Przemysław Nosal, Marek Hebda

Effect of FSW Process Parameters on Properties of Aluminium Joints

Abstract: Ever since its development in the 1990s, the friction stir welding method (FSW) has been increasingly popular in various industrial sectors, e.g. in transport, power engineering or electronic industry. In spite of its numerous advantages in comparison with conventional joining methods, the FSW method continues to be intensively investigates to develop appropriate technological parameters and geometry of tools ensuring the obtainment of joints characterised by excellent properties. The process of optimisation is required for each new material. The adjustment of proper FSW process parameters, particularly the tool rate of rotation and the travel rate, enables the obtainment of imperfection-free joints as well as significantly affects process efficiency decreasing its laboriousness and costs. The article addresses issues connected with the optimisation of the FSW process by analysing the effects of changes in the tool travel rate and the rate of rotation on structural and mechanical properties of aluminium joints. The tests involved the use of aluminium alloy grade 6063. The test joints were subjected to visual tests, hardness tests, microstructural examination, static tensile tests etc.

Keywords: Friction Stir Welding, FSW, aluminium alloys, FSW process parameters, FSW process optimalisation

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Introduction

The continuous technological development requires the use of materials characterised by increasingly favourable properties, which, in turn, entails intensive research aimed to develop technologically advanced joining methods. In cases of separable joints particular attention must be paid to appropriate geometry and dimensions of such joints. In turn, inseparable joints also require detailed analyses of microstructures formed during welding.

Presently, many industrial sectors use aluminium alloys when making complicated and demanding structures. The favourable mechanical properties combined with the low density of aluminium alloys enable the obtainment of light and heavy-duty products. Aluminium alloys play an important role in aviation, automotive industry or railway transport as they make it possible to manufacture lighter structures than those made of steels and, consequently enable the reduction of fuel consumption. The

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mgr inż. Przemysław Nosal (MSc. Eng.) – Tadeusz Kościuszko Cracow University of Technology; Institute of Applied Mechanics; dr inż. Marek Hebda (PhD (DSc) Eng.) – Tadeusz Kościuszko Cracow University of Technology; Institute of Materials Engineering

successful and efficient fabrication of aluminium structures depends on the application of appropriate joining methods. The most popular and important joining methods used when making inseparable joints include fusion welding, brazing and pressure welding.

Because of their low melting point and strong affinity for oxygen, aluminium alloys are commonly regarded as difficult to weld. As a result of the above-named factors, both welds and surface contain numerous oxides characterised by higher melting point, greater hardness and higher density than those of the base material. In addition, during welding, as a result of the adsorption of hydrogen from air humidity, aluminium may develop undesirable porosity (hydrogen dissolves in the weld and, during solidification, gives rise to porosity).

The TIG or MIG welding of aluminium alloys enable the obtainment of good quality welds free from imperfections, yet the major disadvantage of these processes is their high cost. The above-named methods require the use of, among other things, shielding gases, generating purchase, storage and feeding-related costs. More importantly, the aforesaid welding processes are connected with the emission of gases damaging to the environment and human health and cannot be used to join thin-walled structures. All of the reasons enumerated above inspired research aimed at the development of an alternative welding method. In the late 1990s, Britain's Welding Institute's researchers led by Wayne Thomas developed a friction welding method involving the stirring of the weld material (FSW) [1, 2] and making it possible to overcome some of the limitations accompanying the welding of aluminium alloys.

The joining of materials performed using the FSW method takes place in the solid state [3-8]. Temperatures recorded during the FSW process are usually restricted within the range of 70% to 90% of the melting point of a given material [4, 9]. In addition, the FSW process does not require the use of shielding gases and FSW equipment and tools are relatively simple and inexpensive. Joints made using the above-named method are characterised by favourable properties, homogeneity and minimum strains, i.e. qualities very difficult to obtain using conventional joining methods. In addition, in comparison with fusion welding, the FSW method is less laborious, fully repeatable and automatable [3-6, 10, 11].

The joining of materials using the FSW method starts with inserting a rotating tool at the interface of elements. Usually, FSW tools are cylindrical and provided with a probe and a shoulder. The friction between the tool and the joint surface generates heat plasticising the surfaces of joined elements and enabling the tool to penetrate the material, which, however, does not melt. Having reached a required rate of rotation and penetration depth (in the material), the tool moves along the joint line. The stirring of the weld material results from the effect of the probe and the shoulder, the rotation motion of which forces the flow of plasticised material [4, 6, 12]. The FSW method can be used to make, among others, butt, L-shaped, T-shaped, overlap, multi-overlap, T-shaped overlap and fillet joints.

The FSW method is particularly useful when joining elements made of materials regarded as difficult to weld, e.g. copper and titanium, high-strength aluminium, zircon, magnesium, lead or nickel alloys as well as when making joints of considerable lengths. The FSW process can also replace the riveting of sheets in airplane wing or fuselage sheathings [13]. Crucially, materials joined using the FSW method can significantly differ in their mechanical, structural or physicochemical properties. Many research centres continue to work on the optimisation and adjustment of process parameters in relation to grades of materials being joined. Presently, the FSW technology is used in aviation, automotive industry, railway transport, ship-building industry and refrigerating engineering.

Among friction stir welded materials, the greatest microstructural changes directly affecting the quality and properties of joints can be observed in relation to aluminium alloys. This fact is primarily ascribed to significant plastic strains generated during the stirring of the weld as well as to the heating and cooling of materials. The key aspect of the FSW method is the appropriate adjustment of welding process parameters. Numerous ongoing tests performed by many research centres aim at optimising FSW process parameters, tool geometry and process conditions.

The article discusses issues connected with the optimisation of the FSW process performed in relation to aluminium alloy grade 6063. The test joints, made using various values of tool rotation and travel rates, were subjected to visual tests, hardness and microhardness measurements, microstructural examination and static tensile tests.

Test Materials and Methodology

The tests involved the making of FSW butt joints using 10 mm thick flat bars made of aluminium alloy grad e 6063. The chemical composition of the alloy was verified through tests performed using a Q4 Tasman optical emission spectrometer (Bruker). The chemical composition analysis results were compared with the values determined in accordance with the EN 573-1 standard and presented in Table 1.

Table.1. Chemical composition of the aluminium flat bars used to optimise the making of butt joints using the FSW method

Chemical element	[%]	According to EN 573-1
Mg	0.47 ± 0.01	0.45-0.90
Si	0.48 ± 0.02	0.20-0.60
Fe	0.31 ± 0.03	≤0.35
Ti	0.02 ± 0.01	≤0.10
Cr	0.01 ± 0.01	≤0.10
Mn	0.04 ± 0.01	≤0.10
Cu	0.01 ± 0.01	≤0.10
Al	rest	rest

The welding optimisation process was performed for five joints made using varied values of the rotation rate (V_r) and the travel rate (V_w) of the tool (see Table) 2). The tool inclination angle was constant and amounted to 0°.

Table. 2. Process parameters used when making aluminium joints using the FSW method

Specimen no.	Rotation rate V_r [rpm]	Travel rate V_w [mm/min]
1	710	250
2	710	315
3	1000	315
4	500	315
5	710	400

The non-destructive tests were performed using an Epoch 600 ultrasonic defectoscope (Olympus) equipped with an M112 RM probe. The hardness measurements were performed using the Rockwell method in scale F, a CV-600MBDL hardness tester (Innovatest) and a carbide ball indenter. The morphology of the welds was observed using an Eclipse ME 600 metallographic optical microscope (Nikon). The static tensile test was performed in accordance with the PN-EN ISO 6892-1:2010 standard, using an MTS Criterion Model 43 testing machine and a constant cross-bar travel rate of 0.5 mm/min.

Results

Figure 1 presents the butt joints in relation to the FSW process technological parameters, i.e. the rotation rate (V_r) and the travel rate (V_w) of the tool, consistent with values presented in Table 2.

The observations revealed that the increase in the tool rate of rotation had a more significant influence on the joint surface quality than changes in the tool travel rate. The use of a rate of rotation of 500 rpm and 1000 rpm resulted in the formation of considerable flash along the fusion line. The use of a rotation rate of 710 rpm reduced the above-named flash to a minimum. It was also observed that an increase in the tool travel rate from 250 mm/min to 400 mm/min improved the quality of the weld surface. In addition, ultrasonic defectoscopic tests revealed that all of the joint were characterised by proper structure and were free from imperfections in the welding area. The HRF (hardness) tests involved all of the joints and were performed in areas marked schematically in Figure 2. The tests were performed both on the weld face and root side of the joints. The average values of HRF (hardness) measurement results in relation to various joint areas and all of the specimens are presented in Figure 3.

The test results revealed that the highest hardness was measured in the base material area (the lower the material hardness, the closer to the axis of the FSW process). The hardness decrease in the heat affected zone (HAZ) and in the weld area, in comparison with that of the base material, resulted from the plasticisation of the material and the effect of higher temperature. The observed results were independent of the parameters used when making the joints. Figure 4 presents changes in the weld geometry in relation to the rotation rate and travel rate of the tool used in the FSW process when making butt welded joints in aluminium.

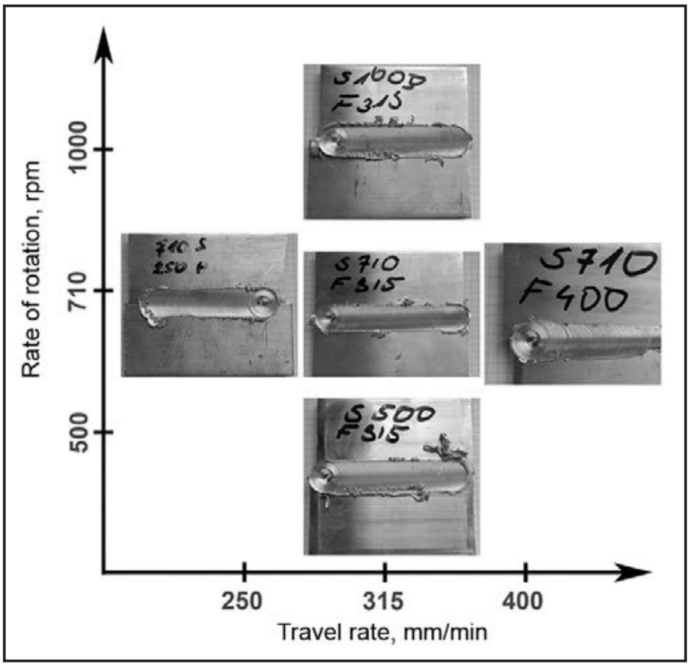

Fig. 1. Butt joints in relation to the rotation rate and the travel rate of the tool used during the FSW process

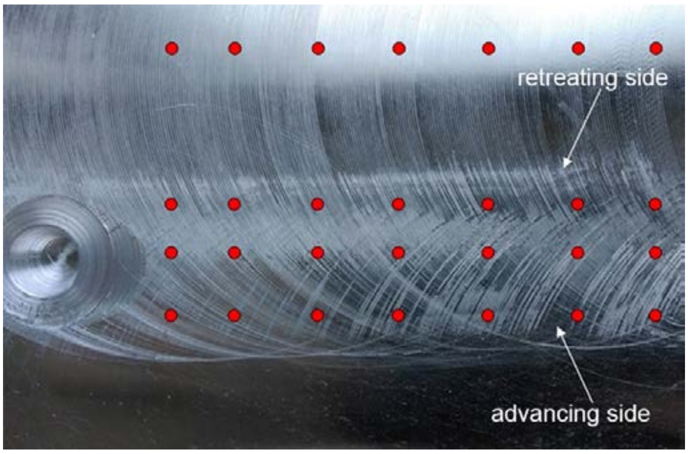

Fig. 2. Areas of HRF (hardness) measurements in various areas of the FSW joint and in the base material

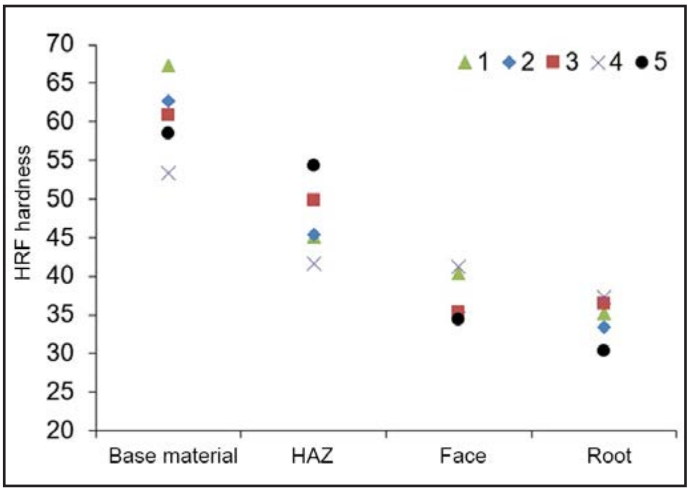

Fig. 3. HRF (hardness) values of all the test joints in relation to areas subjected to analysis

The tests revealed that the weld geometry was significantly affected by the tool travel rate. When a low travel rate of 250 mm/min was used,

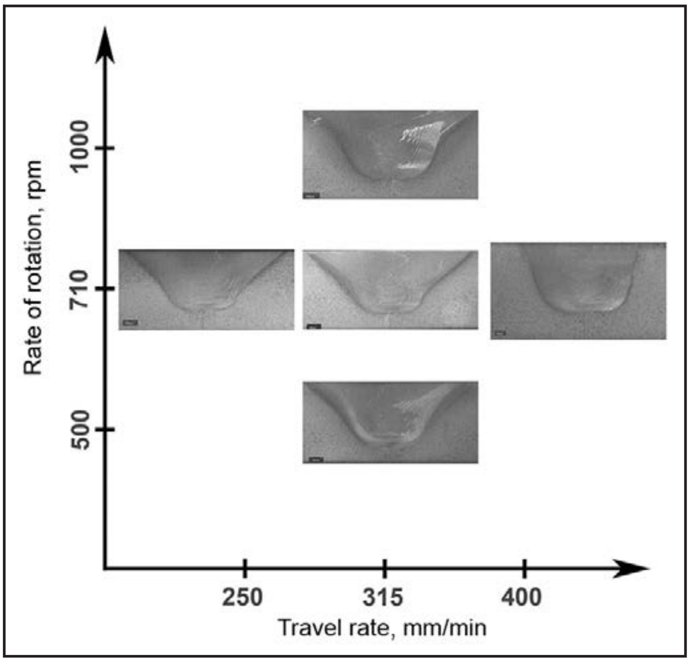

Fig. 4. Cross-section of the welds of the test specimens in relation to the tool rate of rotation and travel rate used during the FSW process

the probe heated and plasticised the material more intensively in comparison with higher travel rates, e.g. 400 mm./min. The weld made using a low travel rate had a trapezoid-like shape. The shape of the weld was more regular and rectangular when higher travel rates were used. In turn, an increase in the tool rate of rotation facilitated the stirring of surface oxides in the weld area, leading to the formation of the oxide line located along the central part of the weld. In addition, the advancing side contained oxidised areas having a characteristic onion-like shape. The above-named effect was connected with the flow of the material around the tool. The joints having the aforesaid microstructure are very likely to develop crack propagation in the above-named areas. The specimen microstructure did not contain the oxide line only where a rotation rate of 710 rpm and a travel rate of 400 mm/min were used. All of the welds made using the FSW method were free from cracks and porosity (characteristic of aluminium welded joints). However, it is a well-known fact that the excessive increase in the rate of rotation and that in the travel rate lead to the formation of discontinuities or gas cavities, usually located on the advancing side (in the structure of joints) [3, 5, 11].

Table 3 presents the mechanical properties of the test aluminium joints in relation to the tool rate of rotation and travel rate applied in the FSW process. The specimens subjected to analysis did not reveal any significant differences. The mechanical properties of the specimens were less favourable than possible to obtain in relation to the aluminium alloy used in the test. Such a situation could be ascribed to the destructive process which always initiated on the opposite side than that of the weld. In each specimen, the joint was not made across the entire thickness of the specimen but at a depth of approximately 8 mm. The remaining part of the flat bar (approximately 2 mm) was not welded, which reduced the cross-section of the specimen. In addition, the above-named area was, in a natural manner, the initiator of specimen failure in static tensile tests. The occurrence of the above-presented phenomenon was confirmed by the fractography presenting two areas, i.e. the plastic deformation in the weld area and the not fully formed region which was not subjected to welding (Fig. 5).

Table 3 Mechanical properties of the joints in relation to applied parameters

Specimen no.	Tensile strength [MPa]	Young's modulus [MPa]
1	132 ± 15	23515 ± 867
2	132 ± 23	27671 ± 915
3	139 ± 18	23467 ± 757
4	125 ± 16	25893 ± 897
5	110 ± 25	21472 ± 1002

Fig. 5. Fractography of the joint in specimen no. 4 after the static tensile tests

Concluding Remarks

The process of the optimisation of FSW technological parameters revealed that the most favourable microstructure not containing the oxide line located in parallel to the welding axis and having the most regular cuboidal weld geometry was that of the joint made using a travel rate of 400 mm/min and a rotation rate of 710 rpm. To improve the mechanical properties of joints, further tests should involve the reduction of the area across the joint thickness not plasticised in the FSW process. Another solution could involve the performance of the welding process on both sides of flat bars being joined.

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