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Formation features of a welding joint of alloy Ti-5Al-3Mo-1V by the friction stir welding using heat-resistant tool from ZhS6 alloy

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ABSTRACT

Introduction. The technological process of fabrication products from titanium alloys is often complicated by low quality of welded joints during electric arc or gas-flame welding operations due to high residual stresses and deformations. An example of a successful solution to this problem is the development and implementation of such high-tech processes of metal joining as friction stir welding, which does not refer to the methods of fusion joining. Friction stir welding as an advanced technology is used to obtain joints of “soft” metallic materials, such as aluminum. For “hard” metallic materials, friction stir welding has been limited due to the high demands on welding tools. **The aim of this work** is investigation of the possibility of using a tool made of the nickel-based heat-resistant alloy ZhS6U in friction stir welding of the titanium alloy Ti-5Al-3Mo-1V. **Results and discussion.** Optical and scanning electron microscopy results revealed that the structure of the weld is typical of this type of welding, gradient, consisting of a heat-affected zone, thermomechanical affected zone and a stir zone with a fragmented structure. When varying welding parameters, it is shown that the defectiveness of the weld is affected to a greater extent by the axial load on the tool, which is caused by a significant difference in the thermal effect on the material. Metallographic analysis methods revealed dissolution of welding tool material fragments in the stir zone of the non-detachable joint. Fractographic analysis of the fracture surface shows that the fracture in the weld zone is ductile, although in this case there are brittle bridges. Varying the parameters of friction stir welding made it possible to obtain an indissoluble joint with at least 90 % of the strength of the base metal.

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Introduction

Titanium alloys are widely used in various industries due to its properties: high specific strength, thermal and corrosion resistance. Besides, titanium alloys can work in aggressive conditions and under variable loads. An opportunity for creation of welded structures from titanium alloys will significantly expand tech

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nological capabilities for manufacturing products for transport and aerospace applications, which explains the research relevance of in this direction. However, the widely used methods of fusion welding, such as laser, electron-beam welding, welding in shielding gases lead to formation of porosity, cracking, decrease in corrosive resistance of a welded joint material [1–3].

Nowadays intensive research is being carried out on friction stir welding (*FSW*) of titanium alloys, which reduces the factors that form defects in the welded joint and are associated with heating the welded material to the melting temperature [4]. The key problems arising in the *FSW* process are an optimization of welding parameters for obtaining defect-free joints with minimal degradation of properties, as well as a selection of a tool material that provides wear minimization and high durability of a welding tool [5, 6].

Optimization of titanium alloys welding process parameters is focused on investigation of influence of each of parameters, mainly, welding speed and tool rotation frequency on strength properties of resulting welded joints [7–9]. Processes of formation of welded joint structure as a result of thermomechanical effect of welding are also intensively investigated [10–11]. It has been established that as a result of thermomechanical effect of welding there are synchronized processes of recovery and dynamic recrystallization, leading to redistribution of α- and β-phases, which contributes significantly to strength properties of a resulting permanent joint [12–14]. At the same time, much less attention has been paid to an influence of an axial force, which determines a degree of deformation of material in conditions of torsion under pressure.

Alloys based on molybdenum, tungsten, tantalum, niobium, cobalt, various types of carbides are used as tool materials for welding titanium alloys [15]. Tools based on tungsten-rhenium alloys are widely used because such alloys are characterized by high working temperature [16, 17]. Tools made of tungsten-lanthanum and cobalt alloys show good durability when welding titanium alloys [18, 19]. Tungsten carbide tools are widely used [20, 21].

However, despite its advantages, the manufacture of such tools is quite expensive and technologically complicated. In addition, a contamination of a welded material by tool wear particles is possible, which has a negative effect on properties of welded joints. All these require a search for new tool materials for welding of titanium alloys. The heat-resistant nickel-based alloy *Ti-5Al-3Mo-1V* appears to be promising for this purpose, which has proven itself in welding high-plastic (Grade 2, *Ti-1.5Al-1.0Mn*) and medium-strength (*Ti-6Al-4V*) titanium alloys [22, 23].

Considering the above-mentioned, the aim of the present work is to study the effect of tool axial force in friction stir welding process using a tool made of heat-resistant alloy *ZhS6U* on the strength properties of high-strength titanium alloy *Ti-4Al-3Mo-1V*.

Materials and methods

Friction stir welding was performed on the special experimental equipment at the *Institute of Physics of Strength and Materials Science, Siberian Branch of the Russian Academy of Sciences*. Rolled *Ti-4Al-3Mo-1V* titanium alloy with a thickness of 2.5 mm and chemical composition indicated in Table 1 was used as workpieces.

When welding, a tool made of a nickel-based heat-resistant alloy *ZhS6U* was used; its chemical composition is indicated in Table 2.

Table 1

Chemical composition of *Ti-5Al-3Mo-1V* alloy, wt. %

Fe	*Si*	*N*	*Ti*	*Mo*	*V*	*Al*	*O*	Rest
≤ 0.25	≤ 0.15	≤ 0.05	86.85–92.8	2.5–3.8	0.9–1.9	3.5–6.3	≤ 0.15	0.3–0.4

Table 2

Chemical composition of *ZhS6U* alloy, wt. %

Fe	*Nb*	*Ti*	*Cr*	*Co*	*W*	*Ni*	*Al*	*Mo*	*Si*	Rest
≤ 1	0.8–1.2	2–2.9	8–9.5	9–10.5	9.5–11	54.3–62.7	5.1–6	1.2–2.4	≤ 0.4	≤ 0.6

To prevent intensive oxidation of titanium alloy as a result of thermomechanical effect of the tool, welding was carried out in a shielding argon atmosphere, fed under pressure through a nozzle into a welding zone. Cooling fluid was supplied and removed into the inner cavity of the tool to increase its durability. The schematic of the friction stir welding process is shown in Figure 1.

Welding of specimens was carried out according to the modes given in Table 3. The axial force on the tool was varied from mode to mode; moreover the axial forces during penetration of the tool in material F_{PN} and tool motion in the welding direction F_W were different. The tool rotation frequency ω and the welding speed V were constant while changing modes. A length of the received weld seams for each mode was 100–180 mm.

In order to form a titanium alloy layer on the working surface of the welding tool, a preliminary pass was made by the tool in the material to be welded at a length of 25 mm before welding the experimental specimens. Preliminary pass parameters were: axial forces F_{PN}/F_W = 2,300/2,600 kg, frequency of the tool rotation ω = 375 rpm, welding speed V = mm/min.

All samples of weld joints were cut by *EDM* method in the direction transverse to the welded joint so that it was located in the middle part of the specimen. Samples for metallographic studies were grinded,

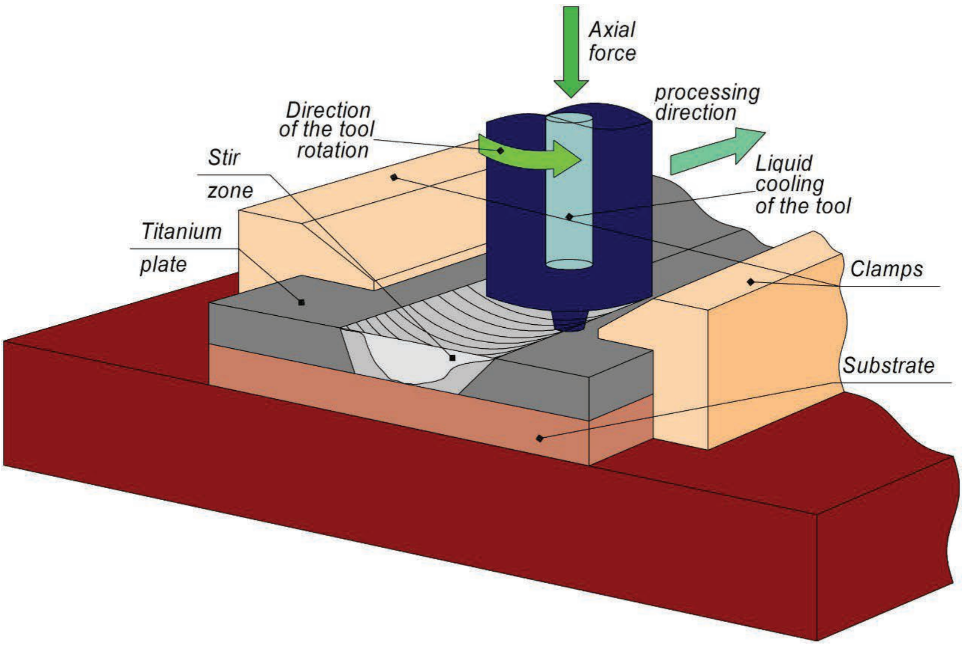

Fig. 1. Schematics of friction stir welding process

Table 3

Modes of *Ti-5Al-3Mo-1V* alloy friction stir welding

No.	F_{PN}, kg	F_W, kg	ω, rpm	V, mm/min
1	2,300	2,600	375	86
2	2,500	2,800	375	86
3	2,700	3,000	375	86

polished and etched. Metallographic research was carried out on a metallographic microscope *Altami MET-1C*, confocal microscope *Olympus LEXT OLS4000*, as well as on a scanning electron microscope *Microtrac SEM* with energy dispersive X-ray microanalyzer *"IXRF systems"*. Static tensile tests were carried out on a universal testing machine *UTS 110M-100* with a strain rate of 1 mm/min. When cutting out samples for testing, the welded joints were conveniently divided by length into 4 sections: 0–25 mm, 25–50 mm, 50–75 mm and 75–100 mm. Samples for tests were cut from each of the above-mentioned sections of the joints.

Results and discussion

Figure 2 shows cross-sectional images of the macrostructure of welded joints obtained by metallographic techniques. As a result of etching, three material zones are clearly identified in the structure of the welded joint: bulk material zone (*BM*), heat-affected zone (*HAZ*) and stirred zone (*SZ*). The heat-affected zone consists of not crystallized and partially deformed grains.

Microstructure analysis of the stirred zone of welded joints showed that the material of this zone consists of fragmented and recrystallized grains of titanium alloy. In addition, it should be noted that, with other constant parameters of the welding mode, an increase in the axial force on the tool leads to a decrease in the grain size of the stirred zone (Fig. 3). This is a positive effect that contributes to the hardening of the stirred zone of the welded joint according to the *Hall-Petch* mechanism.

Fig. 2. Macrostructure of *FSW* joints of *Ti-4Al-3Mo-1V* alloy, obtained by modes 1–3, in the transverse direction

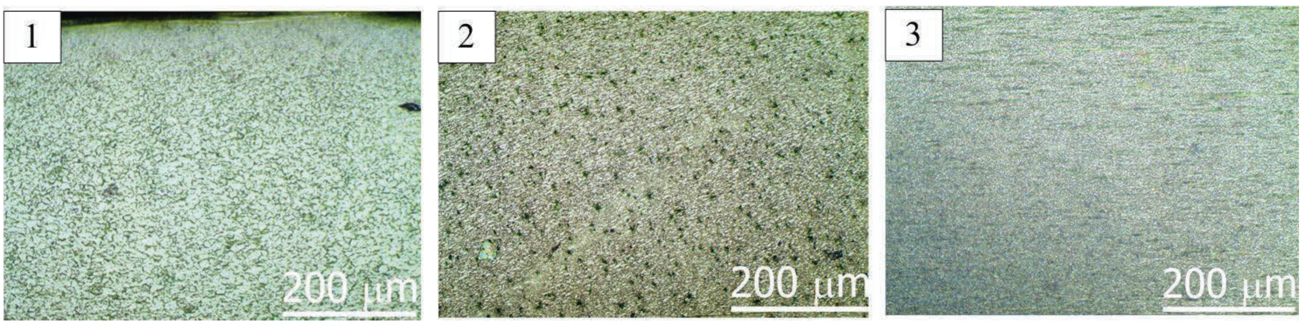

Fig. 3. Stirred zone (*SZ*) of *FSW* joints of *Ti-4Al-3Mo-1V* alloy, obtained by modes 1–3

Microstructural examination of welded joints also indicates the presence of a narrow zone of thermomechanical affection (*TMAZ*), which is characterized by the presence of not recrystallized grains, strongly deformed in the direction of the plastic flow of metal (Fig. 4). It should be noted that an increase in the axial force on the tool leads to an increase in the deformation degree of structural grains in the *TMAZ*.

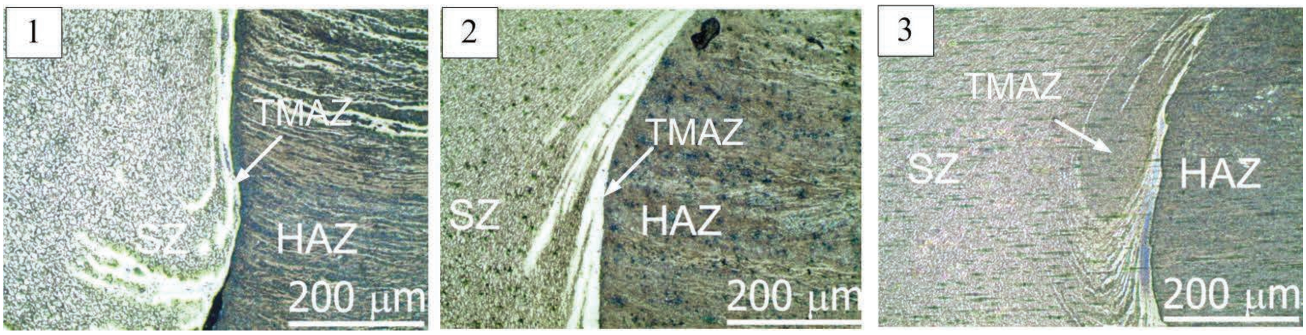

Fig. 4. The boundary between structural zones of *FSW* oints of *Ti-4Al-3Mo-1V* alloy, obtained by modes 1–3

The line that indicates the boundary between the structural zones and is apparent in Figure 2 runs between the *TMAZ* and *HAZ* of the welded joint. An abrupt transition from one structural state of the material to another is related to the low thermal conductivity of the titanium alloy, which provides its local heating directly in the contact zone with the welding tool and prevents its plasticization, sufficient for the formation of an extended zone of thermomechanical effect.

The difference between the structural states in the *HAZ* and *TMAZ* of the welded joint determines an abrupt change in the strength characteristics of its material. The interface of the characteristic zones acts as a factor determining the strength of a welded joint. The appearance of samples of welded joints tested for uniaxial static tension indicates that the failure of the material occurs along the line corresponding to above-mentioned boundary of characteristic zones (Fig. 5).

Fig. 5. Samples of *FSW* joints of *Ti-4Al-3Mo-1V* alloy, obtained by modes 1–3, after uniaxial tension tests

Fractographic investigations showed that when samples are fractured, the surface of samples is formed, that is similar in texture to a fibrous fracture, with the formation of sharp passes (Fig. 6). A microrelief corresponding to a ductile fracture with formation of dimples is formed on the fracture surface. Sufficiently large and branched bridges of plasticity are observed between the dimples. The formation of small zones of material stretching is observed. Thus, the fracture occurred in a place containing a large number of low-dimensional and deformed structural elements, which corresponds to the partially fragmented and highly deformed grains of the *TMAZ* of the welded joint.

According to the results of testing samples of welded joints for uniaxial static tension it was found that the ultimate tensile strength value of the obtained welded joints decreases to 84–93 % of the value for the initial alloy *Ti-4Al-3Mo-1V* (Fig. 7).

According to the tension test results, an increase in the axial force on the tool during friction stir welding leads to a decrease in the ultimate tensile strength of the resulting welded joint of *Ti-4Al-3Mo-1V* alloy. This effect is associated with an increase in the degree of deformation of the material, which contributes to an increase in a strength characteristics gradient. When the mixing zone is strengthened, the zone of thermomechanical affection is softened due to deformation-induced processes of redistribution

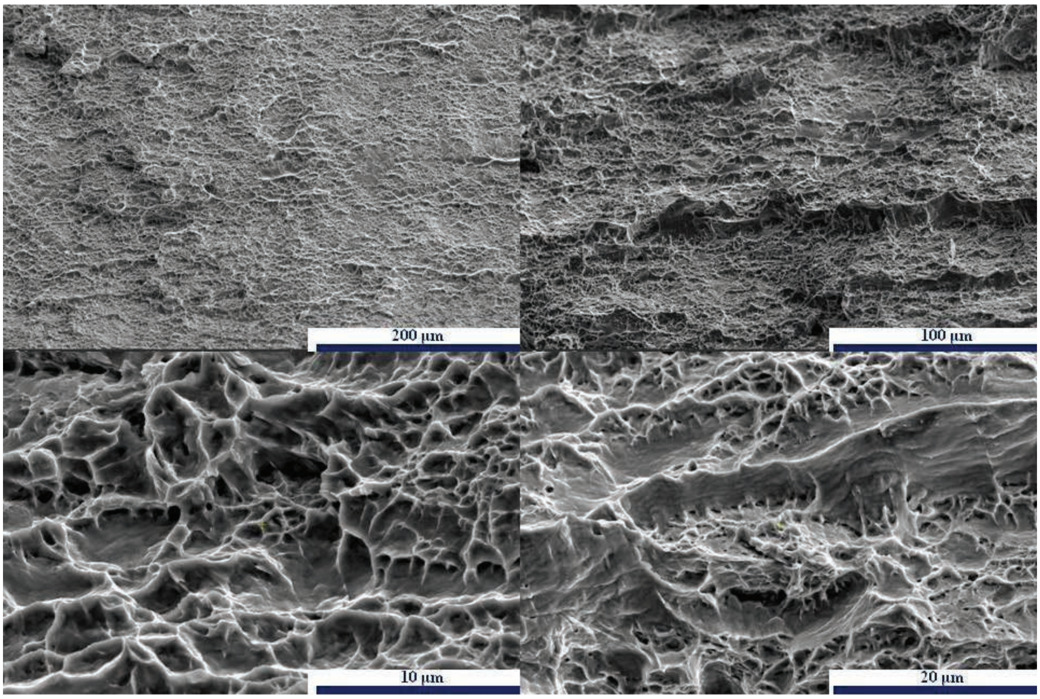

Fig. 6. Fracture surface characteristic images of *FSW* joints of *Ti-4Al-3Mo-1V* alloy

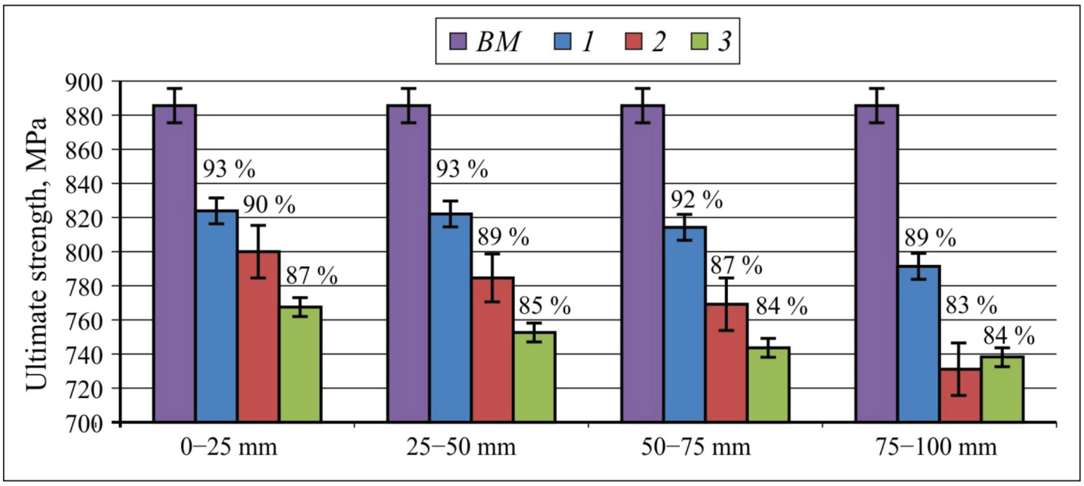

Fig. 7. Tensile strength bar graphs of *Ti-4Al-3Mo-1V* alloy, obtained by modes 1-3

of secondary phases [12, 14]. Also with growth of the length of the welded joint a decrease in the value of the ultimate tensile strength along its length is registered. This may be related to the conditions for the removal of heat, which accumulates due to the low thermal conductivity of titanium alloys, or to the wear of the welding tool. The maintenance of high temperature in the welding zone provides the growth of number and size of particles of secondary phases that contribute to the softening of material. At the same time, the influence of the tool wear factor, in this case, is not significant, because the tool was previously covered with a layer of titanium alloy during the preliminary pass. In addition, visual inspection of the tool used for welding showed that there were no wear features on the tool surface, only a layer of titanium alloy adhesively bonded to the tool surface (Fig. 8).

Thus, the tool made of heat-resistant alloy *ZhS6U* after welding joints from *Ti-4Al-3Mo-1V* alloy with a total length of more than 0.5 m, shows a sufficiently high resistance to associated temperature and mechanical loads and can be effectively used for *FSW* of titanium alloys.

Fig. 8. FSW tool made of heat-resisted alloy *ZhS6U*:
a – before welding; *b* – after welding

Conclusion

The performed research showed that during friction stir welding of high-strength *Ti-4Al-3Mo-1V* alloy, an increase in the axial force leads to an increase in the degree of deformation of the welded material structural elements, which positively affects the strength of the stirring zone. However, it also leads to softening of a welded joint, since it substantially affects the structural-phase state of the thermo-mechanically affected zone, which is the least durable. A low thermal conductivity of titanium alloys provides the formation of a narrow zone of thermomechanical affection and also contributes to the degradation of the strength properties of the welded joint with an increase of its length, since the heat accumulation contributes to the growth of large particles of secondary phases in the zone of thermomechanical affection. Strengthening of the welded joint is not related to the failure factor of the welding tool made of heat-resistant alloy *ZhS6U*, which is resistant to the loads of the welding process and can be effectively used in the processes of friction stir welding of titanium alloys.

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Conflicts of Interest

The authors declare no conflict of interest.

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