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Friction Stir Welding of Wrought Aluminium Alloy EN AW-6082

Abstract: The article presents results of the friction stir welding of 6 mm thick plates made of wrought aluminium alloy EN AW-6082. Tests discussed in the article involved the identification of the effect of primary welding process parameters on the quality of welds. Test welds were subjected to visual tests, measurements of temperature (inside the weld), tensile strength tests as well as macro and microscopic metallographic tests and structural tests (performed using a scanning electron microscope). The application of the appropriate values of the primary welding process parameters (i.e. the tool rotation rate and the welding rate) enabled the obtainment of the high and repeatable quality of FSW joints made of aluminium alloy EN AW-6082. The test results presented in the article can offer technological solutions for potential users representing, among others, the railway, automotive or aviation industries.

Keywords: Friction Stir Welding, FSW, aluminium alloys, EN AW-6082

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Introduction

Presently, the railway, automotive and aviation industries concentrate on materials and joining technologies enabling the production of lightweight structures. In addition to their light weight, such structures should be characterised by high strength, rigidity and repeatable quality. Structural materials satisfying the above-named requirements include, among other things, wrought aluminium alloys. There are several methods enabling the joining of aluminium alloys. These methods are usually based on conventional arc welding processes such as tungsten inert gas welding (TIG) or metal active gas welding (MAG). However, the welding of aluminium alloys is accompanied by structural deformations triggered by welding thermal cycles [1, 2]. Both factors inspire design engineers and technologists to search for innovative joining methods [3, 4].

One of the methods satisfying the above-presented expectations is friction stir welding (FSW). This technology perfectly falls within developmental trends of welding technologies. Lower temperature generated during the FSW process (in comparison with that characteristic of conventional arc welding methods) reduces the generation of hot cracks and deformations. As regards the joining of aluminium alloys, the advantages of the FSW technology (presented

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in reference publications) also include the possibility of increasing fatigue strength and improving the structural reliability of joints [2, 5–7].

The use of the FSW technology to weld wrought aluminium alloys makes it possible to avoid typical welding imperfections and, in cases of certain materials, is the only applicable joining method. Research work results presented in reference publications as well as results of individual FSW-related tests revealed that the type, shape and dimensions of a welding tool significantly affect the process of weld formation and the mechanical properties of welded joints. The quality of welds is also affected by the primary parameters of the joining process including the tool rotation rate and the welding rate [8, 9]. This article presents test results concerning the quality of FSW joints made of wrought aluminium alloy EN AW-6082. The tests aimed to assess the effectiveness and usability of the FSW when making industrial structures of the aforesaid aluminium alloy. The joints were subjected to visual tests, temperature measurements (involving the upper surface of the FSW joint during welding), metallographic tests (concerning the weld structure) and tensile strength. The test results revealed the high and repeatable quality of the joints obtained using the innovative FSW method.

Test rig and materials

The tests involved FSW joints of 6 mm thick plates made of wrought aluminium alloy EN AW-6082. Aluminium alloy EN AW-6082 is characterised by high mechanical strength, high toughness, favourable corrosion resistance and polishability. The alloy is used in engineering and machinery industries, where strength-related requirements are higher than those concerning the 5000 series alloys. More precisely, aluminium alloy EN AW-6082 is used, among other things, to make elements of floors, roofs and doors of railway carriages as well as wing and fuselage elements in civilian and military aircraft and in plating and structural elements of lorry and bus engines [10–13]. The chemical composition of the aluminium alloy used in the tests is presented in Table 1. In turn, Table 2 presents selected properties of the alloy.

The welding process was performed using a welding machine built on the basis of a conventional FYF32 JU2 milling machine (JAFO). The friction stir welding station is presented in Figure 1. The tests concerning the usability of the FSW technology (in production conditions) to make joints of aluminium alloy EN AW-6082 were performed using three values of tool rotation rate, i.e. Vn = 450, 900 and 1800 rpm as well as two values of welding rate, i.e. Vz = 450 and 900 mm/min. The use of a welding rate of 900 mm/min directly increased efficiency when making a structure of the aluminium alloy. During the welding process, to reduce the friction resistance of the material being welded, the friction surface of the shoulder was inclined at an angle of 1.5° in relation to the surface of the plates. The FSW process was performed using a Triflute conical tool. The shoulder diameter

Table 1. Chemical composition of aluminium alloy EN AW-6082 [14]

No.	Designation	Si	Cu	Mg	Mn	Fe	Ti	Cr	Zn	Al
1.	EN AW-6082 (PA4)	0.7–1.3	≤0.1	0.6–1.2	0.4–1.0	≤0.5	≤0.1	≤0.2	≤0.2	bal.

Table 2. Selected mechanical properties of aluminium alloy EN AW-6082 [14]

No.	Designation	Minimum values		
		$R_{p0.2}$, MPa	R_m, MPa	A_{50}, %
1.	EN AW-6082 (PA4)	255	300	9

amounted to 26 mm, the diameter of the pin at the shoulder amounted to 8.0 mm, the diameter of the pin at the end of the cone amounted to 6.0 mm, whereas the length of the pin amounted to 5.9 mm.

Visual tests of FSW joints

Visual tests (performed in accordance with the PN-EN 13018:2004 [15] standard) involved FSW joints on the face side, root side and in the area adjacent to the weld (i.e. 10 mm on each side of the joint). The FSW joints made using various welding process parameters are presented in Figures 2–7. The joints were characterised by the proper structure of the weld face, typical of the FSW process. The root face did not contain any traces of the lack of fusion. The visual tests of the FSW joints revealed their high and repeatable quality. Depending on the potential customers' requirements, the joints can be successfully used when making critical structures of aluminium ally EN AW-6082 in industrial conditions.

Measurements of temperature inside the friction stir weld

The quality of FSW joints depends on primary welding parameters, i.e. the tool rotation rate and the welding rate. The aforesaid parameters affect the process temperature, which,

Fig. 1. FSW station - FSW machine based on an FYF32JU2 conventional milling machine (JAFO, Poland)

Fig. 2. FSW butt weld made of aluminium alloy EN AW-6082; welding parameters: Vn = 450 rpm, Vz = 450 mm/min

Fig. 3. FSW butt weld made of aluminium alloy EN AW-6082; welding parameters: Vn = 450 rpm, Vz = 450 mm/min

Fig. 4. FSW butt weld made of aluminium alloy EN AW-6082; welding parameters: Vn = 1800 rpm, Vz = 450 mm/min

Fig. 5. FSW butt weld made of aluminium alloy EN AW-6082; welding parameters: Vn = 450 rpm, Vz = 900 mm/min

Fig. 6. FSW butt weld made of aluminium alloy EN AW-6082; welding parameters: Vn = 900 rpm, Vz = 900 mm/min

Fig. 7. FSW butt weld made of aluminium alloy EN AW-6082; welding parameters: Vn = 1800 rpm, Vz = 900 mm/min

in turn, affects the structure of the joint structure and, consequently, its quality and strength. To determine temperature inside the joints it was necessary to use type-K thermocouples. The arrangement of the thermocouples is presented in Figure 8. The thermocouples used in temperature measurements were located 5, 10, 15 and 20 mm away from the weld axis as well as 2 and 4 mm away from the weld root.

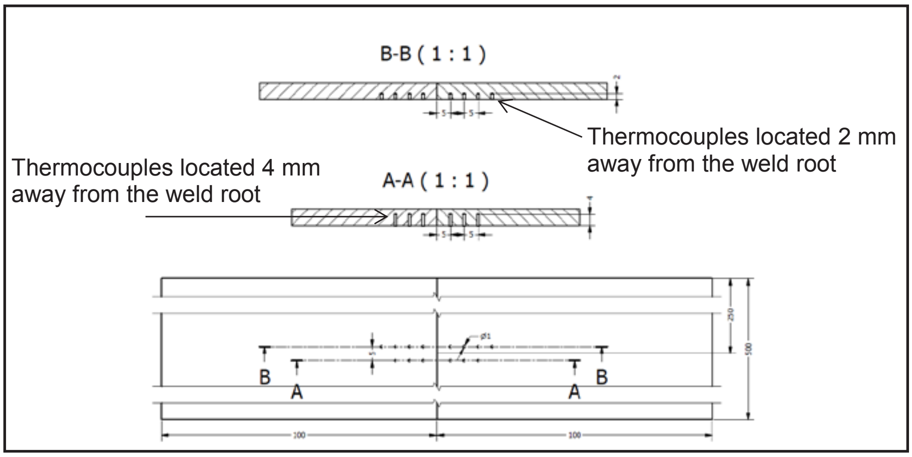

Fig. 8. Locations of the thermocouples used in temperature measurements inside the FSW joint

Exemplary curves of temperature (changes) inside selected FSW joints (during welding) are presented in Figures 9 and 10 – in relation to the same welding process parameters and thermocouples located 2 mm and 4 mm away from the weld root. In turn, Figures 11 and 12 present changes of temperature in relation to a tool rotation rate of 900 rpm and that of 1800 rpm and thermocouples located 4 mm away from the weld root. In each case, the welding rate amounted to 450 mm/min.

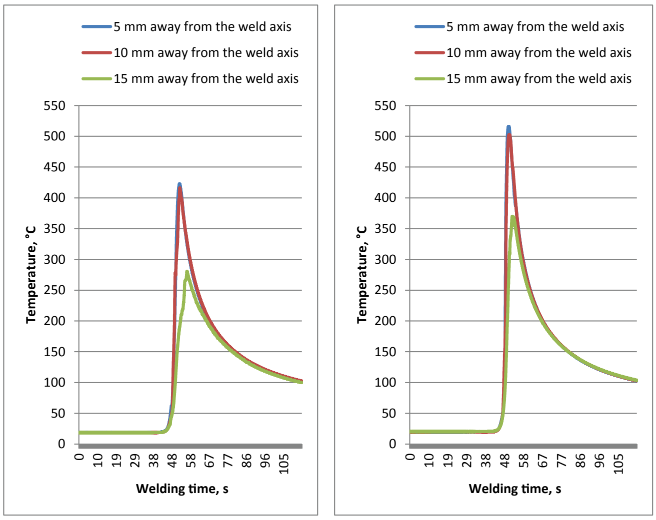

Fig. 9. Changes of temperature inside the FSW joint 2 mm away from the weld root; welding parameters: tool rotation rate: 450 rpm, welding rate: 450 mm/min; conical tool: a) temperature on the advancing side and b) temperature on the retreating side

The analysis of measurements of temperature inside the joint indicates temperature changes along with changes in the tool rotation rate and those in the welding rate. The values of temperature varied depending on thermocouple locations, i.e. distances from the weld root and from the weld axis. The maximum value of temperature amounted to slightly above 500°C in relation to a tool rotation rate of 450 rpm and a welding rate of 450 mm/min. As regards the above-presented parameters and the thermocouples located 2 mm away from the weld root, higher temperature was recorded on the retreating side. The difference between the maximum temperature in the advancing zone and that in the retreating zone amounted to as many as 80°C. Along with the growing distance from the weld axis, temperature differences between the zones in individual measurement areas remained similar (Fig. 9). The fact that the value of temperature during the making of all of

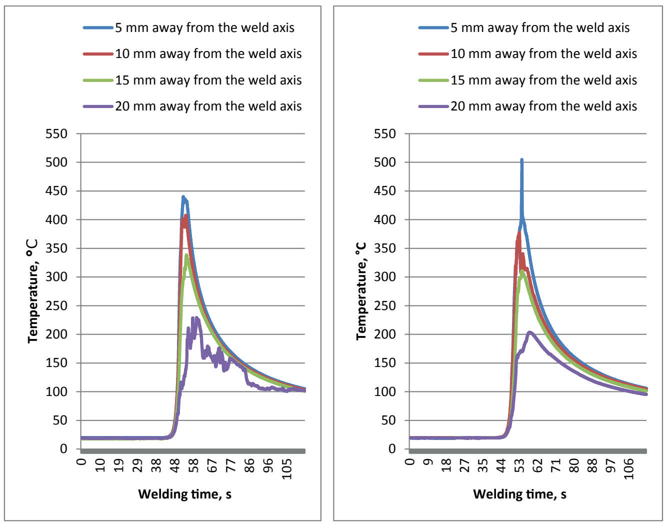

Fig. 10. Changes of temperature inside the FSW joint 4 mm away from the weld root; welding parameters: tool rotation rate: 450 rpm, welding rate: 450 mm/min; conical tool: a) temperature on the advancing side and b) temperature on the retreating side

the joints did not exceed 550°C translated into the lack of the unfavourable effect of temperature (leading to deformations of FSW joints).

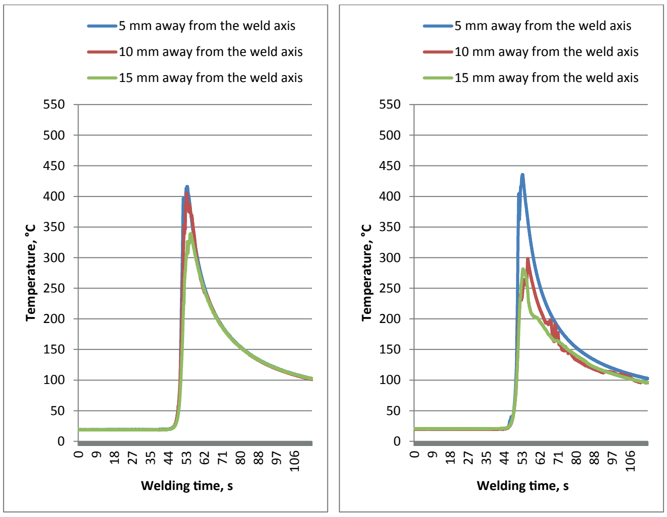

Fig. 11. Changes of temperature inside the FSW joint 2 mm away from the weld root; welding parameters: tool rotation rate: 900 rpm, welding rate: 450 mm/min; conical tool: a) temperature on the advancing side and b) temperature on the retreating side

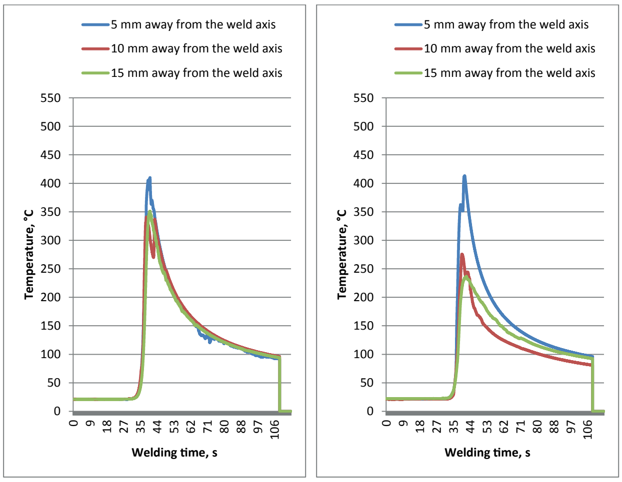

Fig. 12. Changes of temperature inside the FSW joint 2 mm away from the weld root; welding parameters: tool rotation rate: 1800 rpm, welding rate: 450 mm/min; conical tool: a) temperature on the advancing side and b) temperature on the retreating side

Macro and microscopic tests of FSW joints

Selected specimens were subjected to macroscopic metallographic tests concerning the structure of the welds [16]. Metallographic specimens used in the tests were etched using Keller's reagent. Presented below are macro and microstructures of selected friction stir welds (Fig. 13). The marked areas of the test joints were subjected to microscopic metallographic tests (Fig. 14–18).

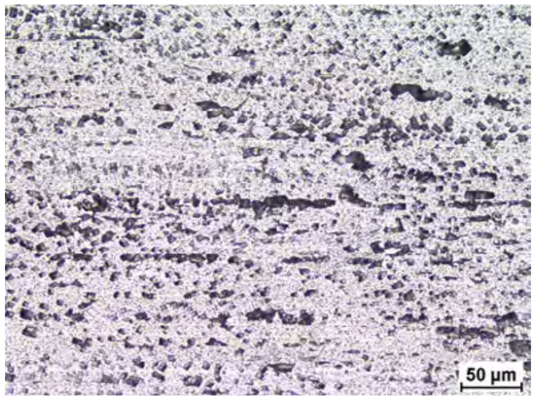

Fig. 14. Microstructure of the FSW joint in the area of the base material of aluminium alloy EN AW-6082; area no. 1 in Fig. 13; mag. 200x

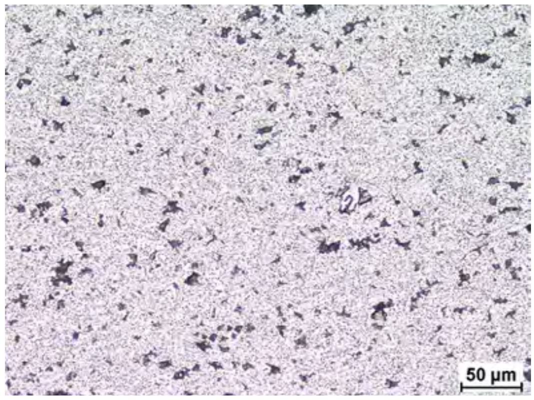

Fig. 15. Microstructure of the heat affected zone (on the advancing side) of the FSW joint made of aluminium alloy EN AW-6082; area no. 2 in Fig. 13; mag. 200x

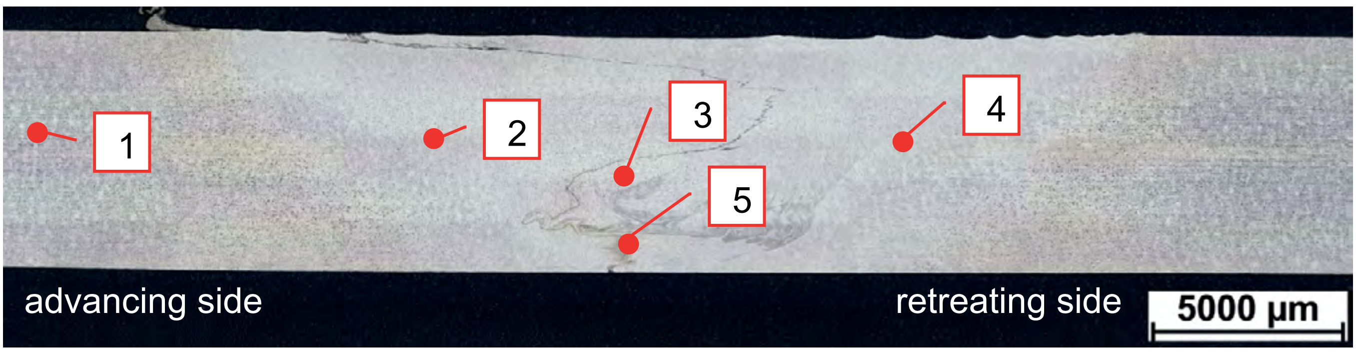

Fig. 13. Main view of the macrostructure of the weld made of alloy EN AW-6082, with marked areas subjected to microscopic observations; welding parameters: tool rotation rate Vn = 450 rpm and welding rate Vz = 450 mm/min; mag. 50x

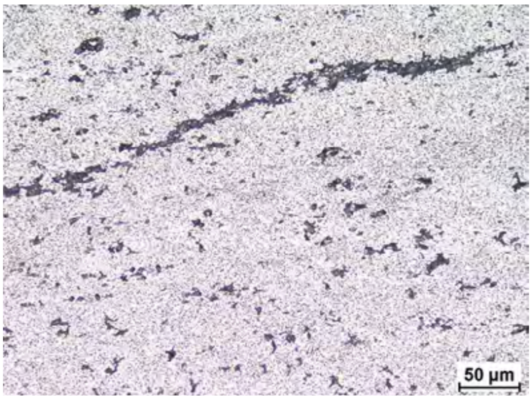

Fig. 16. Microstructure of the upper part of the nugget of the weld of the FSW joint made of aluminium alloy EN AW-6082; area no. 3 in Fig. 13; mag. 200x

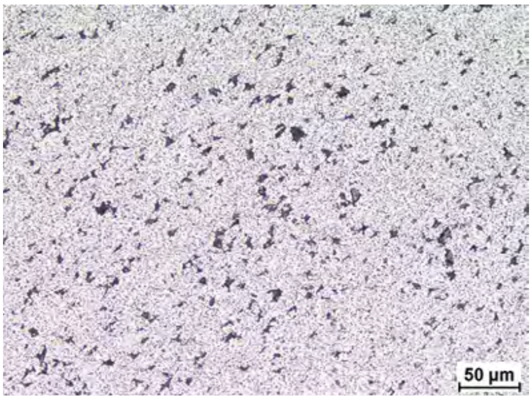

Fig. 17. Microstructure (on the retreating side) of the HAZ of the FSW joint made of aluminium alloy EN AW-6082; area no. 4 in Fig. 13; mag. 200x

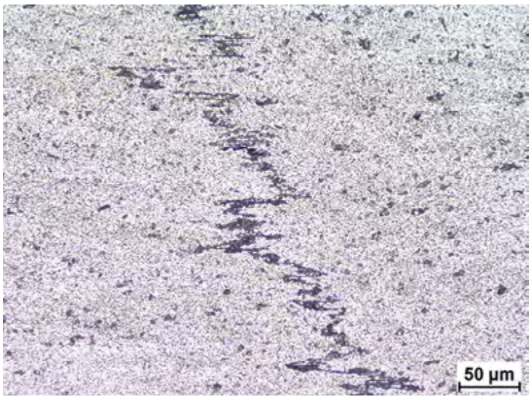

Fig. 18. Microstructure (on the weld root side) of the FSW joint made of aluminium alloy EN AW-6082; area no. 5 in Fig. 13; mag. 200x

The macro and microscopic metallographic test results revealed significant differences between the individual areas of the FSW joint. A particularly visible difference was observed between the base material area and the area of plasticised material (affected by the FSW tool). The welding tool was responsible for grain size reduction and the transformation (in the entire tested area) of the grain arrangement in the structure of the welded material from longitudinal (triggered by rolling) to scattered one. The results of the macro and microscopic metallographic tests revealed the complete metallic continuity of the test joint. The structure of the weld central area was significantly refined in comparison with that of the base material, which would favourably affect the plasticity of the material in the welding area and, consequently, the mechanical properties of the joint [17].

The effect of the FSW tool also transformed (within the entire test area) the arrangement of the grains in the welded material from longitudinal (induced by rolling) into scattered one. In addition, on the weld root side (Fig. 18) it was possible to observe the arrangement of oxides referred to in reference publications as “kissing bonds” or “lazy S”. The foregoing could probably be ascribed to the flow of the material matrix triggered by temperature and, at the same time, by the presence of significant internal friction forces during the stirring of the material.

Microstructural tests of FSW joints under the scanning electron microscope

A selected FSW joint was subjected to structural tests using a scanning electron microscope. The SEM microstructure of the base material is presented in Figure 19. Figure 19 reveals precipitates shaped and arranged through rolling. In turn, Figure 20 presents structures of selected areas of the FSW joint, i.e. the microstructure on the boundary between the thermomechanically strained zone (TSZ) and the stirring zone (SZ), both on the advancing and retreating side. The boundary between the TSZ and the SZ was more visible on the advancing side, where it was possible to observe the area of elongated grains in the thermomechanically strained zone and fine grains in the stirring zone. On the retreating side, the aforesaid border was less visible due to the fact the boundary contained finer grains located between larger grains (thus making the transition between the zones diffuse). The stirring zone contained equiaxial grains, which were smaller than those in the base material. This fact indicated the occurrence of recrystallization triggered by heat and deformations accompanying the welding process. Because of the use of the BSE detector, microstructural photographs revealed the presence of particles containing heavier (in relation to the matrix) chemical elements (Fe – Mn). The arrangement and refinements of the grains indicated the intensity of deformation and material flow directions.

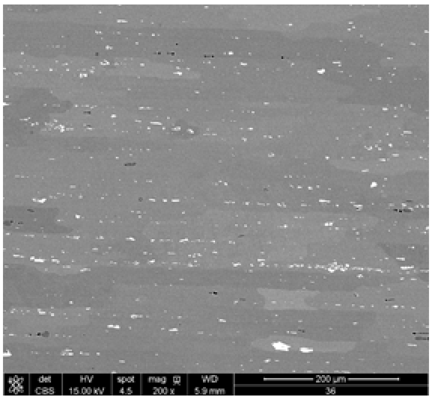

Fig. 19. Microstructure of the base material; BSE image

Tensile tests of FSW joints

The high and repeatable quality of FSW joints requires, among other things, their high tensile strength. The quality of the FSW joints made of aluminium alloy EN AW-6082 was assessed in accordance with standard [18]. In accordance with [18], the specimens used in the tests were cut out across the direction of welding. Each joint was sampled for 5 specimens. The performance of the tests was followed by the calculation of the average tensile strength. The average results concerning the tensile strength of the FSW joints made using the Triflute conical tool are presented in Figure 21. The results are presented in relation to applied tool rotation rates (450, 900 or 1800 rpm) and welding rates (450 and 900 mm/min).

The tensile strength tests concerning the FSW joints revealed that their strength was affected by the primary welding process parameters, i.e. the tool rotation rate and the welding rate. The highest tensile strength values were obtained in relation to a tool rotation rate of 900 rpm and a welding rate of 450 mm/min. The FSW joints were generally characterised by high and repeatable quality, resulting from the application of the appropriate values of welding process parameters, i.e. the tool rotation rate and the welding rate. The tensile strength of the FSW joints amounted to at least 75% of the strength of the base material (aluminium alloy EN AW-6082).

Analysis of test results concerning the FSW joints made of aluminium alloy EN AW-6082

The visual test results concerning the FSW butt joints made of 6 mm plates of aluminium alloy EN AW-6082 were characterised by high and repeatable quality. The plates were welded using three tool rotation rates (i.e. Vn = 450, 900 and 1800 rpm) and two welding rates

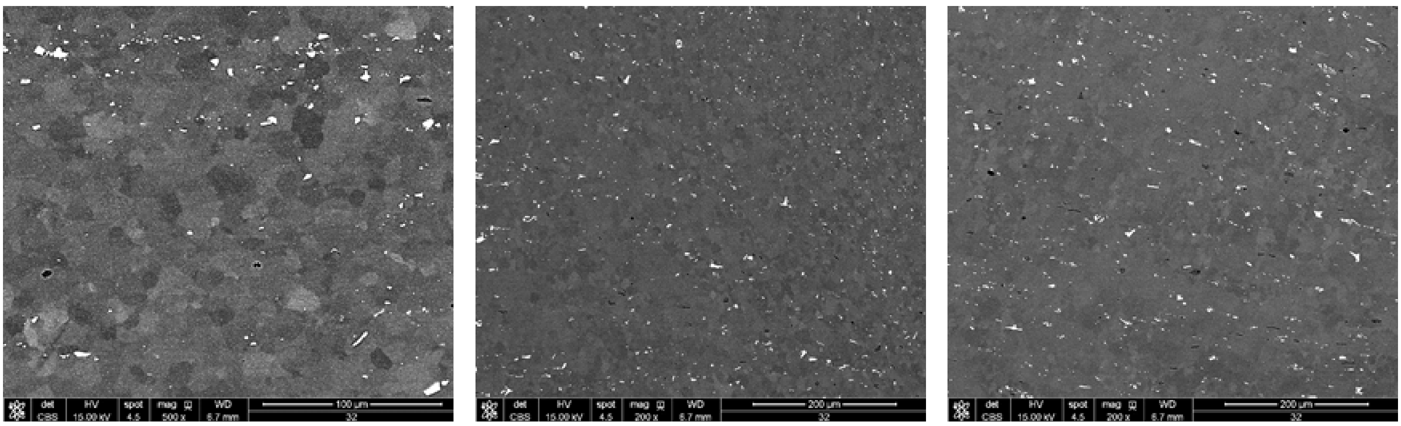

Fig. 20. Microstructure of the FSW joint (welding parameters: Vn=900 rpm, Vz=450 mm/min, Triflute conical tool): a) stirring zone, b) advancing side and c) retreating side

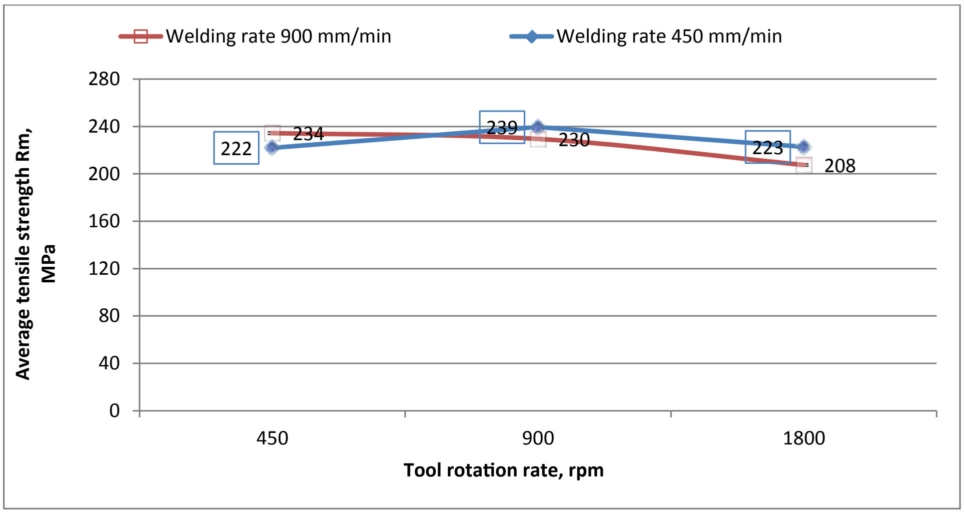

Fig. 21. Effect of the tool rotation rate and welding rate on tensile strength Rmav. of the FSW joints made of aluminium alloy EN AW-6082; Triflute conical tool, welding rates: Vz = 450 and 900 mm/min

(i.e. Vz = 450 and 900 mm/min). Regardless of applied welding process parameters (both the tool rotation rate and the welding rate), the welds were characterised by the regular shape with the greater or smaller collar, in most cases appearing on the retreating side. As regards the FSW method, aluminium alloy EN AW-6082 is characterised by excellent weldability. It is possible to obtain high and repeatable weld quality (in visual tests) within a wide range of welding process parameters, i.e. using a tool rotation rate of up to 1800 rpm.

The tests of the FSW joints involved temperature measurements performed inside the weld. The measurements of temperature were performed using thermocouples. The tests aimed to determine temperature values obtained in the joint as well as to identify temperature differences in relation to various areas of the joint. The temperature measurement results will be used in further FSW joint-related tests, including the modelling of the FSW process in relation to other sets of welding process parameters.

The tensile strength test results concerning the FSW joints revealed that the use of appropriate welding process parameters ensured the obtainment of joints characterised by high and repeatable quality. As regards a tool rotation rate of 450 rpm and that of 900 rpm, strength-related differences were slight. In turn, the application of a tool rotation rate of 1800 rpm and a welding rate of 900 mm/min led to a slight decrease in the value of tensile strength. During the FSW process, the combination of a high tool rotation rate and a high welding rate could adversely affect the quality of a joint (resulting in the excessive amount of the material in the form of the upset metal - see Fig. 7). The average tensile strength of the FSW joints made of aluminium alloy EN AW-6082 amounted to approximately 232 MPa (i.e. above 75% of the base material strength). Joints characterised by the above-presented strength can be used successfully to make structures of 6 mm thick plates (of EN AW-6082) used in the aviation, railway and automotive industries.

The macro and microscopic metallographic tests concerning the quality of the welds revealed that full metallic continuity was not obtained in all of the cases. However, that fact that some joints were characterised by the presence of the so-called “fusion-free” line (resulting from the use of the tool having the overly short pin), the above-named imperfection only slightly decreased the quality of the joint. The average strength of the joints containing the cavity amounted to approximately 222 MPa.

The scanning electron microscopic tests of the revealed the effect of the tool rotation rate on the size and shape of grains. The base material structure contained elongated grains (as a result of the rolling process). The stirring zone of each specimen contained equiaxial grains, (visibly smaller than those of the base material of alloy EN AW-6082). The foregoing directly increased the plasticity of the material (in the stirring zone) and improved the tensile strength of the joints [17].

The analysis of all of the test joints made using various tool rotation rates and welding rates revealed that the above-named parameters affected the temperature of the welding process, the plasticisation of materials subjected to welding and, consequently, the structure of the weld as well as the quality and strength of the joints. The FSW joints made of aluminium alloy EN AW-6082 within the tested range of base material thicknesses could be used successfully in the aviation, railway or automotive industries. The joints were characterised by high and repeatable quality.

Conclusions

1. The application of the above-presented sets of tool rotation rates and welding rates enabled the obtainment of FSW joints made of aluminium alloy EN AW-6082 and characterised by compact structure as well as high and repeatable quality.
2. The strength of the FSW joints depended on process parameters. The combination of certain parameters could lead to the formation of discontinuities in the internal structure of the weld on the root side or to the obtainment of joints characterised by slightly lower strength.
3. The SEM tests of the FSW joints made of aluminium alloy EN AW-6082 revealed that the size and shape of grains changed in relation to an area subjected to the SEM tests. As a result of the rolling process, the base material of the aluminium alloy contained elongated grains, whereas grains in the stirring zone were equiaxial and significantly smaller than those in the base material.
4. Friction stir welded joints made of 6 mm thick plates of aluminium alloy EN AW-6082 can be successfully used in the automotive industry and other industrial sectors. The appropriate adjustment of the FSW process parameters enables the obtainment of joints characterised by high quality. The strength of such joints amounts to at least 75% of the strength of the base material.

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