Upgrading weld quality of a friction stir welded aluminum alloys AMG6

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Abstract. In the course of introduction of FSW technology into the industry there is a keen interest in this process; there are issues such as how does joining take place, what is the structure of the joint, and where there are dangerous zones. The objective of this research is to obtain information about the structure of the joint, what are the temperatures that arise during the joining, what strength is apply to the tool when joining the material, what tensile strength of joint, and where fracture tended to occur. Specimens were produced at different modes of welding at a tool rotation speed of 315 to 625 rpm and tool travel speed of 40 to 125 mm/min. During the experiment, the strength applied to the tool was measured, which reached 8000–16000 N (Fz) and 400–1400 N (Fx) and the temperature on the surface of the tool, which is in the range 250–400°C. Before the welding process the tool was heated to a temperature in the range of 100–250 degrees, but the tensile strength is not had a tangible impact. The tensile strength is about 80% of that of the aluminum alloy base metal tensile strength, and fracture tended is occur not at the line of joint but follow the shape of the tool. In the transverse cross section of a FSW material there is a microstructural regions such as weld nugget, thermomechanically affected zone and heat-affected zone with parent material.

1. Introduction

In all branches of mechanical engineering there are many assembly works. Depending on the industry, assembly works can reach large volumes percentage of the total amount of technology process of production of the device or the machine. For example, the body of the big vessels may contain welded seams with a total length up to 1000 km, at the same time the main assembly works at assembly of vessels are welding works. Among other industries where a lot of welding work is using during assembly there are also an aircraft industry, rocketry, car building, automotive industry. The research of this process takes place at the Moscow Institute of Aviation Materials [1], at the Tomsk Polytechnic University [2], in the Southern Ural State University and other institutes in the territory of Russia. Higher education institutions and the enterprises make out patents [3-7]. Foreign firms and research laboratories also conduct researches and works on introduction of this process in the industry, among them there is ESAB, SAPA (Sweden), Boeings Eclipse Aviation Corporation (USA), EADS (France, Germany), Institute Soudure (France), DanStir (Denmark), etc.
Friction stir welding is a solid state welding process used for welding similar and dissimilar materials by the tool, which have tool shaft, shoulder and pin with threads (Figure 1).

The perspective directions of researches are joining of titanic alloys and joining of dissimilar materials. At the same time, application of an additional effect on a joint and use the special tools may to achieve the increase of efficiency of welding and tensile strength of a joint. However, researches on aluminum alloy welding remains relevant, since aluminum alloys are using in such industries as rocketry, aircraft industry, shipbuilding; for this reason the interest in joining this material is constantly present. Research of this paper is directed to upgrading of tensile strength and efficiency. The authors suppose that tensile strength of joint of aluminum alloys may reach the tensile strength of parent material, to reach this strength it is necessary to research microstructure of joint and investigate broken specimens for identify dangerous zones.

2. Statement of the problem
For carrying out the experimental works, there is the following inventory: educational and research FSW machine based on a vertically milling machine, and the tool for welding (Figure 2).
Figure 2. Educational and research FSW machine.

The machine is equipped with a research system for filing the parameters of the welding process which allows you to file the strength $F_x$ (the strength acting in the welding direction), $F_y$ (the strength acting perpendicular to the welding direction in the plane parallel to the surfaces of the details being welded – the welding plane) and $F_z$ (the strength acting in the direction perpendicular to the welding plane), and the torque $M_z$.

To file the temperature, the Fluke Ti400 thermal imager was used, the area of the captured image covered the shoulder of tool and the surface of the details being welded. For the testing tensile strength, the Instron 8802 fatigue testing system was used.

3. Theory

1. Welding process

The physics of process of thermomechanical welding assumes itself thermal and mechanical impact on a weld material. In the course of FSW, heating is provide with a sliding friction between the tool and the welded products and the plastic strain caused by the tool pressure upon the surface of material and introduction of a pin upon joint depth and tool travel.

Research that was made earlier proved that temperature during the welding equally depends on the tool rotation speed and tool travel speed, but the temperature before welding depends only on rotation speed and speed of introduction of a pin. The temperature in a welding zone increase during the tool travel will not reach a particular range of values yet. In order to make the weld uniform throughout its length, we need to conduct a research about arising strengths and temperature in the course of welding and check affect whether preheating of the tool and the welded products up the 250°C on strength and temperature after the start tool travel.

2. Tensile strength of a joint

The peculiarity of the microstructure of friction stir weld is that grains in a weld nugget subjected to strong deformation and their size much smaller than size of grains in a parent material, and the joint structure is divided into zones with different sizes of grains. It is assumed that the heat-affected zone have full strength of a parent material because the heat-affect in this area not enough to recrystallize
grains. Dangerous zone in the transverse cross section of a friction stir weld is a weld interface where the microstructure changes. This weld interface shown in Figure 3. Between zones B and C and between weld nugget and zone C.

The shape of a pin also affects the strength of a joint strength and microstructure, which is proved in the paper [9]. For identify dangerous zones it is necessary to get a microstructure image, for this reason were made samples for research.

4. Experimental results

Plates of 2-mm-thick AMG6 aluminum alloy were welded with the tool rotating at speeds of 315 to 625 rpm and travel speed, that is, welding speed, was of 40 to 125 mm/min. Herewith several welds were preheated before welding. The vertical strength was applying to the tool shown on the Figure 4, and the horizontal strength shown on the Figure 5.
Figure 5. Horizontal strength.

For testing tensile strength depending on the welding conditions 60-mm-width specimens was made and testing with 2 mm/min speed of tension. The results we have it shown on a Figure 6 and Table 1.

Figure 6. Tensile test of joints. From left to right – 1, 7 – 500 rpm, 50 mm/min; 2 – 630 rpm, 125 mm/min; 3 – 315 rpm, 40 mm/min; 4 – 500 rpm, 55 mm/min with preheating, 5 – 400 rpm, 80 mm/min with preheating, 6-9 – 500 rpm, 50 mm/min with preheating, 10 – 400 rpm, 40 mm/min.

Table 1. Tensile strength of specimens.

| № of specimen | Tensile strength, N |
|---------------|---------------------|
| 1             | 37793.62            |
| 2             | 35572.62            |
| 3             | 31405.99            |
| 4             | 37291.45            |
| 5             | 34828.50            |
| 6             | 27322.94            |
| 7             | 36964.35            |
Table 1. Tensile strength of specimens.

| № of specimen | Tensile strength, N  |
|---------------|----------------------|
| 8             | 23670.91             |
| 9             | 36163.15             |
| 10            | 38448.54             |

For getting a microstructure image were made samples by wire spark erosion, grinding and polishing were manual handling, etching process took place in 20 % caustic soda bath. Samples were analyzed by means of inverted-stage microscope Axio Observer A1m.

Microstructure image we got was connected in full images of the transverse micro-section of a friction stir welded material (Figure 7–10). There is a thin lines that shows the weld interface, the dotted line shows the visible part of a nugget zone, the thick line shows the rupture line after tensile testing. Scale ruler at the bottom corresponds to 1600 microns. 1 – heat-affected zone with parent material, 2 – thermomechanically affected zone, 3 – weld nugget.

Figure 7. Transverse micro-section of friction stir weld at a tool rotation 500 rpm and tool travel 50 mm/min.

Figure 8. Transverse micro-section of friction stir weld at a tool rotation 315 rpm and tool travel 40 mm/min.
Figure 9. Transverse micro-section of friction stir weld at a tool rotation 500 rpm and tool travel 40 mm/min with enlarged images of the defect «hat crack».

Figure 10. Transverse micro-section of friction stir weld at a tool rotation 630 rpm and tool travel 125
mm/min with enlarged images of the weld zones and weld interfaces. Temperature were arise in the place of friction between the surface of the details being welded and shoulder of a tool shown in Figure 11.

| Temperature, °C |
|----------------|
| 0 | 50 | 100 | 150 | 200 | 250 | 300 | 350 | 400 | 450 |
| t, sec | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |

**Figure 11.** Temperature graph in the place of friction on the surface of the tool for the various welding condition.

5. Discussion
As seen on the graphs (Figure 4, 5) preheating (which was done under the following welding condition: tool rotation 500 rpm and tool travel 40 mm/min; tool rotation 400 rpm and tool travel 80 mm/min, tool rotation 500 rpm and tool travel 50 mm/min) had not a tangible impact on the strength compared with the strength applied to the tool without preheating. The temperature that arise during the joining with preheating more by 40–70°C compared with the joining without preheating, but temperature also had not a tangible impact on the tensile strength (Figure 6, Table 1). The microstructure images we got (Figure 7–10) show the interface between thermomechanically affected zone and parent material and clearly see the weld nugget. These zones can be identified from parent material by color and microstructure. The joint has an asymmetrical structure where the advancing side and retreating side as seen, their mutual position depends on the direction of tool rotation. The weld nugget generally has a tear-drop shape as seen on the Figure 7. The fracture of the welded samples is occur not at the line of a joint but follow the shape of the tool. Figure 7-8 show that fracture follow the cone shape of the pin and is located close to the weld nugget in the thermomechanically affected zone. The tensile strength is about 80 % of that of the aluminum alloy base metal tensile strength (Table 1) except when specimens has joint defect. One of the possible joint defects is shown in Figure 9. The “hat craks” can reduce the tensile strength up to 40 %.

6. Conclusion
To obtain additional, exhaustive information about the friction stir welding process, it is necessary to carry out multifactorial experiments with varying factors affecting the quality of the weld, such as welding condition, tool shape etc.

To upgrading tensile strength of a friction stir weld must be a deeper research of the microstructure of joint. We presume that tensile strength of joint can be upgrading by changing the microstructure by
thermal action. It is plan to carry out experiments using the device for local heating, which the authors are developing. In our opinion, the thermal acting during the joining on welded details will affect the change in microstructure of joint, and it will lead to the fact that sizes of grains from different sides of the interface will not be so various, that it will upgrade the tensile strength of joint.

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