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FATIGUE AND STATIC PROPERTIES OF FRICTION STIR WELDED ALUMINIUM ALLOY 6082 LAP JOINTS USING TRIFLUTE-TYPE AND SMOOTH TOOL

WŁAŚCIWOŚCI ZMĘCZENIOWE I STATYCZNE ZAKŁADKOWYCH ZŁĄCZY STOPU ALUMINIUM 6082 ZGRZEWANYCH METODĄ FSW PRZY UŻYCIU NARZĘDZIA GŁADKIEGO ORAZ TYPU TRIFLUTE

Due to numerous advantages, the FSW process more and more frequently used in different industries. Presently 99% of the FSW applications are connected with welding of aluminium alloys and most of FSW connections are butt joints, for which the very good mechanical properties are proved in many research. Instead of butt joints also a few types of shape joints can be friction stir welded, e.g. lap joints, multiple lap joints, fillet joints and T-joints.

This study presents the results of investigation into the impact of the FSW tool type on the structure of FSW lap joints made of aluminium 6082 and their mechanical properties under static and dynamic load. The study also presents the influence of different welding speeds and toll pin lengths on structure of lap joints. The paper also describes and demonstrates the negative influence on joints properties of some common defects that usually occurs in lap joints welded by means of FSW.

Keywords: mechanical properties of FSW lap joints, structure of FSW lap joints, fatigue strength of FSW lap joints, FSW process parameters

Z uwagi na wiele zalet metoda zgrzewania FSW coraz częściej znajduje zastosowanie w różnych gałęziach przemysłu. Obecnie 99% zastosowań metody FSW jest związana ze zgrzewaniem stopów aluminium, a większość połączeń stanowią złącza doczołowe, dla których wysokie własności wytrzymałościowe zostały potwierdzone w wielu badaniach. Oprócz połączeń doczołowych metodą zgrzewania FSW można również wykonać kilka rodzajów połączeń kształtowych, np. złącza zakładkowe, złącza wielozakładkowe, złącza ze zgrzeiną pachwinową oraz złącza teowe.

Artykuł przedstawia wyniki badań nad wpływem rodzaju narzędzia na własności mechaniczne, pod obciążeniem stałym i zmiennym, zakładkowych złączy stopu aluminium 6082 zgrzewanych metodą FSW. Przedstawiono także wyniki wpływu prędkości liniowej zgrzewania i długości trzpienia narzędzia w procesie FSW na budowę złączy zakładkowych. Omówiono i zaprezentowano również niekorzystny wpływ na własności złączy niektórych zwykle występujących niezgodności w połączeniach zakładkowych zgrzewanych metodą FSW.

1. Introduction

A solid state joining method known as FSW (Friction Stir Welding), i.e. friction welding with stirring of weld metal, was invented and patented in 1991. Since then continuing development of this method has been observed and main applications of FSW are connected with welding of aluminium alloys (99% of all joints) and generally there are butt connections of long elements. The advantages of this method and its characteristics are shown in many publications [1-16].

In the last few years, research has focused on lap joints welded by FSW mainly to confirm the possibility of their use instead of riveted lap joints in aircraft construction [17].

Presently, linear lap joints welded by FSW are used in shipbuilding, railway and automotive industry [18-19] where the extruded aluminum sections made of aluminum profiles are welded by FSW. The use of FSW lap joints in the aircraft structures increases the mechanical properties of joints, affects weight reduction and allows for longer intervals between inspections.

Due to the nature of the FSW process of lap joints, where the welding tool axis is perpendicular to the contact area between the joining materials, some typical imperfections for this type of joints can be expected on both sides of the weld.

On the advancing side there is a "hooking" of material, while on the retreating side a reduction of sheet thickness is present. These kinds of welding defects are also present in spot welds welded by FSW. They are a significant notch and reduce the strength properties of lap joints. To minimize the phenomenon of "hooking", several types of welding tools such as Flared-Triflute^{TM}, A-Skew^{TM}, Trivex^{TM} were developed [20]. They are difficult to perform and have a complex geometry. Another kind of imperfection that can occur is called "joint line remnant", being a result of insufficient dispersion of Al_2O_3 oxide particles that come mainly from the surfaces of the welded materials and form a characteristic

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band. It extends around the weld at the area where was the contact of joined elements. Other terms of this phenomenon called “lazy S”, “zigzag curve”, “zigzag line” can be found in the literature [21]. If the oxide inclusions reach the root of weld, then they are called as “kissing bond” or less frequently as “weak bond” [22-27]. Lap joints made by FSW welding may also include several types of weld defects typical for butt joints, but because of the geometry of the lap joints there are no defects in the root of the weld.

This paper presents the results of experimental studies conducted on the lap joints of 6082 aluminum alloy welded by FSW using different types of tools, and includes metallographic and mechanical tests under static and dynamic loads.

2. Production of test joints and experimental procedure

2.1. Material and test specimens

Material used in tests was aluminium alloy 6082-T6 in the form of flat bars of dimensions 100×4 mm. Heat treatment T6 indicates that the alloy was subjected to the artificial ageing, at a temperature of approximately 170°C, after solution treatment. The chemical composition of aluminium alloy 6082 is presented in Table 1. This alloy is weldable by means of conventional fusion welding methods and weldable by means of FSW.

TABLE 1
Chemical composition of aluminium alloy 6082 (according PN-EN 573-3:2010 [28])

Alloy	**Si** %	**Fe** %	**Cu** %	**Mn** %	**Mg** %	**Cr** %	**Zn** %	**Ti** %	**Al** %
6082	0.7-1.3	0.5	0.1	0.4-1.0	0.6-1.2	0.2	0.2	0.1	rest

To produce test joints, 3 types of welding tools that provided different depths of penetration and mixing of welded materials were used. Test joints have been made with an overlap of 50 mm. A scheme of test joints is shown in Fig. 1.

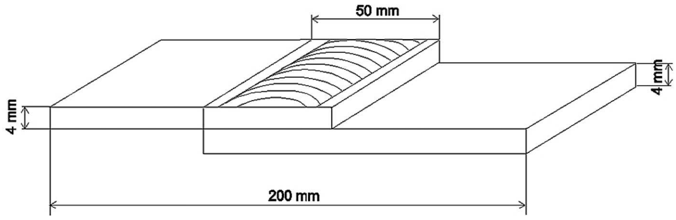


Fig. 1. Scheme of 8 mm thick FSW lap test joint

2.2. Types of FSW tools applied for welding

The lap joints were made with the following tools:

1. Triflute-type tool consisting of a housing, cylindrical threaded probe (also called as pin) of 10 mm diameter and 7.7 mm length with three grooves and a smooth shoulder of 28 mm diameter (Fig. 2a),

2. Triflute-type tool consisting of a housing, cylindrical threaded probe of 10 mm diameter and 5.5 mm length with three grooves and a smooth shoulder of 28 mm diameter,

3. Tool consisting of a housing, smooth cylindrical probe without a thread of 10 mm diameter and 5.5 mm length and a smooth shoulder without a grooved spiral of 33 mm diameter (Fig. 2b).

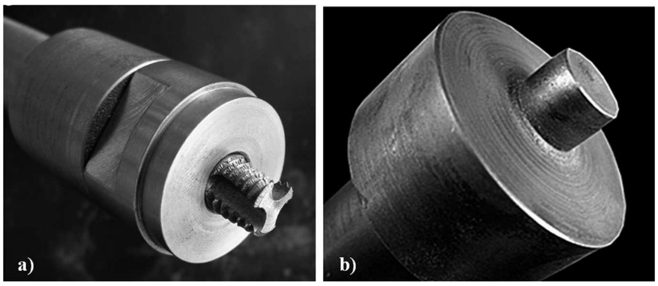


Fig. 2. Tool applied for lap joint welding; a) Triflute-type of a tool consisting of a housing, cylindrical threaded probe with three grooves and a smooth shoulder, b) tool consisting of a housing, smooth cylindrical probe without a thread and a smooth shoulder

2.3. Technological condition of welding

A process of FSW was carried out in the following welding conditions:

- using the Triflute tool with probe of 7.7 mm length a test lap joints were performed at linear welding speed of 224, 560, 900 mm/min,
- using the Triflute tool with probe of 5.5 mm length a test lap joints were performed at linear welding speed of 224, 560, 900 and 1120 mm/min,
- using the smooth tool with probe of 5.5 mm length a test lap joints were performed at one linear welding speed of 900 mm/min.

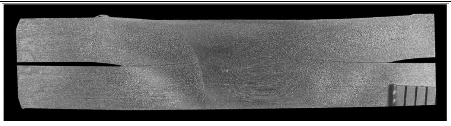
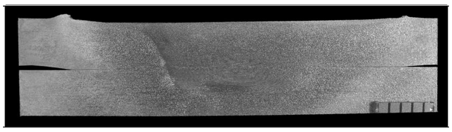
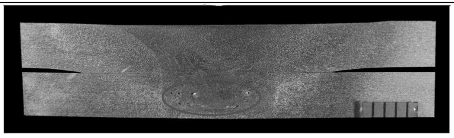
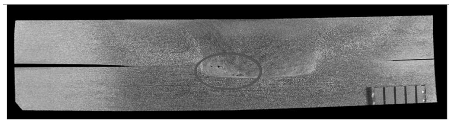
Tool rotational speed was the same for performing each test joints and was equal to 710 rev/min.

3. Conducted tests

3.1. Macroscopic tests of FSW lap joints

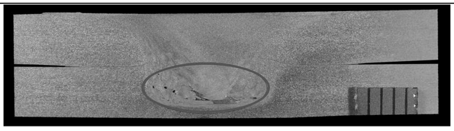
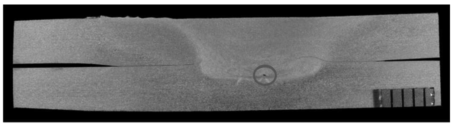
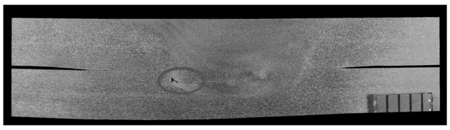
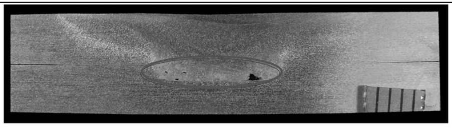
Specimens for macroscopic metallographic tests were prepared in accordance with the requirements of the standard PN-EN 1321:2000 [30]. Tests were carried out on specimens extracted from all test joints welded with various linear welding speeds. The macrostructure of joints was revealed through immersion etching in Keller’s etchant. The macrostructures of test joints are presented in Tables 2-3. Areas marked with ellipses indicate material discontinuity.

TABLE 2
Macrostructures of friction stir welded lap joints, 8 mm thick, welded at linear welding speed of 224 and 560 mm/min

Type of tool and tool pin length	Linear welding speed and macrostructure
Triflute 7.7 mm	Linear welding speed: 224 mm/min 
Triflute 5.5 mm	
Triflute 7.7 mm	Linear welding speed: 560 mm/min 
Triflute 5.5 mm	

Note: Left side on the macrostructure picture corresponds to the advancing side of weld

TABLE 3
Macrostructures of friction stir welded lap joints, 8 mm thick, welded at linear speed of 900 and 1120 mm/min

Type of tool and tool pin length	Linear welding speed and macrostructure
Triflute 7.7 mm	Linear welding speed: 900 mm/min 
Triflute 5.5 mm	
Smooth 5.5 mm	
Triflute 5.5 mm	Linear welding speed: 1120 mm/min 

Note: Left side on the macrostructure picture corresponds to the advancing side of weld

3.2. Microscopic tests of FSW lap joints

Metallographic microscopic tests were conducted using a light microscope LEICA MEF4M. The microstructure of the joints was revealed through double-staged immersion etching in Weck's etchant [31]. The microscopic observation included the parent metal, areas on the advancing side and retreating side of the joints and the area of the so-called "weld nuggets". Selected results of the study in the form of images of microstructures are presented in Figure 3.

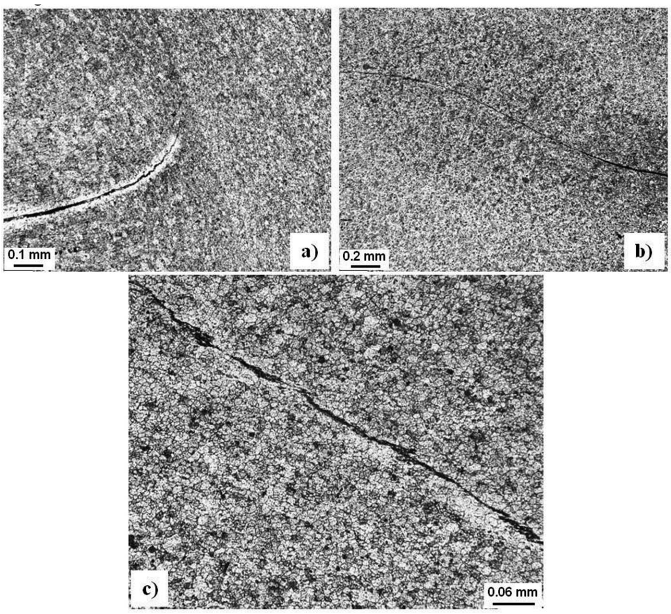


Fig. 3. Microstructure of FSW lap joint of aluminium alloy 6082; a) „hooking" of material; b) effective sheet thickness reduction; c) „kissing bond" (Al_2O_3 inclusions)

In all samples the typical imperfections for lap joints were found. On the advancing side of welds, defects called "hooking" were present (Fig. 3a) and on the retreating side of welds reduction of sheet thickness were found (Fig. 3b). In the test lap joints welded by FSW the concentrations of aluminum oxide, which is often arranged in bands, were observed (Fig. 3c). These oxides mainly come from the surfaces of welded elements and are not properly broken down and dispersed by the action of rotating and moving tool during welding. They are rather rubbed into the weld area. Even if they were mechanically removed prior to welding, they were formed again during FSW process at elevated temperature. The joints containing such imperfections, that look like cracks, were present in all samples and they were extended from retreating side of weld toward the weld axis.

Additionally, microscopic observations were performed on metallographic samples taken from the lap joint after shear test, in which fracture took place along the contact plane of joint and on the fracture there was a dark zone, suggesting the presence of oxide layers. Results are presented in Fig. 4. The study confirmed the presence of an oxide layer strongly adhering to the surface (Fig. 4a) and also revealed areas of fracture where there is no such layer (Fig. 4b). That confirms that its presence is associated with the ability of the tool to the dispersion mixing aluminum oxide from the surfaces of elements welded by FSW.

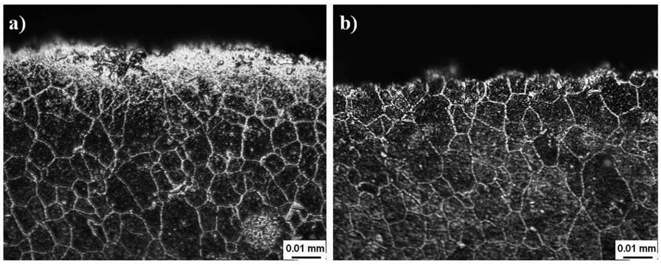


Fig. 4. Microstructure of fracture fragment of FSW lap joint; a) with visible oxides layer in the area of fracture; b) without visible oxides in the area of fracture

3.3. Shear test of FSW lap joints

A static shear test was carried out in accordance with standard PN-EN ISO 15614-12:2006 [29]. Test specimens were loaded by means of a testing machine INSTRON 4210 and the changes of shear force, and its maximum value were recorded. Each test series of joints consisted of three samples. The results are given in Table 4.

On the test fractures of sheared samples one can see that for the lower linear welding speed a destruction (cracking) corresponding to 224 and 560 mm/min occurs along the plane passing through the weld and result in disruption of the joined elements (Fig. 5). The fracture surfaces broken in this way, two characteristic zones can be seen in the weld area, i.e. a bright zone, which occurs on the advancing side of weld, and the darker area, which is visible in the retreating side of weld. They are shown in Figure 5 and their combined width corresponds to the diameter of the welding tool. The bright zone, with a width of approximately 25% of the diameter of the welding tool was a typical ductile fracture that occurs in a static tensile test. Whereas, the darker area was smooth and did not show the typical features of the metallic bond fracture, and certainly contributed to the reduction of the maximum shear force.

The presence of such an area on the retreating side of joint is due to insufficient dispersion of oxides from the surfaces, which are only rubbed into weld area and form strongly adherent layer, thus reduces the mechanical properties of the joint. At higher linear welding speeds corresponding to 900 and 1120 mm/min, fractures occurred mainly on the advancing side of weld (Fig. 6).

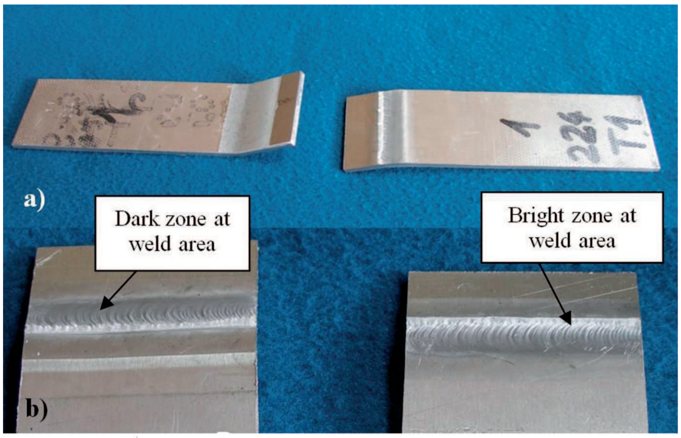


Fig. 5. Fractures of lap joint Triflute tool welded with linear welding speed of 224 mm/min; a) main view; b) surface view at the place of fracture

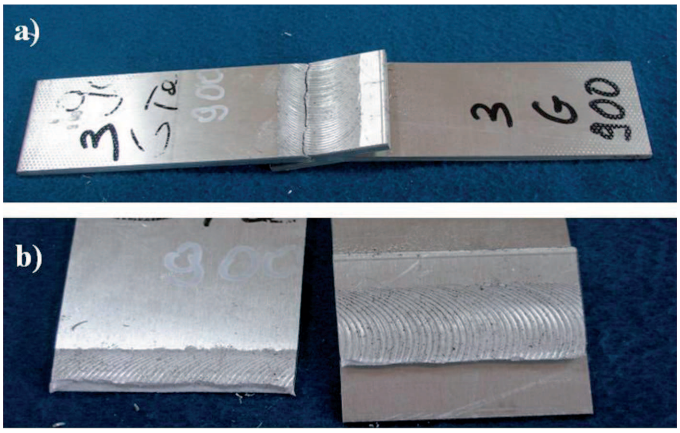


Fig. 6. Fractures of lap joint Triflute tool welded with linear welding speed of 900 mm/min; a) main view; b) surface view at the place of fracture on advancing side of joint

TABLE 4

Results of shearing of FSW lap joints

Specimen mark	**224 T1**	**224 T2**	**560 T1**	**560 T2**	**900 T1**	**900 T2**	**1120 T2**	**900 G**
Shearing force F_{max}, kN	25.5	24.7	28.1	26.8	16.6	27.1	22.7	40.9
	26.0	26.9	33.2	26.2	6.6	26.2	30.5	43.4
	24.3	24.6	30.0	25.7	5.4	27.4	29.1	41.7
Mean value F_{max}, kN	**25.2**	**25.4**	**30.4**	**26.2**	**9.5**	**26.9**	**27.4**	**42.0**

Note: 224, 560, 900, 1120 – linear welding speeds in mm/min; T1- Triflute pin of length 7.7 mm; T2- Triflute pin of length 5.5 mm, G- smooth pin of length 5.5 mm

3.4. Fatigue tests of FSW lap joints

The test joints for fatigue testing were performed at specified welding conditions, for which the static properties of joints were satisfactory, i.e. linear welding speed 900 mm/min and rotational welding speed 710 rev/min.

The fatigue tests were conducted with an MTS 810 fatigue-testing machine, according to guidelines contained in a document of the International Institute of Welding (IIW) [32].

Fatigue tests of lap joints were carried out on four levels of stress range $\Delta\sigma$. Fifth, the lowest stress level, was adopted on the basis of the results obtained for the higher levels in order to guarantee the life of the sample at least $2 \cdot 10^6$ cycles. Fatigue diagrams developed on the basis of test results are shown in Figure 7, where also the calculated fatigue categories (FAT) are presented. The equations describing fatigue categories were obtained by linear regression of the bi-logarithmic system. These equations take the form:

a) $\log(N) = -3{,}94 \cdot \log(\Delta\sigma) + 11{,}48$ – for the lap joints welded by Triflute tool,

b) $\log(N) = -2{,}90 \cdot \log(\Delta\sigma) + 8{,}62$ – for the lap joints welded by smooth tool.

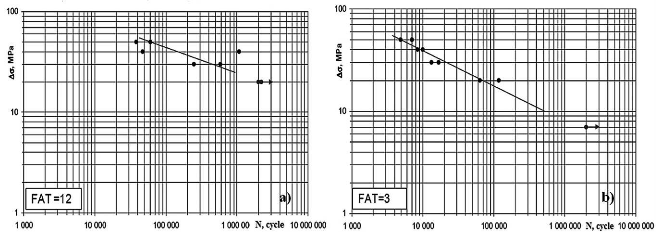


Fig. 7. S-N diagram for lap joints; a) welded with Triflute tool; b) welded with smooth type of tool

4. Results and discussion

Metallographic macroscopic test on cross-sections of the lap joints showed that for the lowest linear welding speed equal to 224 mm/min and a Triflute tool for welding, all the joints achieved correct internal structure with full continuity across the cross-section (Table 2). Such a proper structure was revealed for both joints made with a probe length of 5.5 mm and 7.7 mm. When the linear welding speed increased up to 560 mm/min then material discontinuity were present at the joints, regardless of the length of the probe (Table 2). Similar cases were in the joints made with even higher welding speed of 900 and 1120 mm/min. When applying linear welding speed equal to 1120 mm/min a large linear discontinuity (about 1 mm) was formed on the retreating side of a weld (Table 3).

Metallographic microscopic studies revealed the presence of lap joints imperfections typical for FSW. Instead of the "hooking" of material and reduction of effective sheet thickness, numerous oxide inclusions which form characteristic bands in the joints were revealed. Literature data on the negative effects of Al_2O_3 oxides on fatigue strength connections are not clear. However, the fatigue fracture analysis showed that, in some cases, the fatigue fracture surface corresponded to the mentioned above oxides bands. Thus, for the analyzed test joints they had negative influence from the fatigue strength point of view. Tool with a cylindrical smooth probe without thread breaks the aluminum oxide less effective than a Triflute type tool, where the probe was threaded. Even then, in the lap joints welded by Triflute tool the presence of the oxide bands was also disclosed.

When the linear welding speed increased to 900 mm/min the results showed that the Triflute tool with probe of 5.5 mm length provided, at the given welding speed rate, substantially better mechanical properties than the tool with probe of 7.7 mm length. While welding was performed with the longer tool probe (7.7 mm length), the tool probe fractured a few times. This was due to the high forces in the direction of welding, which increased with the increasing linear welding speed because of lesser degree of the plasticization and heating of welded materials. Therefore, for the highest linear welding speed appointed to perform test joint, equal to 1120 mm/min, a Triflute tool applied for welding had only shorter probe (5.5 mm).

Conducted shear test for 8 mm-thick overlap joints showed that the for the linear welding speed of 224 mm/min, at which the joints were free of internal flaws, the length of the Triflute probe had no effect on the maximum shear force. For an average linear welding speed equal to 560 mm/min maximum shear force was higher even though there were some discontinuities in the joints. Joints welded by tool with a smooth probe had significantly higher shear strength and this is due to tool geometry. The diameter of the smooth probe without the thread is 10 mm. The Triflute type probes have an outer diameter of 10 mm but they are also notched to a depth of thread of 1 mm, which help to move material from the bottom to top during welding, thus provide better mixing, but the core of the probe in this case has a diameter of 8 mm. This translates into smaller cross-section of welds and consequently lower shear strength of joints.

Lap joints welded by FSW using Triflute type tool, for which on the basis of experimental tests fatigue category was calculated as FAT=12, did not have any cracks or other discontinuities. However, the characteristic feature of the lap joints welded by FSW was the presence of notches like "hooking of material" on the advancing side of weld and reduction of upper sheet thickness on the retreating side of weld.

Fatigue tests performed on 4+4 mm thick lap joints, welded using two types of tools (Triflute type tool and a tool with smooth cylindrical probe) showed that generally the fatigue strength is very low. For lap joints welded by Triflute type tool fatigue category is FAT=12, and for welded joints using a tool with a smooth probe fatigue category is FAT=3. Studies have shown that the specific shape of such joints, containing geometrical notches and a numerous presence of aluminum oxides, has a huge effect on the low fatigue strength.

Based on the fatigue test of lap joints it can be said that from the fatigue strength point of view, it is better to use Triflute type tool (except dedicated tools). Referring the achieved results to the IIW document [32] with the recommendations for the fatigue design of welded structures, it should be noted that the lowest fatigue category for aluminum welded joints defined there is equal to FAT=12. According to the document mentioned above to the group of joints of such low fatigue category belong for instance: butt joints with partial weld penetration, lap joints and cruciform joints with fillet welds containing root cracks, butt joints of pipes containing root cracks and others.

5. Conclusions

The conducted tests and the analysis of results enabled the formulation of the following conclusions:

1. Lap joints of aluminium alloy 6082 welded by FSW have low fatigue strength, that is comparable to the welded joints containing cracks in the weld root or those characterized by partial penetration.

2. Probe length (depth of penetration) to perform FSW lap joints does not affect the mechanical properties of joints under a static load, which mainly depend on the width of the weld at the interface between welded materials.

3. Due to the low fatigue strength of FSW lap joints it is not recommended to design them for operation under a variable load.

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