Tensile strength analysis of friction stir welded joints of AlMg6 obtained using additional heating of the parts

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Abstract. During friction stir welding a structure of a material in the welding zone undergoes significant changes: recrystallization occurs with the formation of three different zones: the weld nugget zone, thermomechanically affected zone and heat affected zone. It is known that a significant change in microstructure that observes on the boundaries between the above mentioned zones creates dangerous areas in the weld, and when testing specimens the fracture mostly occurs in these areas. In this study, the tensile strength analysis of friction stir welded joints of aluminum plates of AlMg6 of 3.85 mm thickness obtained using additional heating of the parts was conducted. The macrostructure of the welds was investigated; the fracture line of specimens is shown; the reasons that lead to decrease in durability of welds are identified. The tensile strength of welded joints amounted to 85-93% of the tensile strength of the base metal.

1. Introduction
The friction stir welding (FSW) [1] has proven itself as most effective method for joining aluminum alloys, and its evidenced by the use of this technology at such enterprises as Boeing, Mazda, NASA, Space-X etc. [2-4]. The analysis of publication activity in the ScienceDirect database shows that the number of studies in this topic increases every year. The most perspective areas are joining dissimilar materials, joining of composites and joining of titanium alloys.

2. Formulation of the problem
For increasing the durability of welds it is proposed to use the additional heating of parts during welding. It is assumed that the additional heating will affect the recrystallization process and strengthen the specimens. The aim of the study is to analyze the durability of the specimens of AlMg6 aluminum alloy manufactured using FSW method; the analysis of the macrostructure of the joints and the determination the fracture lines of the specimens that were obtained under various welding modes.

3. Theory
It is known that in the FSW process in the place of the weld seam mechanical stirring of the plasticized material is occur, it is lead to the recrystallization process and formation of the small size grains (smaller than grains in the base metal). Three zones are distinguished in friction stir weld: weld nugget zone, thermo-mechanically affected zone and heat affected zone (Figure 1). It is worth nothing that shape of the zones and their relative dimensions differ when using tools with different geometries. (Figure 2) [5-8]. The research [6] showed that grain size difference between weld nugget zone and thermo-mechanically affected zone can reach 6 nm, and with different welding modes, that difference can be more and less. This research also showed that in the weld seam, reduced grains are found on average 2 times more often than in the base metal. The friction stir weld structure also distinguishes the advancing side and the retreating side, which depend on the direction of rotation of the tool.
From the advancing side, the direction of rotation of the tool and the direction of the tool travel are aligned.

**Figure 1.** The friction stir welding structure

In the case when the tensile strength of the weld is lower than the tensile strength of the base metal, the fracture line if the specimen is observed close to the boundary between the weld nugget and thermomechanically affected zone or between thermomechanically and heat affected zone, if there are no any defects in the specimen [6].

**Figure 2.** Examples of tools for FSW and corresponding macrostructure of welds
4. Experimental results
The experiment was carried out on scientific-research machine for FSW made by JCS “VNIIMALMAZ” equipped with a system for recording welding parameters (axial force in this study). Workpiece material - aluminum alloy AlMg6 thickness of 3.85 mm. The tool for FSW also made by JCS “VNIIMALMAZ”. The tool has a conical pin with helical flutes of various pitch and depth and spiral shoulder. During welding the temperature in the field of contact between the tool and the workpiece was recording using a Fluke Ti400 thermal imager. Four specimens were made: without heating (№1), with additional heating of the area in the front of the tool (№2), with additional heating of the tool during welding (№3), with additional heating of the area behind the tool (№4). Additional heating was carried out by a stream of air heated to a temperature of 400 ºС. The schemes of experiments and the heating area are shown on the figure 3. The tool rotation speed was 800 rpm, and the tool travel speed was 80 mm/min to all specimens. Before welding, pretreatment of sample by milling was not carried out.

Figure 3. The schemes of experiments and the heating area; a) – without heating; b) – with additional heating of the area in the front of the tool; c) – with additional heating of the tool during welding, d) – with additional heating of the area behind the tool

The obtained welds were cut into specimens for static tensile testing (two specimens from each weld) and macrostructure analysis. The specimens were tested using an Instron 8801 fatigue test system at a speed of 2 mm/min. The etching of polished samples for the analysis of the macrostructure was carried out in a 10% sodium hydroxide bath; samples were analyzed using an Axio Observer.A1m inverted microscope. The axial force that has been recording during welding is shown at Figure 4.
Figure 4. The axial force during welding

It can be seen from graph that the axial forces during welding of specimen’s №1, №3 and №4 in the second half of the weld differ slightly, while at the start of welding (section from 0 to 30 seconds corresponds to the first 40 mm of the seam) when welding specimens №1 and №2, the force was less, in contrast to №3 and №4. This can be explained by the difference in temperature in the contact zone and, accordingly, the amount of plasticization of the material and also the error in the plunging depth (± 0.1 mm). To verify this assumption, we look at the temperature graph during welding (Fig. 5).

Figure 5. The temperature in the field of contact between the tool and the workpiece

After the stabilization of the process, the temperature during welding is oscillate in the range of 20–40 °C, which is the usual for this welding method and was repeatedly noted earlier. During welding of specimen №2, the temperature was higher than that of other specimens, throughout the entire weld. This fact can explain the decrease in axial force (Fig. 4). The minimum temperature was observed during welding of specimen №1, which is explained by the absence of additional heating, unlike other specimens. There is no obvious correlation between the temperature and axial force; both values oscillate in a certain range. It can be argued that as the temperature rises, the axial force decreases, but the correlation of the force and temperature during welding requires further more rigorous research.

The received macrosections are shown on fig. 6-10. On the macrosections a white line marked the fracture line of the specimens. On the right side of the image is the advancing side; on the left is the retreating side.
The macrosections clearly show the weld nugget zone and the thermomechanically affected zone, the boundaries between the zones is also clearly visible. When analyzing macrosections on all specimens, a defect «joint line» was found. The defect according to many researchers [9, 10] is a stirring joint line between two plates and is formed in the presence of oxides at the joint before welding. Accordingly, to eliminate this defect, it is necessary to remove the oxide layer from the surface of the workpieces before welding. This defect is a polyline, starting from the root and skirting the weld nugget zone.

The enlarged image of a defect without scale is shown in Fig. 10. With an increase in the duration of etching, the defect is etched more clearly. In specimens №3 and №4, discontinuities in the weld nugget zone are observed, which is also due to the increased etching time.
Figure 10. The «joint line» defect

Analyzing the position of the fracture lines, we can conclude that the fracture begins at the bottom of the joint in a «joint line» defect. In addition to this defect, thinning of the specimens is also observed (Fig. 11), which also reduces the strength (Fig. 12).

Figure 11. Thinning of the specimens №1-4
Figure 12. Tensile strength of the specimens №1-4. The upper dashed line shows the tensile strength of the base metal

5. Discussion
The tensile strength graph (fig.12) shows that the highest values are observed for the specimens №1 and №3. The tensile strength of the specimen №1 is 93% despite the 95% thinning and the ‘joint line’ defect. It can be assumed, that if eliminate these defects, then the tensile strength can reach 100% or more of the base metal.

6. Conclusion
If we take into account the error (error between two tests of the same specimen), analyzing the data we can conclude that additional heating of the area in the front or behind the tool by the stream of air heated to 400 ºС does not have a significant effect on the quality of the joints. In general, we can conclude that additional heating reduces the tensile strength of the joint. The highest value of the tensile strength is obtained by FSW with additional heating of the tool during the welding process. In manufactured joints, the fracture is taking place in the weld seam, which is caused by thinning (from 93% to 96%) and «joint line» defect on all specimens. It can be concluded that to increase the durability of the joints, it is necessary to remove the oxide layer from the workpiece in advance and adjust the plunging depth of the tool in such a way as to exclude thinning, or to do local thickening for a joint.

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