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Increase in the Fatigue Strength of Aluminium Alloy Welded Joints through the Friction Processing of the Joint Surface

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Abstract: Increasingly high requirements concerning welded structures made of aluminium alloys trigger the issue of fatigue strength. Previous tests have indicated that the fatigue strength of FSW joints is higher than that of, e.g. MIG-welded joints. However, it should be noted that the use of the FSW technology may sometimes be limited or impossible. One of the methods enabling an increase in the fatigue strength of arc welded joints includes the treatment of the joint surface. The study presents results of the friction stir processing (FSP) of MIG-welded joints made of aluminium alloy EN AW-6082 and the effect of the aforesaid technique on the fatigue strength of the joints. The tests revealed that the use of the FSP method makes it possible to increase the fatigue strength of butt welded joints by approximately 50%.

Keywords: fatigue strength, FSP-based modification, aluminium alloys, MIG welding

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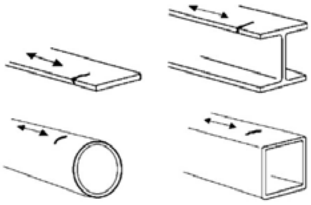
Introduction

Increasingly often design engineers use aluminium alloys as structural materials. The growing popularity of aluminium alloys requires the acquisition of new knowledge concerning the fatigue strength of welded joints made of such materials. Previously performed tests concerning the fatigue strength of joints made in aluminium alloys revealed that friction stir welded joints were characterised by higher fatigue strength than, for instance, those made using arc welding processes [1–5]. According to A. Hobbacher [6], the fatigue strength of arc welded joints made of aluminium alloys can be identified by providing characteristic values of the so-called fatigue (FAT) categories in relation to the base material, joints with excess weld metal subjected to treatment and joints in the as-welded state (Table 1).

Table 1. FAT categories according to A. Hobbacher in relation to the base material and welded joints made of aluminium alloy [6]

No.	Type of element	FAT category	Remarks
1		70 for 6000 series alloys	
2		45	Necessary NDT in the case of linear misalignment < 5 [%] of thickness
3		36	Necessary NDT in the case of linear misalignment < 5 [%] of thickness

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R. Bogucki and A. Pietras [1] demonstrated that the fatigue strength of 8 mm thick FSW joints made of alloy EN AW-6005 was higher than that of TIG-welded joints. In relation to the FSW joints, the FAT category amounted to 75 MPa. In relation to the TIG-welded joints, the FAT category amounted to 54 MPa. C. Zhou et al. [2] tested 10 mm thick FSW and MIG-welded joints made of alloy EN AW-5056. The MIG-welded joints were made using filler metal grade 5356; the joints were double (X-groove joint preparation). Figure 1 presents fatigue strength test results in relation to the base material, FSW joint and the MIG-welded joint.

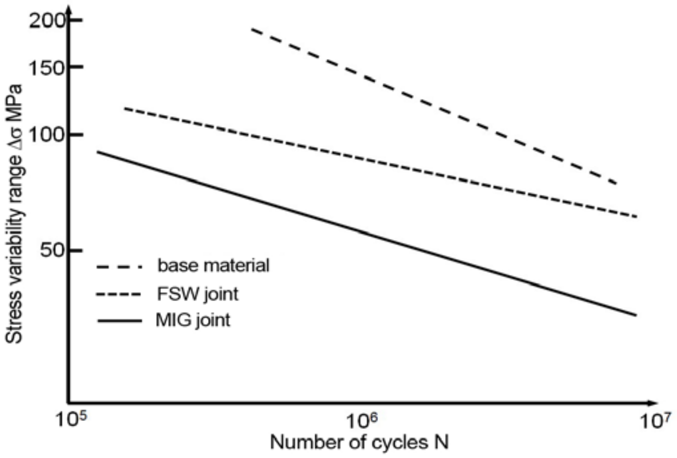

Fig. 1. Fatigue strength results (linear approximation) for base material EN AW-5056, FSW joint and MIG joint [2]

Results related to alloy EN AW-6082 also demonstrate that the FSW technology enables the obtainment of joints characterised by higher fatigue strength than that of MIG-welded joints. Y. Kobayashi et al. [3] stated that the fatigue strength of FSW joints was higher than that of MIG-welded joints; in relation to FSW joints, the FAT category amounted to 68.5 MPa, whereas the FAT category concerning MIG-welded joints amounted to 42.3 MPa. When comparing the fatigue strength of the TIG and MIG welded joints with that of the FSW joints it could be stated that fatigue strength was the highest in the FSW joints, next in the joints made using the TIG method and, finally, in the MIG welded joints [4]. Figure 2 presents S-N curves for 4 mm thick joints made of aluminium alloy EN AW-6082-T6 using the FSW, TIG and MIG methods.

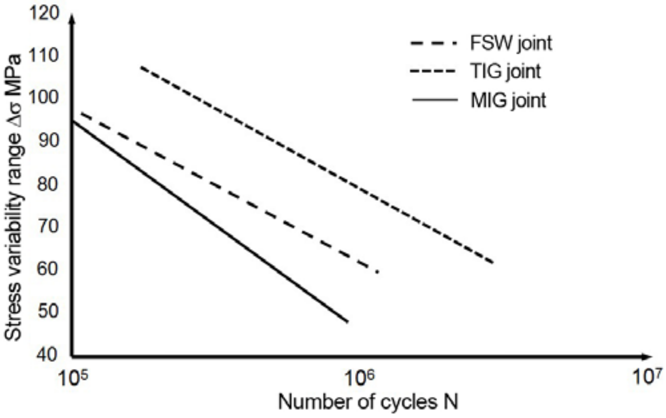

Fig. 2. S-N curves for 4 mm thick FSW, TIG and MIG joints made of alloy 6082-T6 [4]

P. Moreira et al. [5] presented test results concerning joints made of alloy EN AW-6082 and alloy EN AW-6061, indicating that the fatigue strength of 3 mm thick FSW joints was by 40% higher than that of MIG joints. In turn, M. Ranes et al. [7] demonstrated that fatigue strength also depended on the as-received state of the base material.

Previous tests confirmed that the strength of FSW joints is high and always higher than that of arc welded joints. However, as regards the FSW technology, the fatigue strength of welded joints depends on welding technological parameters and a working tool applied in the process [8, 9]. The study presents results of fatigue tests in relation to 8 mm and 10 mm thick FSW joints made of aluminium alloy EN AW-6082-T6. The welding process was performed using three working tools (see Fig. 3).

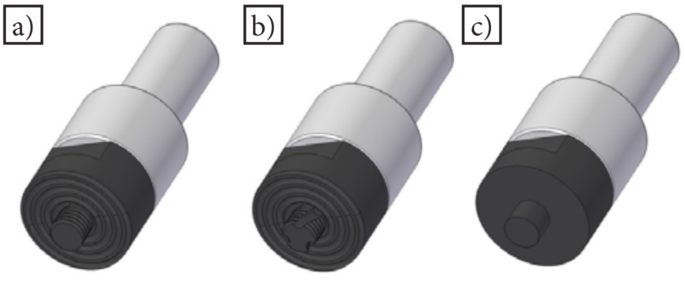

Fig. 3. Working tools used in the friction stir welding process; a) tool N1, b) tool N2 and c) tool N3 [9]

The tests (Table 2) revealed that the highest fatigue strength was identified in relation to double welded joints made using the Triflute type tool (Fig. 3b). As regards the above-named joints, FAT = 98 MPa, which constituted 66% of the fatigue strength of the as-received base material.

Table 2. Results of fatigue tests of FSW butt joints made of aluminium alloy EN-AW-6082 FSW [8]

Type of joint	Fatigue category FAT		
	FSW tool		
	N1	N2	N3
Single butt welded joint, 8 mm, face subjected to treatment	66	40	87
Single butt welded joint, 8 mm, after welding	53	26	36
Double butt welded joint, 10 mm, faces subjected to treatment	98	75	81
Butt welded joint 10 mm, after welding	54	41	43
Base material EN AW-6082-T6	148		

However, it is possible to increase the fatigue strength of arc welded joints.

In relation to already existing structures or structures under design it is possible to apply the following activities aimed to increase fatigue strength [10]:

- excess weld metal treatment,
- elimination or reduction of loads,
- reduction of stresses in hazardous cross-sections,
- structural solution improvements,
- mechanical treatment of welded joints,
- changes of stresses in welded joints.

In practice, methods used to increase fatigue strength [11], include the following:

a) TIG method-based remelting [12],
b) high-frequency impact treatment [13–15] ,
c) Laser peening [16, 17].

In terms of practicality, the application of methods improving the fatigue strength of welded joints made of aluminium alloys entails the issue of porosity. The presence of gas pores inside the weld does not affect the fatigue strength as much as porosity. For this reason, it is necessary to note that the modification of a joint, e.g. through grinding or TIG method-based remelting, may trigger the formation of porosity, thus reducing the fatigue strength of the joint itself [18].

The PN-EN 1999-1-3 standard Eurocode 9 [19] *Design of aluminium structures Part 1–3: Structures susceptible to fatigue*, item 6.5 (Annex H) contains guidelines concerning fatigue strength modification techniques. The authors of the standard indicate that techniques improving fatigue strength are usually expensive and make joint-related quality control difficult. The aforesaid techniques are applied following specialist's advice as their use significantly affects the functional properties of structures as well as their manufacturing costs. The techniques are usually applied to increase the fatigue strength of existing structures.

Following PN-EN 1999-1-3, an increase in the fatigue strength of welded joints can be obtained by using the following methods:

- machining or grinding,
- TIG or plasma gouging,
- peening (chiselling) or shot blasting.

By reducing the stress variability range, the application of the above-presented methods increases fatigue strength of the zones of medium and long-term fatigue service life by up to 30%. The most favourable results are obtained by combining two methods, e.g. machining (or grinding) and peening, providing better results than those obtained using only one method. In addition, when using a given method it is advisable to take into consideration the aspects presented below.

- It is necessary to develop appropriate work procedures.
- Before the commencement of works it is necessary to establish whether critical zones are free from surface cracks. If need be, it is possible to perform non-destructive (e.g. penetrant) tests.
- Apart from areas directly subjected to the treatment it is also necessary to take into consideration other locations of potential fatigue damage. If, for instance, the edge of the weld was improved, critical cracks may be present in the root or the weld (incomplete penetration).
- When selecting fatigue strength improving method it is necessary to take into

consideration both fatigue strength to be obtained and the usability of a given method in practice.

- If a given structure is exposed to a corrosion environment, fatigue strength improving methods are less effective. For this reason, it is recommended to provide the structure with additional anti-corrosion protections.

The aforesaid standard emphasizes that computational values related to modified welds should be determined on the basis of appropriate tests.

One of the methods improving the mechanical properties of arc welded joints is the friction stir processing (FSP) of the joint surface [19–20]. The modification of welded joints can be performed both on the face and the root side. It is also possible to modify the entire face in one run (the shoulder diameter is greater than the width of the face) or in many stages, e.g. by only modifying transition areas between the face and the base material [21]. The FSP-based modification of arc welded joints makes it possible to increase fatigue strength [22] and reduce residual stresses in joints made of aluminium alloy EN AW-5083 [23] or steel 304L [24]. H. Fuller et al. [22] obtained an increase in immediate strength from 259 MPa to 283 MPa and in fatigue strength by approximately 30% in MIG-welded joints made of aluminium alloy EN AW-5083.

Work [25] demonstrated that the additional FSP of MIG-welded joints increased the stress corrosion resistance of overlap joints made of aluminium alloy EN AW-7003. The authors associated the aforesaid increase in corrosion resistance with the elimination of the unfavourable phase T (Mg32(Al,Zn)49) from the weld face area. At the same time it was observed that the immediate strength of the welded joints subjected to the modification was decreased by 10–15% in comparison with that of the joints not subjected to friction stir processing. The tests [26] also revealed that the MIG-welded butt joints made of aluminium alloy EN AW-6061 were more susceptible to plastic strains, which was connected with the limitation of microporosity in the weld itself, typical of arc welded joints made of aluminium alloys [27].

Individual tests

The research aimed to develop a method making it possible to increase the fatigue strength of 20 mm thick MIG-welded joints made of aluminium alloy grade EN AW-6082-T6. The welding process was performed using PROMAG 530 device equipped with a PRO5200 Evolution power supply unit, in accordance with a software programme developed by Kemppi for the pulsed current welding of aluminium alloys. Based on the authors' own experience, the base material used in the test was the grade AA5183 wire (PN-EN ISO 18273 [28] (Lincoln Electric LNM AlMg 4.5 MnZr)) having a diameter of ø 1.2 [mm]. Welded joints were made in accordance with a related Welding Procedure Specification developed at Łukasiewicz – Instytut Spawalnictwa. The obtained test joints were double (subjected to X-groove joint preparation) and single (subjected to V-groove joint preparation) joints.

Because of the fact that aluminium alloy 6082 belongs to precipitation hardened alloys, the joints (after welding) were subjected to heat treatment (solutioning and ageing).

The assessment of the quality of the welded joints required the performance of non-destructive tests (X-ray), metallographic tests and mechanical tests. The X-ray tests made it possible to select joints to be subsequently used in fatigue tests.

The determination of fatigue test parameters required the performance of the mechanical tests of the base material. A static tensile test was carried out using an INSTRON 4210 testing machine. The specimens used in the test were flat and cut out along and across the direction of rolling in accordance with PN-EN ISO 6892-1 [29]. The test results are presented in Table 3.

Table 3. Mechanical properties of alloy EN AW-6082

Property	Along the direction of rolling		Across the direction of rolling		Inspection certificate	PN-EN 485-2 [30]
	value	mean	value	mean		
R_m [MPa]	329.5	332.0	324.0	324.6	295	min. 295
	331.8		324.6			
	334.6		325.3			
R_e [MPa]	316.1*	319.6	291.7	292.3	250 230 **	min. 240
	319.5		284.1			
	323.1		301.2			
A_5 [%]	13.4	13.3	11.1	12.4	8	8
	13.2		12.8			
	13.2		13.3			

Note:*$R_{0.2}$ ** plate

Figure 4 presents the results of the macroscopic metallographic tests of the welded joints. The joints did not contain welding imperfections and represented quality level B (determined on the basis of PN-EN ISO 10042 [31]). Hardness tests were performed in accordance with PN-EN ISO 9015-1 [32]. Figure 5 contains the schematic diagram presenting the hardness measurements. Figure 6 presents the test results.

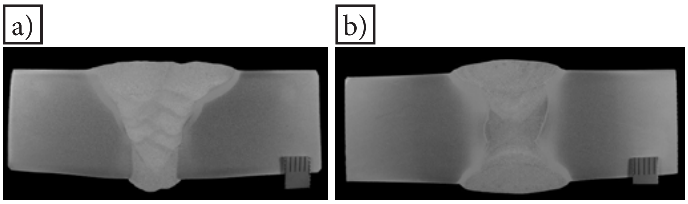

Fig. 4. Macrostructure of the joints with V (a) and X-groove preparation (b); etchant: Keller

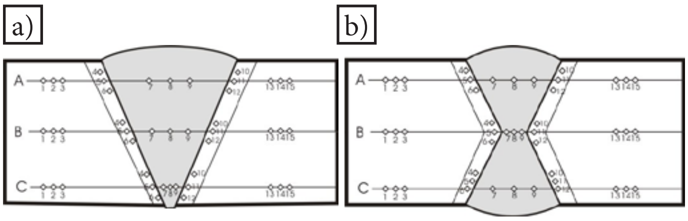

Fig. 5. Schematic arrangement of hardness measurement points

The transverse bend tests (with 2 specimens on the root side and 2 on the face side) were performed in accordance with PN-EN ISO 5173 [33]; the diameter of the bending probe amounted 140 [mm]. The joints obtained a required bend angle of 180°. The surface of the joints subjected to the bend test did not contain any tears or cracks.

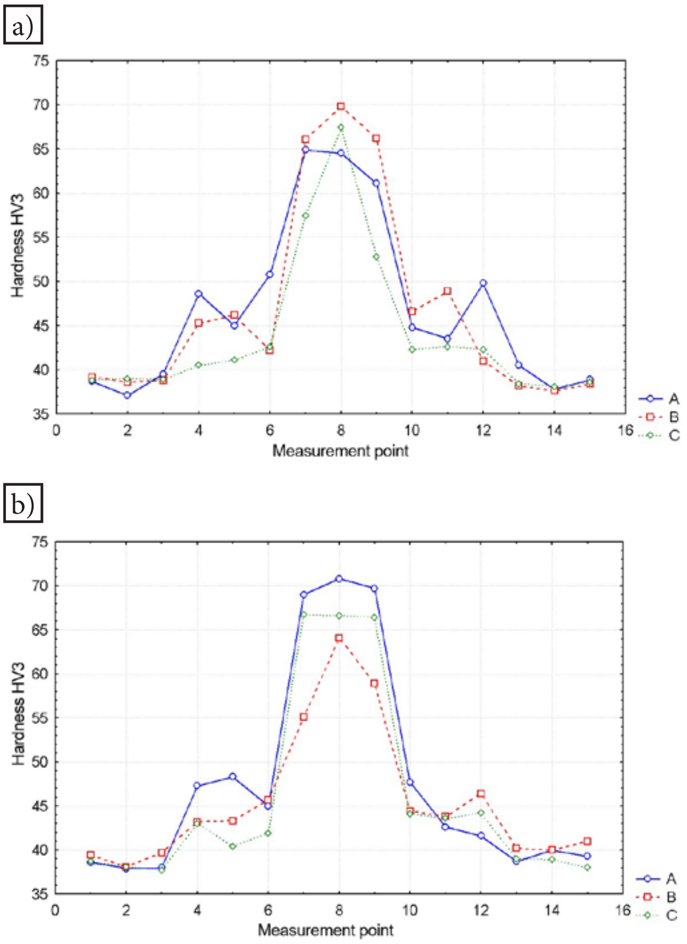

Fig. 6. Hardness distribution in the joints with V (a) and X-groove preparation (b)

Tensile tests were performed in accordance with PN-EN ISO 4136 [34] (the number of specimens rose to 3, as in relation to the base material in accordance with PN-EN ISO 6892-1). In all of the cases, the rupture took place outside the weld. The test results are presented in Table 4.

Table 4. Static tensile test results concerning the welded joints not subjected to heat treatment

Property	Joint with V-groove		Joint with X-groove	
	value	mean	value	mean
R_m [MPa]	144.8	144.9	144.7	145.1
	145.5		144.2	
	144.3		146.3	

The identification of the effect of the heat treatment on the mechanical properties of the joints subjected to solutioning and ageing required the performance of hardness measurements (Fig. 7) and tests of mechanical properties (Table 5).

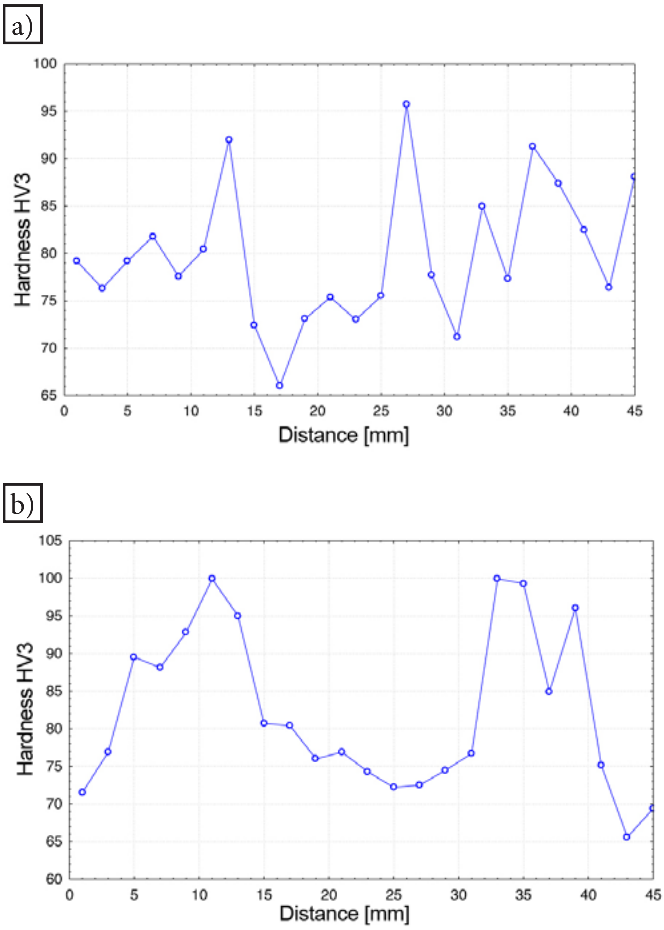

Fig. 7. Hardness distribution in the welded joints subjected to heat treatment: a) joint with V-groove preparation and b) joint with X-groove preparation; line B

Table 5. Static tensile test results concerning the welded joints subjected to heat treatment

Property	Joint with V-groove		Joint with X-groove	
	value	mean		value
R_m [MPa]	155.8	155.2	167.2	160.7
	155.6		149.7*	
	154.2		165.3	

*rupture in the weld

The tests concerning mechanical properties revealed that the MIG-welded joints subjected to mechanical treatment were characterised by higher strength than that of the joints directly after welding. The immediate strength of the single joints increased by 7%, whereas that of the double joints rose by 10.7%. At the same time it was noticed that the hardness of the aforesaid joints decreased (Fig. 7).

To achieve the objective of the study, the first stage of the research work involved the identification of the fatigue strength of the base material as well as the fatigue strength of the joints subjected to X and V-groove preparation. The fatigue tests of the base material and welded joints were performed in accordance with a procedure developed at Łukasiewicz – Instytut Spawalnictwa using an MTS fatigue testing machine (Fig. 8). The tests of each series of the specimens (until the rupture) were performed at several levels of stresses Δσ, constant stress ratio R = 0.2 (R = σmin/σmax) and load changing frequency restricted within the range of 18 Hz to 20 Hz. The tests involved 13 specimens of the base material and 12 specimens of welded joints. The test results in the form of a number of cycles (N) preceding the unrepairable damage of the specimens were recorded using an MTS MultiPurpose TestWare software programme and, subsequently, subjected to statistical calculations resulting in the determination of Wöhler curves and FAT categories. The calculations were performed in accordance with the procedure described in document MIS XIII-2151-07 / XV-1254-07 [6].

Fig. 8. Fatigue test rig equipped with the MTS 311.31 fatigue testing machine

The test specimens used in the fatigue tests were prepared in accordance with the guidelines contained in ASTM E466 [35] and after taking into consideration the fatigue testing machine characteristics. The test results are presented in Figures 9–11. The joints subjected to V and X-groove joint preparation were subjected to the tests after the removal of excess weld metal.

The primary objective of the research work was to develop a method making it possible to increase the fatigue strength of welded joints through the friction processing of their surface. To achieve the goal it was necessary to perform technological tests aimed to identify the FPS field of parameters enabling the obtainment of the modified surface of the MIG-welded joints without imperfections. The technological tests were performed using the FSW test rig provided with an FYF32JU2 milling machine and a system fixing the test plates (Fig. 9).

Fig. 9. Test rig for the FSP-based modification process

The design and making of tools used subsequently in the FSP modification process were preceded by the analysis of data contained in related scientific publications [35–36] and of requirements concerning the shoulder width (which could not be narrower than the width of the weld subjected to V-grove joint preparation).

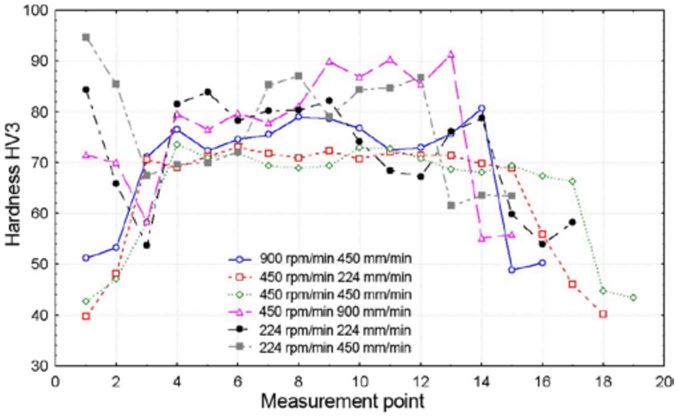

Fig. 10. Distribution of hardness in the welded joints in the area modified using the FSP method

The adjustment of parameters enabling the most favourable modification of the welded joint surface required measuring the depth of shoulder effect and hardness in areas subjected to modification. The results of hardness measurements are presented in Figure 10. Based on the test results, the set of FSP technological parameters included tool rotation rate ω = 450 rpm, and tool travel rate v = 450 mm/min. The adjustment of process parameters involved taking into consideration the uniformity of the depth of the modified layer (60.9%) and the uniformity of hardness.

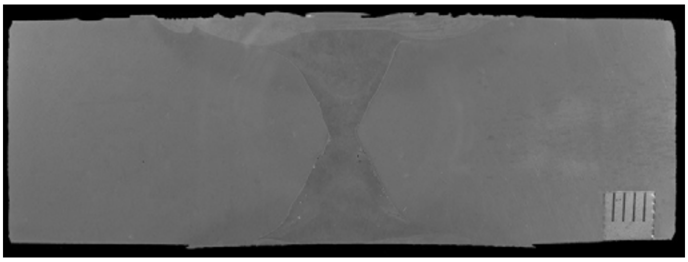

Fig. 11. Results of the metallographic tests of the welded joint subjected to modification performed using previously determined process parameters

Table 6. Values of FAT categories in relation to the MIG-welded joints before and after the FSP-based modification

Type of joint	FAT category [MPa]	
	Joint before the FSP-based modification with removed excess weld metal	Joint after the FSP-based modification
X-groove	63	65
V-groove	43	67
Base material of aluminium alloy EN AW-6082	81	

Figure 11 presents the macrostructure of the double MIG-welded joint (X-groove joint preparation) after the FSP-based modification. Figure 12 presents the area itself after the modification. Metallographic tests did not reveal the presence of welding imperfections in the joint after the modification process.

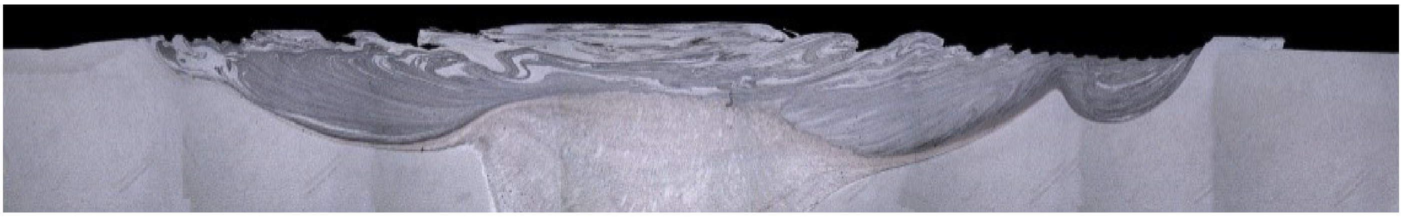

Fig. 11. Results of the metallographic tests of the welded joint subjected to modification performed using previously determined process parameters

The comparison of the values of FAT categories in the MIG-welded joints before and after the modification process is presented in Table 6. The test results, i.e. a significant increase in the fatigue strength of the joint subjected to V-groove joint preparation, revealed the significant usability of the FSP technology in the modification of arc welded joints.

Concluding remarks

- The welding process affects fatigue strength (fatigue category). In relation to the base material of aluminium alloy EN AW-6082 (plate thickness of 20 mm), the FAT category amounted to 81 MPa. In relation to the MIG-welded joint subjected to V-groove joint preparation, the FAT category amounted to 43 MPa, whereas in relation to the joint X-groove joint preparation the FAT category was 63 MPa.
- The use of a working tool provided with the flat shoulder made it possible to modify the surface of TIG-welded joints in one run.
- The FSP of welded joints affects their fatigue strength. It was possible to observe a significant increase in the FAT category in relation to the joints subjected to V-groove joint preparation (from 43 MPa to 67 MPa) and a slight increase in the FAT category in relation to the joints subjected to X-groove joint preparation (from 63 MPa to 65 MPa).

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