# EFFECT OF WELDING PARAMETERS ON MECHANICAL AND MICROSTRUCTURAL PROPERTIES OF AL 2024 JOINTS PRODUCED BY FRICTION STIR WELDING

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***Abstract***

*Results of Friction Stir Welding (FSW) of aluminium 2024 are presented in this paper. Investigations were conducted on the welding machine, built on the base of the conventional, vertical milling machine. The quality assessment of joints was done on the grounds of the visual inspection, tensile and fatigue tests, the analysis of the welds structure and hardness. Heat treatment was not done after the welding process. The goal of the research was to know the relationship between welding parameters and mechanical and microstructural properties of 2024 joints.*

*Results indicate that weldability of aluminium alloys of Al 2024 4 mm in thickness with FSW method is good. Properties of joints with the FSW method on the milling machine equipped with LOWSTIR device fulfil requirements of this kind of joints. The structure is correct and the tensile properties are higher than properties of arc welded joints. With wide range of welding parameters the high quality of joint is possible. Joints welded with the different tools and in different conditions had characteristic shape of nugget, heat affected zone and thermo-mechanically affected zone. The kind of tool is not affected on properties of FSW joint at the same parameters. The proper quality at four different kind of tool is possible to achieve. Fatigue properties of the FSW joints made in correct way are very high, higher than properties of arc welded joints. Hardness profile of welds had characteristic run, typical for joints welded with the FSW method. The LOWSTIR device is not getting worse the quality of FSW joints.*

***Keywords:*** *friction stir welding, aluminium alloy 2024, microstructural properties, mechanical properties, fatigue properties*

## 1. Introduction

The difficulty of making high-strength, fatigue and fracture resistant welds of aerospace aluminium alloys, such as highly alloyed 2XXX and 7XXX series, has long inhibited the wide use of welding for joining aerospace structures. These aluminium alloys are generally classified as non-weldable because of the poor solidification microstructure and porosity in the fusion zone. Also, the loss of mechanical properties as compared to the base material is very significant. These factors make the joining of these alloys by conventional welding processes unattractive. Some aluminium alloys can be resistance welded, but the surface preparation is expensive, with surface oxide being a major problem. There are some works that study the Friction Stir Welding of aluminium sheet of 2024 alloy [1-13], including microstructure mechanical properties and fatigue properties.

Jones et al. [3] pointed out that the HAZ on the retreating side of a friction stir welded 2024-T351 aluminium alloy contains two distinct hardness minima on either side of a maximum. The inner hardness minimum close to the TMAZ was found to be due to coarsening and overaging of the S phase occurring during the thermal cycle. The outer hardness minimum was thought to be due to dissolution of the very fine S phase occurring towards the outer edge of the HAZ. The hardness maximum interjacent to these two minima was seen to be due to the presence of very fine S phase precipitates, and is likely to be a result of optimum aging conditions being achieved. The nugget zone was found to be typically fine grained (~ 4μm) and contained complex dislocation structures within the grains, together with evidence that fine scale S and larger Ω phase precipitation had occurred from a solutionized state.

Authors of publication [4] have reported a quantitative investigation of the effect of welding on precipitation in the 2024 alloy in the T351 and the T6 states, using small angle X-ray scattering, transmission electron microscopy, differential scanning calorimetry and hardness measurements. Depending on the peak temperature, the main precipitation phenomena are Guinier Preston Bagaryatskii zone dissolution, precipitation of S0(S), which can be either a hardening agent at small sizes or detrimental to the mechanical properties at large sizes. The quantification of the microstructure has allowed modelling of the yield stress evolution through the weld according to an appropriate mixing law for the contributions of the different obstacles. The effect of a T6 post-welding heat treatment has also been studied on a T351 weld. This treatment actually results in a further softening of the thermo-mechanically affected zone. In parallel, the susceptibility to strain localisation during tensile testing of the weld has been evaluated by the digital image correlation technique.

The authors [5] have presented the influence of plastic deformation on the precipitation kinetics of the S‘(S) phase in the AA2024 aluminium alloy, with the objective of understanding the microstructures found in friction stir welds of the same alloy. Different types of thermo-mechanical treatments have been investigated, where plastic deformation has been carried out either before heating in a salt bath, or concurrently with the thermal treatment in a Gleeble compression apparatus. The volume fraction of precipitates has been measured by differential scanning calorimetry and the precipitate morphology has been observed by transmission electron microscopy. These results are shown to be valuable tools in understanding the microstructures of friction stir welds of the same material. It is shown that taking into account the effect of plastic deformation is not absolutely necessary in the thermo-mechanically affected zone. However, they have been shown that the precipitate microstructure in some parts of the heat-affected zone is strongly influenced by a small amount of plasticity.

Besides the attractive mechanical properties, especially in fatigue and load bearing capacity strength, FSW integral structures are claimed to offer cost and weight savings.

Authors of publication [6] have compared the results of fatigue properties of AA2024-T4 friction stir welds and base materials and the influence of zigzag-curve defects across weld section on the fatigue properties of FSW joints were investigated. It was shown that the zigzag-curve defects were the inherent feature existed in the friction stir nugget and could make the characteristic fatigue strength decreases from 96 MPa for base material to 73 MPa for welded joints with a reduction of 23.4%. Although the fatigue strength is lower than the corresponding base material, the FSW joints of AA2024-T4 Al alloy achieved higher fatigue strength compared to the traditional fusion design curves IIW FAT40 and Draft Eurocode 9 design category 55-6 for structural aluminium alloy components.

The authors [7] presented the results of fatigue of FSW joints of 2024-T3 Al alloy and a detailed analysis towards the potential of CSP (Controlled Shot Peening) to improve the fatigue strength of 2024-T3 aluminium alloy friction stir welds. They achieved increase of fatigue strength about 100 % after CSP process in compare to welded joint.

Fersini et al. [8] reported for the fatigue behaviour of FSW overlap joints. They concluded that the FSW overlap joint shows fatigue strength lower with respect to the design curve of bolted joints proposed in Eurocode 9.

The researchers [9] have shown friction stir welds manufactured using 6.25 mm thick, 2024-T351 aluminium rolled sheet material. Results from metallurgical, hardness and quantitative EDX measurements clearly show that the friction stir welding process can create a segregated banded microstructure consisting of alternating hard particle-rich and hard particle-poor regions.

The authors [10] have presented the results of FSW of 2024 aluminium to 6061 aluminium and flow visualization. Differential etch contrast has allowed complex, residual solid-state flow patterns to be visualized in FSW of dissimilar aluminium alloys. Intercalating lamellae of these two dynamically recrystallized alloys creates complex vortex, whorl, and swirl features characteristic of chaotic-dynamic mixing

Other studies of FSW of dissimilar materials [11] have shown the microstructure and mechanical properties of joints of 2024-T3 Al alloy to 7075-T6 Al alloy. Effects of welding speed and fixed location of base metals on microstructures, hardness distributions, and tensile properties of the welded joints were investigated. Hardness minima were observed in the HAZ both sides and their values increased with the welding speed. Quite wider scattering of hardness was observed in the stir zone corresponding to the onion ring pattern. Defect-free joints were fractured in the HAZ on 2024 Al alloy side, viz. hardness minimum area, while the defect-containing joints fractured in the stir zone. Maximum tensile strength of the joints of 423MPa was achieved at a welding speed of 1.7 mm/s when 2024 Al alloy plate was located on the advancing side. In another interesting studies [12], 2024 Al alloy has been friction-stir welded at a starting temperature of -30°C, and maximum weld zone temperatures did not exceed about 140°C (~410K or 0.4 TM, where TM is the absolute melting temperature). The residual FSW zone grain structure consisted of equiaxed, fine-grains having a uniform size of about 0.8 μm throughout. This compares with a central weld zone grain size of about 10 μm in 2024 Al FSW at a starting temperature of 30°C, where the weld zone temperature maximum was measured to be 330°C (or 0.6 TM).

Results of Friction Stir Processing of 2024 alloy are also available [13]. That results have demonstrated that superplasticity at higher strain rates can be achieved in a commercial 2024 Al alloy via friction stir processing. Ductility values for the FSP alloy are substantially higher than that of the parent alloy (non-superplastic) at comparable temperature and strain rate ranges. Furthermore, superplasticity is achieved at higher strain rates of $10^{-2}$-$10^{-1}$ $s^{-1}$ in this alloy, which was hitherto not possible with conventional TMP (Thermomechanical Processing).

Although, some results of FSW of 2024 aluminium alloy sheet are available, there exists an urgent need of developments of these new techniques. Industry uses much different kind of tools. Most of the available results apply to FSW of aluminium conventional tool. In the presented study four types of tools were used: Triflut with flat bottom pin, Triflut with round bottom pin, Triflat with flat bottom pin and Triflat with round bottom pin. The experiments were carried out on the milling machine equipped with LOWSTIR device. The obtained results can be useful for the automotive industry.

## 2. Friction stir welding process

Friction stir welding (FSW) was invented at The Welding Institute (TWI) of UK in 1991 as a solid-state joining technique, and it was initially applied to aluminium alloys. The basic concept of FSW is remarkably simple. A non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and traversed along the line of joint (Fig. 1). The tool serves two primary functions: (a) heating of workpiece, and (b) movement of material to produce the joint. The heating is accomplished by friction between the tool and the workpiece and plastic deformation of the workpiece. The localized heating softens the material around the pin and combination of tool rotation and translation leads to movement of material from the front of the pin to the back of the pin. As a result of this process a joint is produced in 'solid state'. Because of various geometrical features of the tool, the material movement around the pin can be quite complex. During FSW process, the material undergoes intense plastic deformation at elevated temperature, resulting in generation of fine and equiaxed recrystallized grains. The fine microstructure in friction stir welds produces good mechanical properties [1]. Generally FSW produces five distinct microstructural zones [2], namely the weld nugget, the thermomechanical affected zone (TMAZ), the heat affected zone (HAZ) and unaffected zone or parent plate. Figure 2 shows these characteristic regions of FSW welded joint [2].

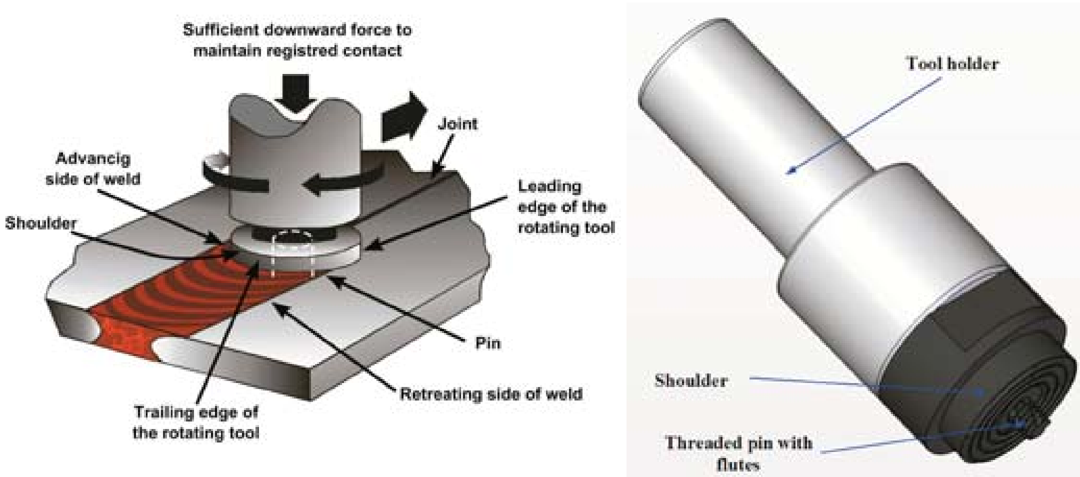



*Fig. 1. Schematic drawing of friction stir welding process and the tool*

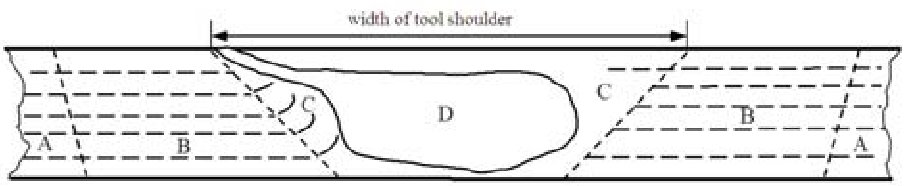



*Fig. 2.Characteristic region in the FSW welded joint A- parent material, B - Heat affected zone, C - Thermomechanically affected zone, D - Weld nugget [2]*

Unaffected material or parent material: This is material remote from the weld that has not been deformed and that, although it may have experienced a thermal cycle from the weld, is not affected by the heat in terms of microstructure or mechanical properties.

Heat affected zone: In this region, which lies closer to the weld centre, the material has experienced a thermal cycle that has modified the microstructure and/or the mechanical properties. However, there is no plastic deformation occurring in this area.

Thermomechanically affected zone (TMAZ): In this region, the FSW tool has plastically deformed the material, and the heat from the process will also have exerted some influence on the material. In this case of aluminium, it is possible to obtain significant plastic strain without recrystallization in this region, and there is generally a distinct boundary between the recrystallized zone (weld nugget) and the deformed zones of the TMAZ.

Weld nugget: The fully recrystallized area, sometimes called stir zone, refers to the zone previously occupied by the pin.

## 3. Experimental details

Investigations were carried out on the welding machines, built on the base of the conventional, vertical milling machines. The welding stand in Instytut Spawalnictwa was built on the base of the milling machine FYF 32JU2 equipped with LOWSTIR device. LOWSTIR is the acronym of LOW cost processing unit for friction STIR welding. This system, using advanced modelling techniques, can be used in conjunction with the milling machines, to create high quality Friction Stir Welded joints. The LOWSTIR system measure: weld force, down force, tool torque, tool temperature and sensor temperature. Measurement of these signals can be used to monitor of FSW process. During investigations four types of tools were used: Triflut with flat bottom pin, Triflut with round bottom pin, Triflat with flat bottom pin and Triflat with round bottom pin. Tools were made of the high-speed steel (SW7M). Materials used during the investigations were: EN AW 2024, 4 in thickness. The chemical composition (wt. %) of the 2024 alloy was as follows: 4.4 %Cu, 0.6 %Mn, 1.5 % Mg, 0.5 %Si and 0.1 %Cr. The mechanical properties of Al2024 sheet are: $R_m$=443.5 MPa, $R_e$=259.3 MPa, $A_5$=10.5 %. Plates were pressed against, fixed with the special holders and then butt welded. The contact surface of welded plates was not cleaned. Series of test samples welded with parameters, shown in Table 1 was made in conditions which guarantee that a proper and resistant weld will be obtained.

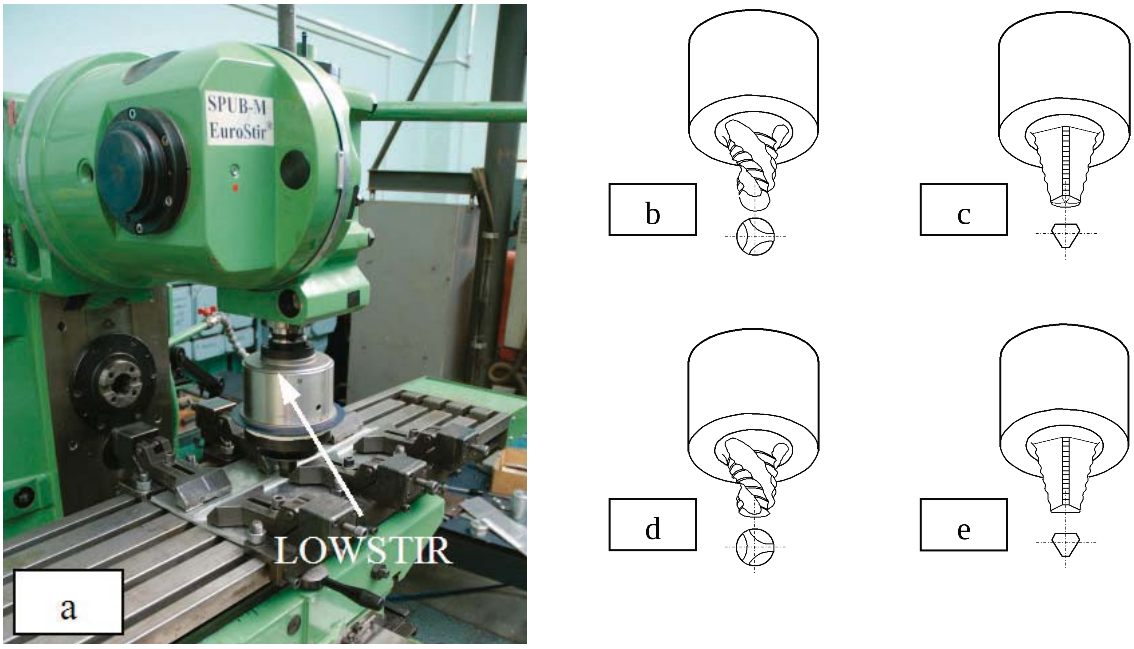



*Fig. 3. The welding stand a) built on the base of the milling machine FYF 32JU2 equipped with LOWSTIR device with tools b) - e). See Table 1*

*Tab. 1. Parameters of FSW process*

| Joint number | Spindle rotation [rpm] | Welding speed [mm/min] | Kind of FSW tool |
|---|---|---|---|
| 1 | 350 | 210 | Triflute with round bottom pin (Fig. 3b) |
| 2 | 350 | 210 | Triflat with round bottom pin (Fig. 3c) |
| 3 | 350 | 210 | Triflute with flat bottom pin (Fig. 3d) |
| 4 | 350 | 210 | Triflat with flat bottom pin (Fig. 3e) |

## 4. Results and discussion

The first main goal of this investigation was to know the influence of the welding conditions on the mechanical and fatigue strength and the welds structure, during the welding process with the use of the conventional tool. The second goal was to check the influence of the LOWSTIR device on the quality of FSW welds. To this end, the technological trials, metallographic examination and mechanical tests and fatigue tests were carried out.

The specimens for macro and micrographic examinations were cut out from selected types of joints. Examinations were carried out on the optical microscope MeF4M LEICA. For optical microscopy the samples were etched by the Keller reagent. Selected structures of joints are shown in Fig. 4 – 7.

*etch. Keller* *mag.×0.3*

*Fig. 4. Cross section of FSW join No1*

*etch. Keller* *mag.×0.3*

*Fig. 5. Cross section of FSW join No2*

*etch. Keller* *mag.×0.3*

*Fig. 6. Cross section of FSW join No 3*

*etch. Keller* *mag.×0.3*

*Fig. 7. Cross section of FSW join No 4*

All test plates demonstrate good quality of welds from the root side and correctly shaped face. The kind of tool not affected on macrostructure of FSW welds. The full penetration was possible to achieve regardless of the shape of pin. Results from metallographic examination clearly show that the FSW process carried out on milling machine equipped with LOWSTIR device can create proper joints.

Distribution of hardness on the welded joints (base metal, HAZ, TMAZ, nugget zone) was measured by the use of a manual Zwick Vickers hardness tester with a load of 9.8 N (HV1). The scheme of measurements is shown in Figure 8. Results of hardness measurement are shown in Figure 9. Hardness profile of welds had characteristic run, typical of joints welded with the FSW method. Hardness decreases in HAZ and hardness increases in the nugget.

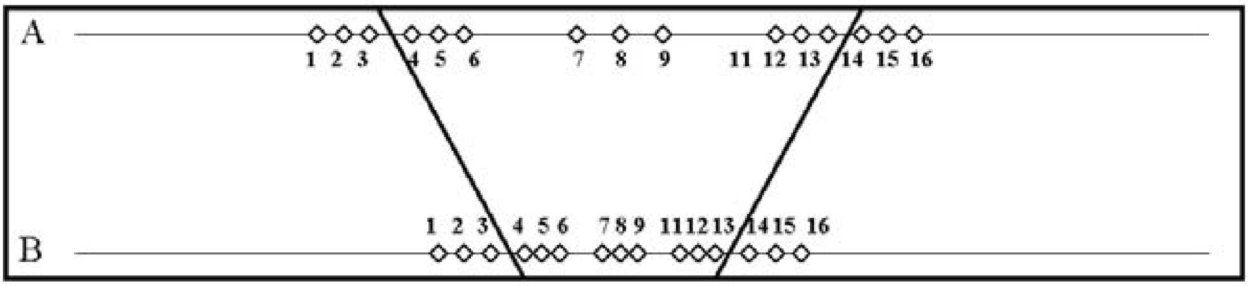



*Fig. 8. Scheme of measurement of hardness on the FSW joints*

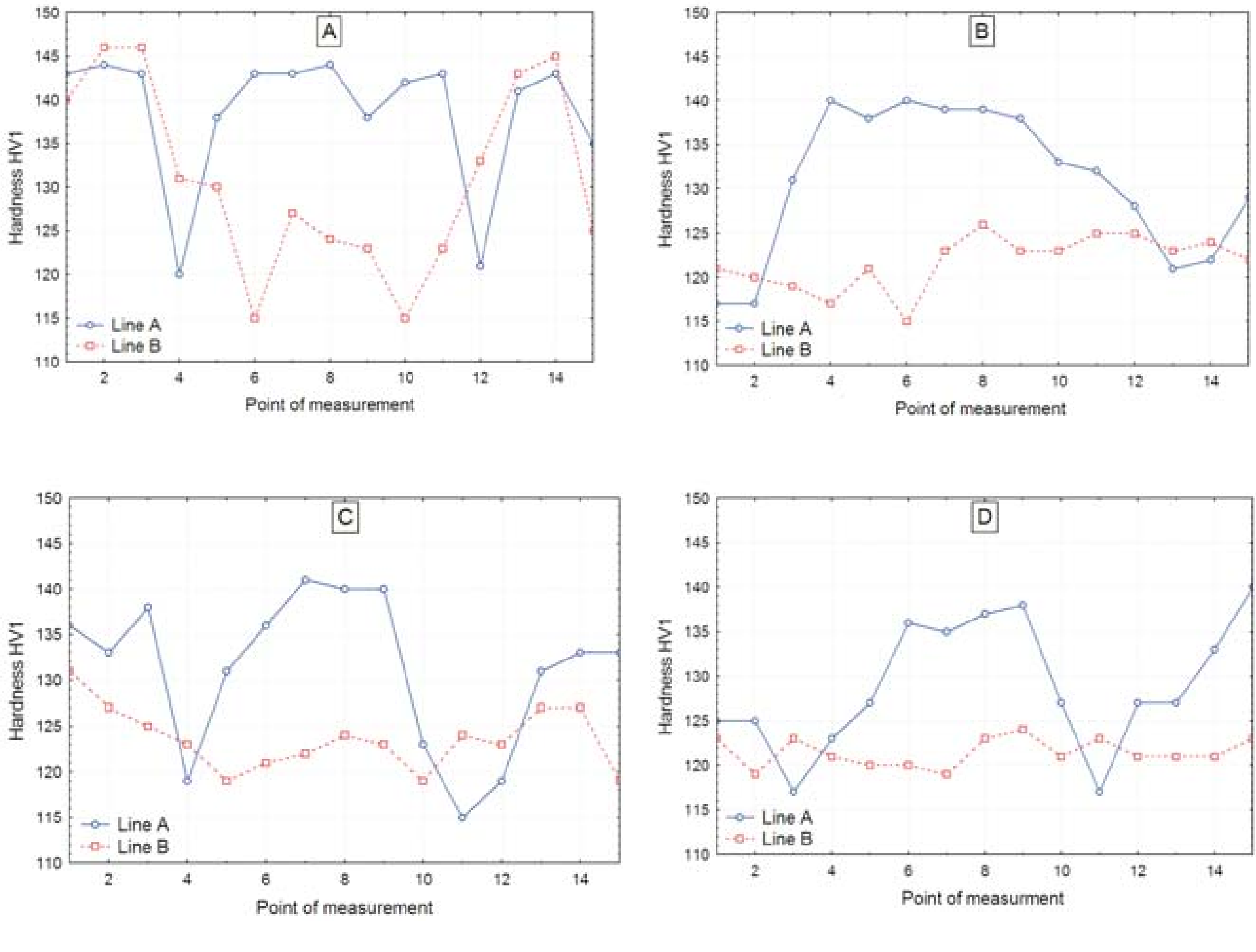
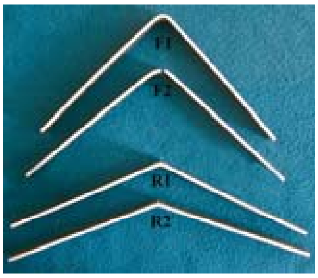
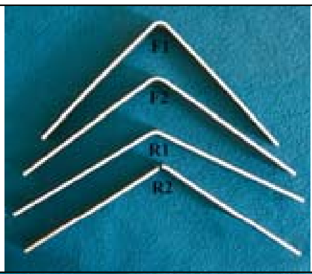
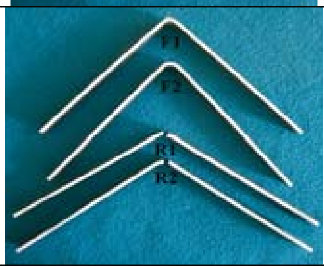
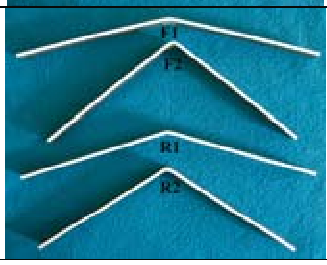



*Fig. 9. Distribution of hardness profiles of FSW joints, welding parameters are given in Table 2, A- weld No1, B-weld No 2, C-weld No3, D-weld No 4*

All samples were subjected to a bend test. In the bend test the mandrel 15.0 in diameter was used. The bend test showed that joints welded in all welding conditions were very brittle and subjected of very low bend angle without cracks. Results of the bend test are presented in Table 2.

*Tab. 2. Results of bend tests*

| No of weld | | Bend angle | Remarks |
|---|---|---|---|
| 1 |   | From the face side (F): $90^o$; $65^o$ From the root side (R): $50^o$; $45^o$ | Rupture from the advancing site of the weld |
| 2 |   | From the face side (F): $70^o$; $95^o$ From the root side (R): $50^o$; $55^o$ | Rupture from the retreating site of the weld |
| 3 |   | From the face side (F): $55^o$; $100^o$ From the root side (R): $90^o$; $90^o$ | Rupture from the advancing site of the weld |
| 4 |   | From the face side (F): $75^o$; $30^o$ From the root side (R): $65^o$; $35^o$ | Rupture in the weld zone |

Tensile testing transverse to the weld was executed on a 600 kN mechanical Instron 4210 universal testing machine at room temperature, in acc. with PN-EN 895. All presented test data are mean values of two tensile sample results. The results are given in Table 3.

*Tab. 3. Results of tensile tests*

| No of joint | Load at Peak [kN] | Stress at max. load [MPa] | Place of rupture |
|---|---|---|---|
| 1 | 42.4 | 424.2 | Advancing side |
| 2 | 41.8 | 423.4 | Retreating side |
| 3 | 39.9 | 414.5 | Advancing side |
| 4 | 40.4 | 404.8 | Weld zone |

The results of bend tests indicated that the best results was achieved at the tool No 3 - Triflute with flat bottom pin and the worst at tool No 4 - Triflat with flat bottom pin. But the results of the tensile tests (see. Table 2) shown that better results can be achieved at tools No 1 and 2 then tools No 3 and 4. So, based on the metallographic examination and mechanical tests the authors can not indicate the best FSW tool.

For selected welding conditions, joints for the fatigue test were prepared. The purpose of tests was to determine the basis fatigue parameters of samples from the AA 2024 - 4 mm in thicknesses, which were welded in TWI Ltd. The main aim of investigations was to determine the fatigue limit on the base of the diagram of the fatigue life, as the stress value by the durability of samples at 2·106 cycles.

Tests were carried out on the fatigue machine INSTRON 8502 with the numerical control system INSTRON 8500+. Nine samples from the series were put to the fatigue test.

The analysis of data was performed acc. to the document XIII-2151-07/XV-1254-07 [14] of the International Institute of Welding (IIW). The fatigue class FAT was estimated as 71 MPa.

The results of fatigue test indicate that the fatigue properties of FSW joint of aluminium alloy 2024 are higher then for fusion weld (FAT for fusion welded joint amount 45 MPa acc. to XIII-2151-07 [14]).

## Conclusions

The properties of FSW 2024 aluminium alloy joints were investigated in respect of hardness, microstructure, mechanical properties and fatigue strength and the following results were found:

- properties of joints of AA 2024 welded with the FSW method on the milling machine equipped with LOWSTIR device fulfil requirements of this kind of joints. The structure is correct and the tensile properties are higher than properties of arc welded joints
- kind of tool is not affected on properties of FSW joint at the same parameters. The proper quality at four different kind of tool is possible to achieved,
- the LOSTIR device is not getting worse the quality of FSW joints,
- fatigue properties of the FSW joints made in correct way are very high, higher than properties of arc welded joints.

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