Improving the quality and efficiency of friction stir welding of aluminum alloy plates

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Abstract. Friction stir welding (FSW) is best suited for welding large-sized aluminum alloy parts. Finding optimal welding conditions and methods for minimizing defects arising during welding is an urgent task, the solution of which is necessary for the commissioning of FSW technology into the industry. The introduction of this method for welding rocket fuel tanks will increase the productivity of manufacturing products and their strength. The aim of this study is to improve the quality of friction stir welding of 7.6 mm thick Al-Mg6% aluminum alloys, as well as to increase productivity. The aim is achieved by finding optimal welding conditions and modernizing the welding method for simultaneous stripping by milling. The optimal welding modes found as a result of the study allow ensuring the strength of the welded joint, reaching 98% of the strength of the base material. The modernized welding method allows milling (deburring) to be carried out simultaneously with welding, which can significantly reduce the manufacturing time of the product, for which deburring is a necessary operation. As a result of the study, the welding modes were also revealed, leading to the appearance of hidden defects, which can reduce the strength of the welded joint by 2 times. A conditional diagram showing the appearance of defects in various combinations of modes has been compiled.

1. Introduction

The friction stir welding method was patented 30 years ago [1]. An active study of this began in the 2000s, mainly for joining structures made of aluminum alloys. At present, several independent directions have emerged from this process on the basis of friction stir processing – surfacing, the creation of composite materials, forming, tunneling, etc., which are being studied and developed by researchers around the world.

Most of the studies are aimed at finding optimal conditions or modeling of the welding process. The data obtained during the research is used in the commissioning of the welding process in the industry. It is known that the FSW process has proven itself well in welding aluminum alloys and dissimilar metals and is currently used by Eclipse Aviation, Honda, Mazda, Boeing, NASA, etc. [2] FSW has found application in aircraft and rocket building, shipbuilding, automotive and car building. FSW is most effective when welding large-sized parts made of aluminum alloys, since: welding can be carried out at a sufficiently high speed, which has been proven by researchers AG Boytsov, VV Kachko and DN Kuritsyn [3]; the strength of the joints can reach a strength close to that of the base material [4]; there is practically no tool wear under optimal conditions; welding temperature does not exceed 500 °C, which allows the use of alloy steel tools. These products include the tanks of carrier rockets, for example, tanks of fuel and oxidizer "Proton-K", which are made of AMg6 alloy. The welding method will also be used to weld the fuel tanks of the Angara launch vehicle. When welding such critical parts as fuel tanks, great attention must be paid to the quality of the seam and its strength. The second task is to increase productivity, since the total length of welded seams of large-sized tanks can reach tens and hundreds of meters.
For welding of the above parts, it is necessary to determine the optimal welding conditions and the strength of the resulting welded joints. Previously, the optimal welding conditions of the AMg6 alloy with a thickness of 2 and 4 mm were determined [5, 6], but they are applicable only for the indicated thicknesses. In this regard, it is necessary to conduct a study on the welding of 7,6 mm thick AMg6 alloy plates, which is close to the thicknesses of real products of the rocket industry.

2. Formulation of the problem
The aim of this study is to find the optimal FSW conditions for plates made of AMg6 alloy with a thickness of 7.6 mm, at which the maximum strength of the welded joint is achieved, and to increase the efficiency of welding.

To achieve this goal, it is necessary to make samples of welded joints using various welding conditions, to investigate their quality and strength; and also to modernize the welding method to increase the productivity of manufacturing products using the FSW.

3. Theory
It is known that one of the most common defects is the appearance of burrs at the edges of the joint, as well as the rise of the edges relative to the surface of the welded parts due to plastic deformation of the heat-affected zone (Figure 1).

![Figure 1. The cross-section of the AlMg6 joint with a thickness of 4 mm, showing defects "burr" and the rise of the edges relative to the original surface of the parts to be welded](image)

Techniques that minimize the possibility of these defects exist, including finding optimal modes and using a tool that guides the plastic metal during welding inside the weld [7]. However, these techniques do not lead to the complete elimination of the defect, but only reduce its size. Slight burr and edge lift is acceptable on many products, but in critical products such as missile tanks, these defects must be eliminated. Most often this is done by subsequent deburring by grinding or milling. Most welding machines allow for deburring, for this it is enough to replace the welding tool with a milling one and process the parts. However, the milling deburring can be quite lengthy on large-sized products, the total length of welded seams of which can reach significant values. In addition, it is necessary to take into account the time of tool change and changeover to the deburring operation, which on small machines can take about 10 minutes, and on machines for welding large-sized products - up to 1 hour. This leads to an increase in the production time of the product.

One of the significant features of FSW is the formation of a tool trace from welding, which is visible on the outer surface of the welded products and is formed as a result of the contact of the rotating tool shoulder with the plasticized metal. This trace represents semicircles following one after another, which in the section along the plane of the joint have a wavy relief (Figure 2, a). Most often, the trace is not considered a defect and may not be eliminated, but this does not apply to products of the rocket industry, in which the maximum surface roughness, for example, of a tank, is clearly indicated in the technical documentation. An additional defect, unacceptable on critical products, is the formation of tears on the surface of the weld (Figure 2, b), which can appear even under optimal conditions.
Figure 2. a) relief after the tool, shown in section along the plane of the joint; b) image of a defect in the form of scoring on the surface of the weld

To determine the order of magnitude of the surface roughness of the relief after welding tool, the roughness of the samples obtained in different welding conditions was measured, the measurement results are presented in table. 1. Roughness was measured with a MahrSurf PS1 profilometer in the direction of movement of the welding tool. It is clear that the roughness values significantly exceed the surface roughness of the tank, which should be no more than Ra 6.3. Accordingly, this is unacceptable and subject to improvement.

Table 1. Roughness of the surface trace of the welding tool

| Rotational speed, rpm | Transverse speed, mm/min | Surface roughness (Ra, µm) |
|----------------------|--------------------------|----------------------------|
| 800                  | 40                       | 5.3                        |
| 630                  | 100                      | 11.3                       |
| 800                  | 125                      | 7.0                        |
| 800                  | 40                       | 7.8                        |

It is because of the appearance of the above defects in the rocket industry that the weld is cleaned. To increase the productivity of manufacturing welded products in the rocket industry, it is necessary to modernize the welding method and develop a tool for simultaneous milling deburring. Combining the welding and deburring operations into one will significantly reduce the time for manufacturing a product due to the enlargement of operations and the elimination of changeover time.

4. Experimental results

Experiments were carried out on a scientific research machine for FSW, which was presented earlier in another study [5]. The welding tool has a tapered pin with double helical grooves with different angles of inclination, spiral grooves are also made on the shoulder. An image of the instrument was presented earlier in the study [5]. During the welding process, the tool pressure force on the workpieces being welded was monitored and recorded using an automated system, and the temperature at the point of contact of the shoulder with the surface of the workpieces to be welded was recorded in the video recording mode using a Fluke Ti400 thermal imager.

Quality control of welded joints was carried out by metallographic examination using an Axio Observer Alm microscope. For metallographic studies, the samples were pressed into a two-component resin, then they were subjected to grinding and polishing, followed by etching with a 20% sodium hydroxide solution by washing to reveal the macrostructure.

The strength of the samples was tested using an Instron 8802 dynamic and fatigue testing system. Selected samples were tested for tensile strength at a tensile rate of 4 mm/min. A photograph of the machine with the samples under study is shown in Fig. 3.
Figure 3. Tensile strength test of specimens

The used welding machine has 18 standard rotational speed steps, of which the minimum is 31.5 rpm, and the maximum is 1600 rpm with a step corresponding to the denominator of the series $\varphi=1.26$. For welding the samples, the values of rotation frequencies were selected in the range from 500 to 1250 rpm with intermediate values of 630, 800, and 1000 rpm, respectively. The transverse speed was chosen for similar reasons, according to the possible feeds on the machine from 40 to 125 mm/min. The angle of inclination of the tool relative to the parts to be welded is 2° and 3°. The plunge depth of the tool was selected in such a way that the distance between the substrate and the tool end was from 0.1 mm to 0.2 mm.

Before welding, the specimens were placed on a ground hardened steel substrate and fixed with clamps from above. The parts were fixed against each other in a direction perpendicular to the joint using side screws on a fixture for fixing the parts to be welded.

To find the optimal welding conditions, samples 1-9 were made (Table 2). For welding, samples were cut with a length of 120 mm, a width of 50 mm and a height of 7.6 mm by milling. Before welding, the edges to be welded were cleaned by milling and degreased. The tool tilt angle for most samples was 3 °. When the angle was changed to 2° on sample No. 4, a joint with significant visible defects was obtained, for this reason the tool tilt angle on subsequent samples was set to 3 °.

| №  | Rotational speed, rpm | Transverse speed, mm/min |
|----|-----------------------|--------------------------|
| 1  | 800                   | 40                       |
| 2  | 1250                  | 100                      |
| 3  | 1250                  | 80                       |
| 4  | 800                   | 80                       |
| 5  | 800                   | 40                       |
| 6  | 500                   | 80                       |
| 7  | 630                   | 100                      |
| 8  | 800                   | 125                      |
| 9  | 1000                  | 40                       |
The welding temperature and the pressure force of the tool on the parts to be welded is shown in Fig. 4 and fig. 5. The graph of temperature depending on the welding time was built point by point every second from the beginning of the tool movement, and then a polynomial trend of the sixth degree was built for greater information content and readability of the average, minimum and maximum temperatures in different sections of the weld. The welding forces were recorded using an automated system with a step of about 0.15 seconds. In Fig. 5, the axial force data were excluded when welding sample No. 1, since this sample was used to select the optimal immersion depth of the tool, and the axial force changed significantly, which made it difficult to read the graph. To increase the readability of the graphs, the modes of welding samples from Table 1 were duplicated in the legend on the graphs, where \( n \) is the rotational speed (rpm), \( s \) is the feed rate (mm/min), and \( a \) is the tool tilt angle (deg.).

**Figure 4.** Graph of temperature versus welding time for samples 1-9, obtained using a thermal imager

**Figure 5.** Graph of axial force versus welding time for samples 2-9
After welding, a visual inspection of the obtained samples was carried out. During the inspection, samples were identified that had significant defects visible on the surface of the weld, an example of a sample with and without a defect is shown in Fig. 6. In addition, a defect in the form of a burr was present to a significant (Fig. 6, a) and an insignificant extent (Fig. 6, b) on all samples.

![Figure 6. The front surface of the welded seams: a) a sample without visible defects and with a slight burr (No. 6); b) a sample with visible defects and significant burr (No. 2)](image)

To study the samples for tensile strength and manufacture microsections, samples were selected that did not have visible defects, namely: No. 1, No. 6, No. 7, No. 8 and No. 9, obtained with a rotational speed of 800, 500, 630, 800 and 1000 rpm and feeds 40, 80, 100, 125 and 40 mm/min respectively, with a tool tilt angle of 3°. Samples were cut from the second half of the seam at the same distance from its beginning, the cross-section of the samples had dimensions of 19.95x7.6 mm. The graph of the dependence of the relative elongation of the samples on the load is shown in Fig. 7. When testing sample No. 6, a rupture occurred not in the welding zone, but in the base metal, near the place where the sample was fixed in the test setup. In this regard, the sample was reinstalled and again loaded in tension; the data on repeated loading are shown in Fig. 7 as "No. 6 add." In the same place, "BM" - the base material, without a weld seam, to assess the relative strength of the seams. The obtained values of the tensile load, ultimate strength and relative strength are presented in table. 3.

![Figure 7. A graph of the dependence of the relative elongation on the load during tensile testing of specimens 1, 6, 7, 8, 9](image)
Table 3. Results of specimens tensile test

| №   | Breaking load, N | Ultimate strength, MPa | Relative strength, % |
|-----|-----------------|------------------------|---------------------|
| 1   | 31311,62        | 211,5                  | 59,54               |
| 6   | 48641,15        | 317,9                  | 89,50               |
| 6 add. | 54456,70    | 355,6                  | ~100                |
| 7   | 52974,88        | 350,33                 | 98,63               |
| 8   | 42853,60        | 282,7                  | 79,59               |
| 9   | 22217,98        | 146,48                 | 41,24               |
| BM  | 54082,74        | 355,2                  | 100                 |

Specimens No. 1, 6, 7 and 9 were also prepared for the macrostructure investigation. Microsections of this after etching are shown in Fig. 8.

![Fig. 8 Macro image of the cross section of welds](image)

To increase the efficiency of the welding process, a method of welding with simultaneous deburring by milling was developed. The method allows simultaneous welding using a combined tool that includes milling cutting inserts. The developed method makes it possible to eliminate a defect in the form of burrs and a trace of the tool movement almost immediately after their occurrence. The method implementation diagram is shown in Fig. 9, a. The weld obtained using the developed method is shown in Fig. 9, b. Surface roughness measurement with a profilometer after deburring showed the value Ra=0,9-0,7, which is much better than the required Ra=6,3.
Figure 9. a) – scheme of the method of FSW with simultaneous deburring by milling (1 – parts to be welded; 2 – welding tool; 3 – milling fixture; 4 – cutting plate; 5 – deburred area; 6 – joint of the parts to be welded); b) – a sample obtained using the developed welding method with simultaneous deburring by milling

5. Discussion

According to the data obtained, it can be seen that samples that do not have visual defects may have hidden defects in the form of lack of penetration, which significantly reduce strength. Such defects include a defect on sample No. 1, shown in Fig. 8. The presence of a defect in the form of lack of penetration led to a decrease in the strength of the welded seam to 59.54% of the base material strength. This defect can be caused by a combination of elevated temperature, which can be seen in Fig. 4 for this sample in combination with the optimal value of the axial force (Fig. 5, sample No. 5). It can also be seen from the graphs that low transverse speed lead to high temperatures during welding, which leads to overheating and the appearance of defects.

The best results in tensile strength were for specimens 6, 7 and 8. The modes, using which these samples were made, it is advisable to recognize as optimal. These modes minimize the appearance of defects in the structure of the weld. The appearance of defects in the form of micropores on sample No. 6, which showed high results in strength, is subject to further study, as well as its effect on the strength of the joints.

Figure 10 shows a summary diagram of the combination of welding conditions, in which the combinations of modes for defect-free and defective samples are shown in different colors. The numbers next to some of the points show the relative strength of the sample obtained with the corresponding combination of modes. The diagram clearly shows that the optimal modes are located on one line, which should be extrapolated and verified in the future.
Also, a welding method was developed and tested using a combined tool that allows for deburring by milling. The results showed that the application of the method with the developed fixture can be implemented using a tool of any design and allows obtaining a roughness with a value of not more than 0.9 Ra at a rotational speed of 500 rpm and a feed rate of 80 mm/min.

6. Conclusion
Based on the results of the study, the following conclusions were made:
1) Found 2 optimal combinations of friction stir welding modes of AlMg6 aluminum alloy 7.6 mm thick: rotational speed 500 rpm and transverse speed 80 mm/min, as well as 630 rpm and 100 mm/min respectively at a tool tilt angle 3°.
2) The use of the found combinations of modes makes it possible to obtain a defect-free joint with a strength reaching 98% of the strength of the base metal.
3) Tensile testing of specimens showed that the optimal modes allow to reach the strength values of the base material rather closely, however, specimens with a welded seam have a 10-15% lower relative elongation, which allows us to conclude that the ductility in the welded seam zone is lower than with base material.
4) It has been revealed that certain combinations of modes make it possible to obtain an externally defect-free welded seam, which may contain hidden defects that reduce the strength of the welded seam to 41% relative to the base material. A conditional diagram has been drawn up, which makes it possible to identify the area of the combination of modes leading to hidden defects.
5) The optimal values of the axial force have been found, which ensures defect-free joints at optimal conditions - from 20 to 31 kN (Fig. 5, values from the graphs of the axial forces of the samples with the highest strength).
6) The optimal temperature was found in the contact zone of the tool shoulder with the surface of the welded parts, providing defect-free joints at optimal conditions - from 310 °C to 380 °C (Fig. 4, values from the graphs of the welding temperature of samples with the highest strength)
7) It was determined that the values of the axial force below 20 kN and temperatures above 380 °C lead to the appearance of defects, including hidden ones (Fig. 4 and 5, values from the graphs corresponding to samples with low strength and samples with visible defects)
8) The method of friction stir welding has been modernized, which allows simultaneous deburring by milling, which leads to the elimination of a defect in the form of burrs and a trace of the movement of the
The use of the modernized method makes it possible to significantly increase productivity in the manufacture of large-sized products by combining welding and deburring operations and eliminating the time for tool changeover. The developed milling fixture can be installed on a friction stir welding tool of any design on any machine, while the high temperature arising during the welding process does not negatively affect the fixture.

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