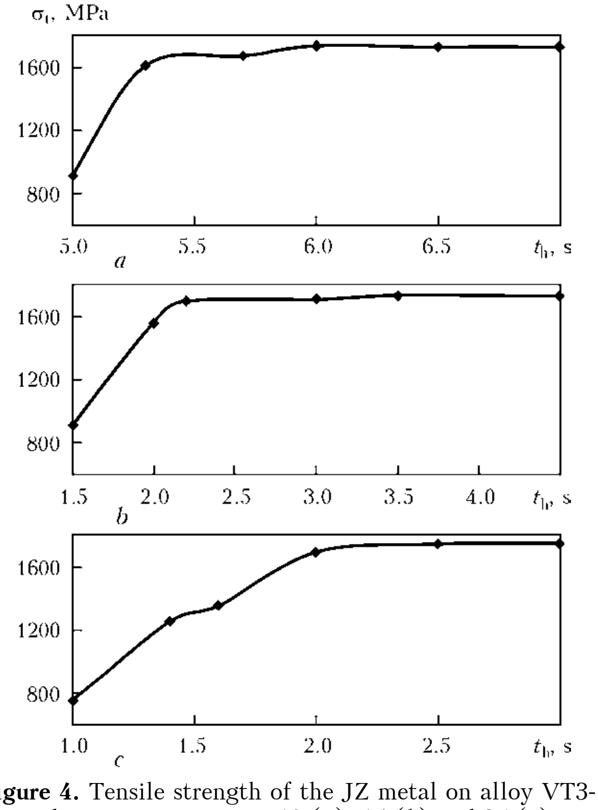

Figure 4. Tensile strength of the JZ metal on alloy VT3-1 versus heating time at P_h = 10 (*a*), 15 (*b*) and 27 (*c*) MPa

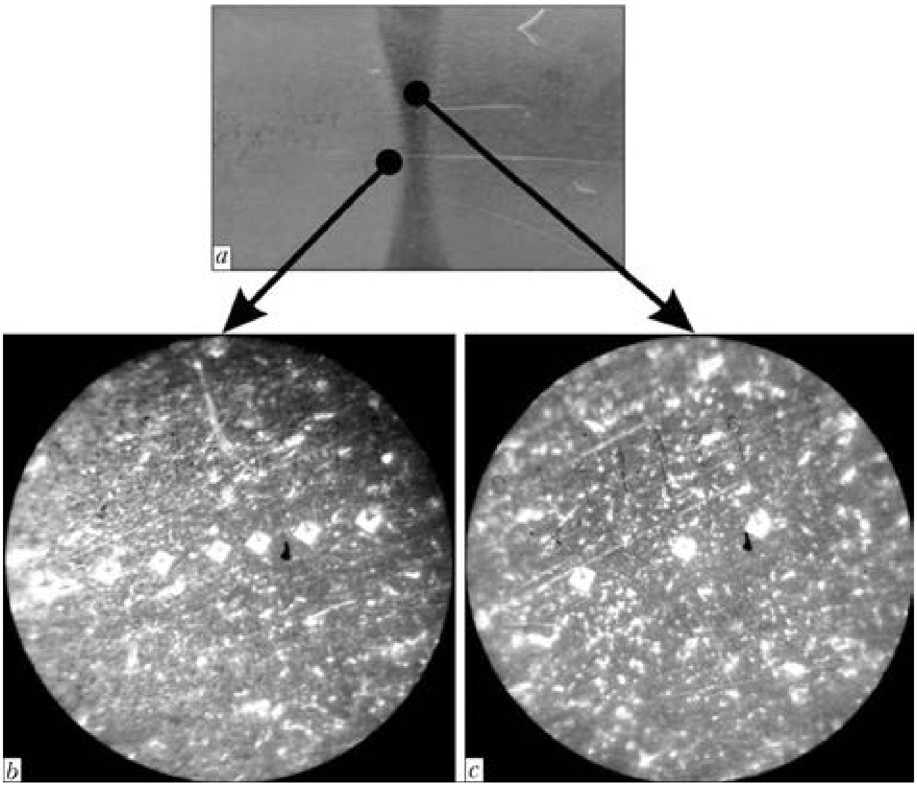

Figure 5. Macrostructure (*a*) and zones of measurement of microhardness (*b*, *c* — ×100) of FW joint on alloy VT3-1

The results obtained allowed establishing that the strength values of the welded joints exceed those of the BM. Examination of microstructure of the welded joints made in air and in argon revealed the difference in etchability of the JZ, near-weld and base metals (Figure 5, *a*), the values of microhardness changing from 4.6 GPa in BM to 4.8 GPa in the JZ metal.

In our opinion, increase in strength and hardness values of the weld metal is related to intensive thermomechanical deformation of metal at the temperature above the β-transus temperature. Refining and stirring of structural components of alloy VT3-1 in FW and during rapid cooling after welding result in considerable structural changes occurring in JZ: formation of fine-grained, dynamically recrystallised structure of β-grains with dispersed precipitates of the α-phase (Figure 6).

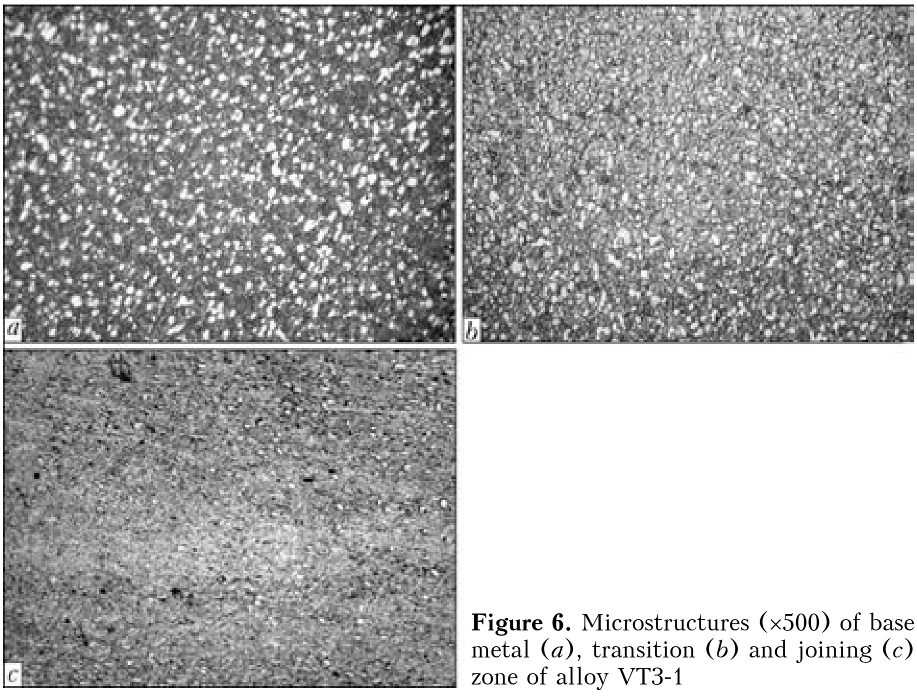

Figure 6. Microstructures (×500) of base metal (*a*), transition (*b*) and joining (*c*) zone of alloy VT3-1

In addition, increase in hardness of the joints made by FW in air can be caused by short-time oxidation of the faying surfaces at the initial stages of the process (prior to pressing out of the softened metal from the joint) and redistribution of the formed oxide phases of titanium in JZ. Formation of JZ with increased hardness results from peculiarities of decomposition of β-titanium under conditions of rapid cooling and presence of small amounts of oxygen in the weld, as well as from a partial presence of the β-phase in the meta-stable state [3]. The higher the content of the residual β-phase after high-temperature thermomechanical treatment, the higher the strengthening of (α + β)-titanium alloys during this treatment [21].

Therefore, during the FW process the JZ metal is subjected to high-temperature thermomechanical treatment, which provides refining of structure, increase in dislocation density and increase in the content of the β-phase, which, according to the data of [22] for alloy VT3-1, provides increase in strength by 280–480 MPa, compared to conventional heat treatment.

Conclusions

1. It was experimentally proved that the FW parameters affect formation of structure and mechanical properties of the welded joints on titanium alloy VT3-1. Strength values of the joints at P_h = 15–27 MPa and t_h of more than 2.2 s exceed those of BM.

2. Increase in strength of the welded joints on alloy VT3-1 compared to that of BM is related to high-temperature thermomechanical deformation of metal in FW. Refining and stirring of structural components of alloy VT3-1 during heating and deformation, as well as rapid cooling after welding result in considerable structural changes occurring in JZ: formation of fine-grained, dynamically recrystallised structure of β-grains with dispersed precipitates of the α-phase.

3. Based on the results obtained, optimisation of parameters of FW of alloy VT3-1 was achieved at a comparatively low linear velocity of a relative motion, which is technically feasible with LFW of titanium alloys by using existing welding equipment.

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