Friction welding with stirring of aluminium alloys AMg-5

A E Balanovsky, M V Grechneva, N O Tyurin, A I Khusanov
Irkutsk National Research Technical University, 83, Lermontov St., Irkutsk, 664074, Russia

Abstract. The results of friction-stirring welding with stirring are presented on the example of the aluminum alloy AMg-5. The technological process on the experimental installation is briefly described. Defects arising in the process of friction stirring welding are assessed. Main stages of friction welding technological process are singled out. In the course of researches it is established that during the process the tool rotation speed and feed speed are combined in such a way that an asymmetric metal flow is obtained. Welding parameters and the size of the tool in the FSW process have a decisive influence on the total torque, which determines the need for clamping equipment and tool lifecycle. It is shown that the total torque and torque components from different parts of the tool at different welding parameters and size of the tool change slightly depending on the welding speed, but the total torque remains constant.

1. Introduction
Aluminum alloy is one of the most promising light materials due to a number of excellent characteristics, such as light weight, corrosion resistance, strength, etc., which is widely used in aircraft engineering[1, 2]. Currently, the only process providing for the production of finned panels of aircraft made of high-strength aluminum alloys is the milling technology. In the process of milling, the bulk of the billet metal is converted into chips (the percentage of metal usage is 2-3)[3, 4]. After milling, the finned panels are molded by stretching on special standards. Considerable technological allowances are also given for this operation. Traditional technologies of point connection of aluminium alloys are contact point welding, fusion welding and riveting. In order to reduce the material intensity of the welded contact welding technological plates are used, which often do not withstand the applied loads. There are many shortcomings[5,6], such as high power consumption, high current and high deformation for contact spot welding, as well as low production efficiency and harmful working conditions for riveting. Despite many improvements in the field of fusion welding[7,8], contact spot welding and riveting, there has been no qualitative breakthrough in the mechanism and properties of the joint over the past 20 years. The new FSW technology has great potential[8,9] because it can significantly reduce weld defects such as oxide inclusions, porosity, cracks and deformations commonly found in aluminium alloy welds. In contrast to fusion welding methods, FSW allows the heating of materials to be joined below their fusion temperature. Therefore, during the whole FSW process, there is no large-scale or obvious liquid state in friction stirred welds [9,10]. Nowadays, the main research and development activities related to FSW technique have been focused on aluminum alloys, which allowed expanding the commercial application of FSW for aluminum alloys in various industries [11,12]. At the same time it is necessary to understand[8,13] that the flow of viscoplastic material flow during FSW is asymmetrical between the retreating side (RS) and the advancing side (AS) only when the process parameters at the FSW plant are constant. The behaviour of the plastic flow of the material along the direction of the workpiece thickness, which is also parallel to the Z-axis of the tool, depends to a large extent on the geometrical design of the
mixing tool [14-20]. If the constancy of welding parameters at FSW is not carried out, then inevitably there are various visible or potential defects in the zone of the weld, the zone of thermomechanical influence or on the border of the section [16-24]. This paper presents the results of research of technological parameters of friction welding with mixing on the formation of a quality weld.

2. Materials and methods of the research
Industrial thermally unstable deformable aluminum-magnesium alloy AMg5 (foreign analogue - alloy 5083) in the form of rolled plates 4.5 mm thick was chosen for the study. The experiment was carried out on a universal milling machine, temperature measurements in the heating zone were carried out with the help of a pyrometer. The clockwise rotating tool was buried in the sample at different angular speeds until the shoulder was touched, after which the longitudinal feed of the table was turned on and welding was carried out [9,10]. The working tool is a cylinder with a diameter of 22 mm and length of 65 mm, one of the ends of which is a truncated cone with a threaded cut Fig. 1. Fig. 1 shows the general view of the welding process and the shape of the working tool before the beginning of welding pos.1 and after welding pos.2,3. Welding modes are presented in Table 1. Samples for testing of welded joints met the requirements of GOST 6996 cut across the welded joint with the location of the weld in the middle of the working part of the samples. The test result for each welding mode was an arithmetic mean of the strength values of three destroyed samples. Static bending tests were carried out to determine the ability of the welded joint to withstand a given plastic deformation to assess the ultimate plasticity of the metal at bending.

![Figure 1. Friction stir welding process diagram and shape of the working tool](image)


Table 1. Basic parameters for friction stir welding

| Number of the sample | Density, mm | Tool speed, turn/min | Delivery speed, mm/min | Pressing force, kg |
|----------------------|-------------|----------------------|------------------------|-------------------|
| 1                    | 4           | 1550                 | 300                    | 2600              |
| 2                    | 4           | 1200                 | 300                    | 2600              |
| 3                    |             | 800                  | 300                    | 2100              |
| 4                    |             | 550                  | 300                    | 1500              |
| 5                    |             | 1550                 | 500                    | 2700              |
| 6                    |             | 1200                 | 500                    | 2900              |
| 7                    |             | 800                  | 500                    | 2600              |
| 8                    |             | 550                  | 500                    | 2100              |

3. Results of the research and discussion

In the carried out researches in the general case the width of a welded seam (Lw) depended on the size of the used welding tool. All the welded joints studied in this paper (Fig. 2) were made with tools that formed for 4.5 mm thick plates with a width of ~20 mm. In order to obtain an effective vertical flow of material, different forms of pins can be used, such as cylindrical, conical or smooth conical [10-24]. However we noticed that the thread of the tool wears out during FSW, which leads to "self-optimized" smooth surface of the pin Fig.1 - 2,3. Spindle torque, tool speed and force applied to the spindle were measured during welding experiments and used to evaluate the process. The torque has an initial jump in absolute value, which corresponds to the immersion phase of the tool. Then the torque tends to follow a constant range of changes resulting from the displacement of the tool during welding. In the last step, the tool movement is stopped and the tool is retracted, resulting in a rapid reduction of torque to near-zero values. The force applied to the spindle represents a very similar behavior. The main stages of the friction stirring welding process have been established in the course of the experiments. Cutting stage: The tool, which rotates at a constant speed, cuts through the starting point of the workpiece joining line under the action of the axial force directed vertically downwards until the shoulder touches the workpiece surface. This stage initiates the deformation process. Heating and plasticizing stage: the rotating tool is delayed by 5-10 s depending on the material and thickness under the action of axial force from its shoulder, which is in contact with the surface of the workpiece. This action generates sufficient heat from the friction process on the tool and workpiece interface and causes the workpiece to plasticize, generating more heat for plastic deformation. Plasticized material in front of the tool ensures smooth running of the tool at the next welding stage. Welding stage: the rotating tool is driven by axial load and shoulder, covering the plasticized volume, and moves at a constant speed along the required connection line by the force of movement. The rotation of the tool continues to generate heat due to friction and deformation. Another important function of tool rotation is to mix the plasticized material in the form of a material flow. Rotating and transverse movements of the tool cause the plastic material to flow from the moving side to the back of the tool pin near the tool pin. The arm applies pressure to the material behind the pin, effectively filling the cavity created by the progressive movement of the pin. This causes the material to mix in the form of atomic diffusion or binding depending on the temperature and pressure conditions, resulting in a joint behind the tool. Tool withdrawal and cooling stage: upon arrival at the end of the weld, the tool is retracted from the workpiece, leaving an exit slot behind. Several procedures are in place to avoid the exit wound in the weld. These include refilling the outlet or using a longer weld length than the estimated length (outlet strips) and automatically lifting the tool smoothly for a specified period of time before the process is completed.

In the course of the carried out researches it is established that during the process the speed of rotation of the tool and the speed of feeding are combined in such a way that an asymmetric metal flow is obtained. In particular, the moving side and the retreating side are observed: the first one is characterized by a "positive" combination of tool feed speed and peripheral tool speed, while the second one has opposite vectors of tool feed and rotation speed. Detailed observation of the microstructure of the material in the weld section by Nelson and his colleagues [18] has shown that there is an area located in
the center of the weld, called the "core", where the initial boundaries of grain and subgrain, apparently, are replaced by thin recrystallized equal-axis grains, having a nominal size of several micrometers [14-20]. As the speed of the tool increases at a constant speed, the trend towards internal defects in material loss becomes more obvious. The defects of material loss include the tunnel, porosity, void and flash. The main reason for the internal material loss defect is that the material defect cannot immediately fill the cavity left by the movement of a rotating FSW tool. During rotation and transfer of plasticized material, if the resistance to the materials coming to the rear edge of the tool is too high, the filler material is converted into an excessive flash defect (metal splash) on both sides of the welded seam in Figure 2. On the contrary, the large immersion depth of the tool causes excessive flash and cavity (tunnel defect) due to overpressure on the tool arm. Optimization of the process parameters is of course closely linked to the weld defect mechanisms of the FSW welded joint and the robust FSW butt joint. Fig. 2 shows the appearance of the stirred welds, which have a serious flare defect (Fig. 2, item 1, 3). This defect is due to the high pressure of the tool shoulder on the metal surface and the result is a large mass of plastic metal displaced to the periphery of the weld in the form of a thin strip. On the other hand, the defect in the flash can be caused by excessive frictional heat from the tool arm during FSW and as a consequence of the softening of the material. The defect of the "tunnel" type (Fig. 2, item 1, 2, 3) is formed at the end of the process at the point of tool stop.

Figure 2. Appearance of the weld after friction stir welding

Around the tunnel defect (i.e. continuous duct-shaped cavities extending in the direction of welding and located on the moving side of the weld near the GTW/ZTMV boundary), "bulbous structures" with intermittent appearance are formed. Tunnel defects are most likely to be caused by uneven mixing when the direction of material flow in the horizontal plane from the moving side to the retreating side of the friction welds and then around the rotation of the tool from the beginning. As the tool moves in motion, the plastic material flows in the direction of rotation around the tool pin and moves layer by layer, the resulting tunnel defect cavity remains close to the pin due to the unused volume of the submerged pin. Limiting the flow of material on the retreating side to fill the cavity on the advancing side depends on the width of the plasticized material around the pin and the volume of material transferred per revolution. If the flow of plastically deformed material on the retreated side is not sufficient to fill the cavity completely and immediately before cooling to a stationary state, the tunnel defects will remain without hydrostatic pressure. While the shoulder is the main source of heat generated during the FSW process, the main obstacle to material ejection and the main source of material flow around the tool, the pin is the main source of material deformation and a secondary source of heat release in the core of the metal intensive mixing zone. It is obvious that shoulder and pin geometry are important parameters of the FSW process. Thus, the integrity of the weld across the entire cross-section depends primarily on a well-designed tool. First of all, tool geometries such as the height and shape of the pin and shoulder surface of the head have a great influence on both the metal flow and heat generation due to friction...
forces. Second, either the force applied to the rotating tool during the process, or the tool falling into the sheet, must be selected correctly, as the pressure created on the surface of the tool shoulder and under the end of the pin determines the heat generated in the process. Finally, both the speed of rotation and the feed rate should be chosen in order to improve the integrity of the structure over the seam section, resulting in a proper microstructure and ultimately good strength, fatigue resistance and plasticity of the joint. Based on the above, the optimal set of process parameters allows to avoid defects in welded joints. The final requirement for the FSW process is to create a certain amount of heat by friction, which can keep the welding material in a well plasticized state at a suitable temperature, and to create a high hydrostatic pressure along the joint line to ensure a reliable weld.

4. Conclusion
In the course of the carried out researches it is established that the heat generated both by friction and plastic deformation, softens a material near to the tool, and at tool movement there is a strong plastic deformation and a current of this plasticized metal. The material is transported from the front of the tool to the rear edge. The simultaneous rotation and transverse movement of the tool creates an asymmetrical temperature distribution and material flow between the two sides of the weld, resulting in different microstructures and mechanical properties between the moving side (AS) and the retreating side (RS) of the weld. Welded joint asymmetry is a unique feature of the FSW method. The main parameters of the FSW process are: tool speed, travel speed, tool immersion depth, spindle angle and clamping conditions. FSW requires relatively high torque and plunging force for adequate softening of the material to form a good weld structure. The relatively high stress caused by the tool causes severe tool wear and premature tool failure. In addition, the relatively high tangential velocity at the periphery of the shoulder can lead to overheating or even to the beginning of melting along the edge of the shoulder when welding thicker plates, which can lead to a reduction in the mechanical properties of the joint.

References
[1] Nikiforov G D 1972 Metallurgy of Aluminum Alloy Fusion Welding (Moscow: Mechanical Engineering) 264 p
[2] Mathers G 2010 The Welding of Aluminium and its Alloys (Cambridge: Woodhead Publishing Ltd) 236 p
[3] Ryazantsev V I, Fedoseev V A and Matsnev V N 2001 Technological aspects of the assembly-welding of the all-welded passenger aircraft made of the aluminium alloys Technology of mechanical engineering 6 23–6
[4] Muravyov V I, Bakhmatov P V and Melkostupov K A 2010 To the question of the relevance of friction welding with stirring of the high-strength aluminum alloy structures II–1(2) pp 110–25
[5] Balanovskii A E 2018 Study of the Attachment Stage of a Welding Arc Discharge of Direct-Current Straight Polarity on Aluminum Surface High Temperature 56(4) 486–95
[6] Balanovskii A E 2018 Spark Stage of Welding Arc Discharge Binding on an Aluminum Surface High Temperature 56(3) 319–26
[7] Sarrafi R and Kovacevic R 2010 Cathodic Cleaning of Oxides from Aluminum Surface by Variable-Polarity Arc Welding J. 89 1-s
[8] Thomas W M, Nicholas E D, Needham J C, Murch M G, Templesmith P and Dawes C J 1995 Friction Stir Butt Welding Int Patent App PCT/GB92/02203 and GB Patent App 9125978.8, December 1991. US Patent no. 5,460,317, Oct 1995
[9] Thomas W M 1998 Friction stir welding and related friction process characteristics Proceedings of 7th International Conf. “Joints in Aluminium” (Cambridge) 16 April p 52
[10] Dawes C J and Thomas W M 1996 Friction Stir Process Welds Aluminum Alloys Welding J. 3 41–5
[11] Pietras A, Zadroga L and Lomozik M 2004 Characteristics of welds formed by pressure welding incorporating stirring of the weld material (FSW) Welding Int. 1 5–10
[12] Johnsen M R and Johnsen M 1999 R Friction Stir Welding Takes Off at Boeing Welding J. 2 35–9
[13] Tretiak N G and Tretiak N G 2002 Friction welding with mixing of the aluminium alloys (review) Automatic welding 7 12–21
[14] Ryazantsev V I V N and Matsnev V Yu 2004 Friction welding with mixing of the deformable and cast aluminum alloys Aviation industry 4 33–6
[15] Liu H J, Fujii H, Maeda M and Nogi K 2003 J. Mater. Process. Tech. 142 692–6
[16] Rhodes C G, Mahoney M W, Bingel W H, Spurling R A and Bampton C C 1987 Scripta Mater. 36(1) 69–75
[17] Guerra M, Schmidt C, McClure L C, Murr L E and Nunes A C 2003 Mater. Charact. 49 95–101
[18] Su J Q, Nelson T W, Mishra R and Mahoney M 2003 Acta Mater. 51 713–29
[19] Shigematsu I, Kwon Y J, Suzuki K, Imai T and Saito N 2003 J. Mater. Sci. Lett. 22 343–56
[20] Lee W B, Yeon Y M and Jung S B 2003 Mater. Sci. Eng. A 355 154–9
[21] Song M and Kovacevic R 2003 Int. J. Mach. Tool Manu. 43 605–15
[22] Colegrove P A and Shercliff H R 2004 Sci. Technol. Weld. J. 9(6) 483–92