Formation of $\alpha'$ titanium welds by friction stir welding

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Abstract. In the present study, investigation of the macrostructure of $\alpha'$ titanium alloy weld produced by the friction stir welding has been carried out. The welding process modes were also selected. It is shown that in case of insufficient load on the tool, an open weld defect is formed. Increasing the load (with decreasing RPM) eliminates the open tunnel and minimizes defects. Despite the presence of defects, the strength of welds has reached the strength of the initial material. As a result of FSW, grain size has been reduced by 7.3 times, but the load increase has not affected the grain structure. The results of the research show that the part of welding tool had been stirred in the structure of weld. However, nickel base alloy tool had passed about 500 mm of weld, before starting to wear out.

1. Introduction
The technology of friction stir welding (FSW) is a solid-phase method of connecting materials by the way of mass-transferring layers from one of the connecting detail to another. This is a well-proven, high-performance welding technology which makes a possibility to produce the high quality welds with excellent performance properties and thus has a high industrial potential. Such kind of welding is often used for “soft” metals such as aluminum, magnesium and copper alloys. Due to high requirements to the welding tool, this process for "hard" alloys, such as titanium alloys or steel alloys, was relatively difficult and work in this area was limited until recent times [1-2]. However, the development of manufacturing tools technology in the last few years has led to increased interest in friction stir welding of titanium alloys.

In practice, titanium alloys have become widely used in aviation, space, military, chemical, medical and marine industries due to a number of useful properties such as corrosion resistance, heat resistance and high specific strength, as well as biocompatibility with biological tissues. These alloys are divided into high-strength, $\beta$-phase, the middle-strength and middle-plastic $\alpha+\beta$-phase, and high-plastic alloys consisting of $\alpha$, or $\alpha'$-phase [3]. The latter group belongs to high-technological alloys, because of they are well deformed despite on their relatively low strength. One of such alloys is Ti-1.5Al-1Mn alloy, which was used not only for producing of civil aircrafts, but also found application in military industry for creation of bullet-proof vests and winged rocket missile [4]. But at the same time titanium alloys have a number of disadvantages, such as active chemical interaction, grain growth and phase transformation at high temperatures, which leads to difficulties in the technological process of manufacturing products, for example, in the classical method of joining materials – fusion welding. Therefore, a possible solution of this problem may be the use of solid-phase welding, which is friction stir welding.

Considering the high mechanical loads and temperatures, friction stir welding tools are usually made of heat-resistant materials such as tungsten-based alloys, cobalt-based alloys, molybdenum-based alloys and polycrystalline boron nitride [5-7]. These tools are usually difficult to manufacture, expensive and not low-wearing enough. The recent studies [8] have shown that it is possible to use the heat-resistant alloy ZhS6U based on nickel as a tool material for FSW of commercial pure titanium Grade2. In practice, this alloy is successfully used for manufacturing turbine blades operating under increased temperature and mechanical loads since the 1960s.
The purpose of present research is to consider the possibility of producing welds by friction stir welding of titanium α’-alloys using the tool manufactured of heat-resistant alloy ZhS6U. Also the objective of work is to determine the influence of technological parameters on the quality of the weld.

2. Material and methods
In the process of experiment the flat rolled products of titanium alloy Ti-1.5Al-1Mn with the thickness of 2.5 mm were welded. Its chemical composition is presented in Table 1.

| Table 1. The element composition of Ti-1.5Al-1Mn titanium alloy, % mass. [9] |
|------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Fe                    | up to 0.3       | C               | up to 0.1       | Si              | up to 0.12      | Mn              | 0.7-2           | Ti              | 94.3-97.5       |
|                       |                 | Al              | 1.5-2.5         | Al              | 1.2-2.4         | Zr              | up to 0.3       | O               | up to 0.15      |
|                       |                 |                  |                 |                 |                 |                 |                 |                 |                 |
|                       |                 |                  |                 |                 |                 |                 |                 |                 | other 0.3       |

Welding was produced at the FSW laboratory facility in a protective argon atmosphere. Welding tool was made of ZhS6U heat-resistant alloy on the nickel base (the element composition is given in Table 2). This alloy is the analogue of MAR-M247 alloy. The diameter of the tool shoulders was 20 mm, the diameter of the tip of the pin was 3 mm, the length of the pin was 2.4 mm, and the angle of the pins cone was 60°.

| Table 2. Chemical composition of ZhS6U alloy, % mass. [10] |
|--------------|-----------------|-----------------|-----------------|
| Fe           | up to 0.3       | Pb              | ≤ 0.001         |
| Pb           | ≤ 0.001         | Cr              | 8-9.5           |
| Cr           | ≤ 0.02          | Ce              | 1.2-2.4         |
| Ce           | ≤ 0.04          | Mo              | 0.4            |
| Mo           | ≤ 0.04          | Zr              | 0.4            |
| Zr           | ≤ 0.035         | Bi              |                |
| W            | Y               | Co              | 9-10.5          |
| Y            | 0.8-1.2         | Nb              | 2-2.9           |
| Nb           | 5.1-6           | Ti              |                |
| Ti           | ≤ 0.0005        | Al              |                |
| Al           | Bi              |                 |                |
| C            | P               | Si              | 0.13-0.2        |
| P            | ≤ 0.015         | Mn              | ≤ 0.4           |
| Mn           | ≤ 0.4           | Ni              | 54.3-62.7       |
| Ni           |                   | S               | ≤ 0.01          |
| S            |                   |                 | Ni-basis        |

The parameters that were used to make joints during the FSW process are summarized in Table 3. Welding heat-energy input is directly proportional to axial force on the tool and rotational speed of the tool and inversely proportional to the tool traverse speed. For this reason, changing one parameter often also requires changing others. The first mode was obtained in a previous FSW research of commercial pure titanium and allowed to produce the quality welds. Because the Ti-1.5Al-1Mn alloy is stronger than commercial pure titanium, a larger heat input is necessary to weld it. For these reasons, the welding process gradually increased the axial force and reduced the load speed and the rotational speed of the tool.

| Table 3. Welding parameters |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| # weld                      | F_p (kg)                    | F_w (kg)                    | V (mm/min)                  | L (mm)                      |
| 1                           | 850                         | 950                         | 180                         | 40                          |
| 2                           | 850                         | 950                         | 150                         | 30                          |
| 3                           | 900                         | 1000                        | 140                         | 30                          |
| 4                           | 1050                        | 1200                        | 140                         | 30                          |
| 5                           | 1300                        | 1400                        | 140                         | 30                          |
| 6                           | 1400                        | 1500                        | 130                         | 32                          |
| 7                           | 1600                        | 1700                        | 130                         | 32                          |
| 8                           | 1600                        | 1700                        | 100                         | 32                          |
| 9                           | 1750                        | 1900                        | 100                         | 32                          |
| 10                          | 1850                        | 2000                        | 100                         | 45                          |
| 11                          | 1950                        | 2100                        | 100                         | 35                          |
| 12                          | 2050                        | 2200                        | 95                          | 35                          |
| 13                          | 2050                        | 2200                        | 90                          | 35                          |
| 14                          | 2400                        | 2400                        | 90                          | 35                          |

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where $F_p$ - the axial force on the tool during plunging into the specimen, $F_w$ – the axial force on the tool during the FSW process, $V$ – tool traverse speed, $L$ – the length of weld, $\omega$ – the rotation speed of the tool.

Transverse polished and etched metallographic cross-sections were made to investigate macro- and microstructure of welded joints. The received cross-sections were etched in reagent of $C_3H_8O_3$ – 30 ml, $HNO_3$ – 10 ml, HF – 10 ml, during 30-35 sec. Metallographic researches were performed on laser confocal scanning microscope Olympus LEXT OLS 4100. Elemental analysis was performed using a scanning electron microscope ZEISS LEO EVO 50. Strength tests were carried out on a machine for testing structural materials UTS 1100M-100 1-U. For static strength tests the specimens were cut out in the direction perpendicular to the welding direction.

3. Results and discussion

The visual analysis of the received joints demonstrates that the last modes, where $\omega \leq 450$ RPM have better quality in comparison with the starting modes, where $\omega \geq 600$ RPM, as there is no open tunnel on the last joints as on the first ones.

![Figure 1. Ti-1.5Al-1Mn alloy FSW joints (a) – #1 and (b) – #11.](image-url)

The macrostructure of FSW joints made of titanium alloy in the cross section, shown in figure 2.

![Figure 2. The macrostructure of joints (a) #11 and (b) #15.](image-url)

A stir zone (SZ) with strongly recrystallized grain structure and a thermomechanical affected zone (TMAZ) can be identified in the joints. The boundary of the stir zone is characterized by a sharp gradient, which is typical for titanium alloys [11]. As can be seen from the figure 2, the void in the joint began to
decrease with the increasing axial force on the tool and decreasing traverse speed and the rotational speed of the tool. Also the increased force resulted in a visual growth in SZ and TMAZ.

Figure 3 presents metallographic of the grain structure of the base material and the stir zone of the samples #9 and #15. Both the base material and the stir zone are described by the availability of equiaxial grains of solid solution, which is typical for compounds of this type [12]. As a result of dynamic recrystallization at friction stir welding, the grain become smaller in ≈ 7.3 times. Increase of axial force in one and a half time has not brought to evolution of the grain size.

![Metallographic image of the grain structure of (a) base material, (b) specimens #9 and (c) #15.](image)

The results of the static strength tests are shown in figure 4. Specimen #15 had the highest strength. Its tensile strength was 782 MPa, which is about 104% of the tensile strength of the base material, which was equal to 762 MPa.

It can be summarized that in order to produce a quality weld it is necessary to increase the axial force on the tool, while reducing the rotation speed of the tool and the welding speed. This mode is different from the mode indicated in [8], because Ti-1.5Al-1Mn alloy has higher strength characteristics as compared to Grade2 alloy. Because of this, in the process of FSW at high tool rotation speeds there is an adhesive transfer of layers that are in close proximity to the tool, but the farther layers are not caught due to incomplete adhesion. The necessary degree of adhesion can be achieved by reducing tool rotation speed and tool traverse speed, but the quantity of heat-energy that was introduced into the welded material by friction is also reduced. This loss of thermal energy can be compensated by the way of increasing the axial force on the tool. These considerations are coinciding with the adhesion-cohesion concept of mass transfer at FSW [13].

![The results of static tensile test for FSW Ti-1.5Al-1Mn joints.](image)

Investigation by methods of scanning electron microscopy demonstrated the existence of extraneous elements on the advancing side of the stir zone, as well as in the lower part of the joint (figure 5). These elements in the form of layers were submitted to elemental analysis.
According to the elemental analysis results, the extraneous objects mixed in the stirring zone contain elements that are part of ZhS6U alloy. It seems that part of the FSW tool was mixed in the joints. Visual analysis of the FSW tool before and after welding (figure 6) demonstrated that the tool wear was imperceptible. In fact, there was a slight change in the shape of the pin and metal pickup of oxidized titanium over the entire friction surface.

Figure 5. Element analysis stirring zone of specimen #15.

Figure 6. FSW tool produced from heat-resistant alloy ZhS6U (a) before welding, (b) after 545 mm of welding.

4. Conclusions
In the work produced Ti-1.5Al-1Mn alloy fixed joints by friction stir welding using a tool made of heat-resistant alloy ZhS6U on a nickel base. The results of the investigation demonstrated that in order to achieve quality welded joints of 2.5 mm titanium α'-alloys sheet, FSW modes should have a lower speed (less than 400 RPM) and high axial force (more than 2.5 tons), compared with modes used at FSW for titanium α-alloys. Grain size as the result of dynamic recrystallization at FSW in the stir zone was reduced by 7.3 times. The increase of axial force on the tool by one and a half time did not result in the change of grain size.

A joint with the strength of 104% of the base material was produced. The tool had passed over 500 mm of weld with minimal wear, which suggests that the heat-resistant nickel-based alloy ZhS6U is appropriate for FSW titanium α'-alloys.

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