Friction stir welding of titanium alloys OT-4 and VT-20

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Abstract. The products made with titanium alloys are widely used in aircraft building, rocket engineering and shipbuilding. In the assembly of these products in these industries fusion welding is used, but its labour intensive and costly process. Reduction of the labour intensity and cost value of joining titanium alloys is possible by using a friction stir welding (FSW) method. In article, FSW distribution in Russia is considered and provides research of weldability of OT-4 (Ti-4Al-1.5Mn analogue) and VT-20 (Ti-6.5Al-1Mo-1V-2Zr analogue) titanium alloys by FSW. The aim of the research is obtaining sound welds of these alloys, designing of a FSW tool, gathering information of a welding process and compiling a list of recommendations for welding. A series of experiments was carried out; the aim of the research for OT-4 was incompletely achieved and for VT-20 was completely achieved. A tool for FSW was developed, data of welding forces and temperatures at different modes are given.

1. Introduction
Friction stir welding (FSW) (TWI patent of 1991 [1]) is used in Russia for joining mainly aluminum alloys. Aims of most of the researches is obtaining information about microstructure and tensile strength of weld, welding process simulation and finding the optimal modes [2-7]. It is worth noting the successful work of Russian researchers in developing a method of active control by acoustic emission, in the high-speed welding and welding of products that are approximate to the space missile products. According to the public data, the using of FSW in Russia is at the stage of implementation into the aerospace industry. FSW method is planned to use in manufacturing of family of launch vehicles “Angara”, a FSW technology is being developed at JSC RCC "Progress" for the manufacturing of launch vehicle of the super-heavy class "Energia". In the civil engineering FSW is used by CJSC Cheboksary enterprise "Sespel" for welding aluminum semi-trailers. Using the FSW method allows to reduce the time for welding the circumferential seam of the shell ring from 8 hours to 8 minutes. According to the annual reports and patents [8-10], the FSW process at the VNIIALMAZ enterprise, which is the manufacturer of the FSW machine in OmSTU (Figure 1), is being also actively investigated.
Figure 1. Educational and research FSW machine

FSW can be implemented both at special machines, and on modernized machines, or on metal-cutting machines with a tool for FSW without modernization. The FSW tool has a various design. In the general case is a primitive pin (triangle, square, cylinder, cone) with threads for better stirring, and shoulder. Tools for FSW of aluminum alloys basically made of heat treated tool steel. The heat resistance of these tools is in the range of 500-650 °C. Researchers due the last decade are actively investigated FSW of titanium alloys [11-13]. The results of the experiments show that the joining of titanium alloys such as Ti-6Al-4V and Ti-5111 is possible. Many researchers consider FSW method as a promising welding method for use in the aerospace industry products using titanium alloys. FSW of structural elements used in the aerospace industry was conducted [14]. It is known that FSW is used on Boeing; on Eclipse aircraft with the license and technical assistance of the TWI [15].

2. Formulation of the problem
The aim of the research is obtaining a joint by FSW of OT-4 and VT-20 titanium alloys, experimental finding of optimal modes, designing of a tool for FSW and gathering data of a temperature and axial force during welding.

3. Theory
FSW of aluminum alloys occurs at a temperature approximate 400-450 °C and this can vary on different alloys. These values are due to an increase in the plasticity of the heated metal. FSW of steel and titanium alloys occurs at the higher temperature. Depending on the alloys to be welded and the tool, the temperature can reach up to 1200 °C when welding titanium alloys [16] and 800 °C when welding steel [17]. This is the reason for high heat resistance of the tool.

4. Experimental results
FSW method was tested by joining OT-4 plates with a thickness 1.8 mm using a tool of hardened 4H5MFS (1.2343X37CrMoV5-1 analogue) tool steel. Welding was carried out at reduced speeds (specimen №1 at a rotation speed 80 rpm with travel speed 16 mm/min, specimen №2 at a 160 rpm
and 25 mm/min). During welding, the pin of the tool melted and destroyed (Figure 2). This indicates an insufficient heat resistance of a tool made of 4H5MFS for FSW a titanium alloy. The temperature in the place of contact between shoulder and welded plates was measured by the Fluke Ti400 thermal imager and reached 300 °C when welding specimen №1 and 640 °C when welding specimen №2 (Figure 3).

![Figure 2. The destruction of the pin of the tool from 4H5MFS steel](image)

![Figure 3. Graph of temperature versus time for FSW of OT-4 alloy with tool made of 4H5MFS steel. (specimen №1 was obtained at a rotation speed of 80 rpm and travel speed of 16 mm/min, specimen №2 was obtained at a 160 rpm and a 25 mm/min)](image)

According to the results of this experiment, the following conclusions were drawn: the welded joint was observed only on the outer surface of the specimens; an opposite surface, there was a mixing area of 6 mm in length, and the boundary between the plates was visible on the remaining surface of the plates. The specimens are shown in Figure 3, 4. The macrostructure images (Figure 5) shows partial joining of metals, but the weld have defects. From the outer surface in the structure of the material in specimen №1, a cast, layered zone with a depth of up to 0.7 mm and a heat-affected zone (HAZ) with a depth of up to 0.3 mm is observed. In specimen №2, a cast zone with a depth of 0.17 mm, and a HAZ to 0.07 mm is observed.
Figure 4. Specimen №1

Figure 5. Microsection of specimen №1 (right section 1, left section 2)

Figure 6. Weld interface between fusion zone with the base material
Based on the results of experiments, a FSW tool for titanium alloys was designed. As a workpiece for manufacturing, the shank of the carbide end mill of SECO from YK30F alloy for ISO-N material milling was chosen. This tool is shown in the Figure 8.

An experiment was conducted using this tool. Specimen №3 was manufactured with a rotation speed of 200 rpm and a travel speed of 50 mm/min, specimen №4 of 315 rpm and 50 mm/min, specimen №5 of 400 rpm and 80 mm/min, specimen №6 of 630 rpm and 100 mm/min.

Increasing the rotation speed and travel speed resulted in an increase in the welding temperature (Figure 9), but nevertheless the joints had a defect along the entire length (Figure 10).
Figure 10. Graph of temperature versus time for FSW of OT-4 alloy with carbide tool

Figure 11. Specimen №3 (left) and №4 (right)

During the welding of specimen’s №5 and №6 at temperatures above 700 °C, the plates were oxidized. Specimen №7 was manufactured using shielding gas argon. Modes for specimen №7: a rotation speed of 1250 rpm, a travel speed of 100 mm/min. On the specimen №7, there are zones of a good stirring of the metal with the formation of a homogeneous welded joint (Figure 11).

Based on the results of the experiments, it was concluded that for the welding of titanium alloys, it is necessary to use a heat-resistant tool (for example carbide tool), a temperature of at least 800 °C, a protection of the weld with an inert gas and required axial force of the tool pressure on the plates, which varies depending on the specific welding conditions.

It is found that when the axial force decreases, the temperature increases and material becomes more plastic (Figure 12).
Based on these requirements, a nozzle was manufactured, which provides the supply of protective gas to the welding zone. The welding scheme is shown in Figure 13.

Figure 13. Graph of axial force versus time for FSW of OT-4

Specimen №8 (Figure 14) and №9 of VT-20 alloy with a thickness of 1.5 mm, manufactured using this welding scheme, unlike specimen's № 1-7, had no visual defects. Modes for specimen №8: a rotation speed of 1250 rpm, a travel speed of 80 mm/min; for specimen №9: a rotation speed of 1000 rpm, a travel speed of 63 mm/min. The temperature during welding was 800-1000 ºС. Inspection of the cross section of the weld showed the absence of voids and fissures, which can be seen with the naked eye. On the instrument there is a "fusing" of oxidized metal, a worn tool is shown in Figure 16. However, the reuse of such a tool makes it possible to manufacture a weld that is visually indistinguishable from the weld manufacture using a "new" tool. Repeated experiments under the same conditions showed a similar result, which indicates the stability of the process.
Figure 15. Specimen № 8

Figure 16. The back side of the weld

Figure 17. Worn FSW carbide tool

The axial force when welding specimens № 8 and № 9 was 2-10 kN (Figure 17).
5. Discussion
The aim of the research was achieved completely for the VT-20 alloy: a joint is obtained, which has no imperfections; with complete stirring of the material; in the cross section of the weld there are also absence of voids and fissures. This joint is manufactured using the designed FSW tool; modes are selected by experience.

For the OT-4 alloy, the aim of the research was achieved incompletely: the joint had defects. Further work on the FSW of this alloy will include the designing of a new nozzle that provides the supply of protective gas to the welding zone and the selection of optimal modes.

6. Conclusion
The result of the research proves that the manufacturing of a joint by the FSW for the VT-20 alloy is possible, and the welding scheme for the OT-4 alloy needs further work. FSW allows obtaining sound welds with less labor. This process is amenable to automation, does not require the presence of many skilled workers and a space completely filled with protective gas.

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