Fatigue behaviour of friction stir welded AA-2024 aluminium alloy sheets

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Abstract. The presented paper deals with the mechanical and fatigue properties of the alloyed aluminium alloy AA-2024 welded by the Friction Stir Welded (FSW) process. Using the optimized tool and welding procedure, 6 mm thick plates made of about quoted material were connected. In the first part of the paper, the influence of welding speed on the microstructure and mechanical properties of treated FSW welded joints is studied. In the continuation, the fatigue behaviour of treated welded joints is analysed based on the experimental testing on a servo-hydraulic fatigue testing machine at room-temperature under the stress ratio \( R = 0.1 \). The experimental results have shown that the welding parameters have a significant influence on the mechanical and fatigue properties of AA-2024 welded sheets.

1. Introduction
The high-strength aluminium alloys such as 2xxx, 6xxx and 7xxx series are often used to produce the components for many important areas in automotive, aerospace and defence industries due to their reasonable mechanical properties for relatively low densities [1-3]. Their strength has been increased by the addition of elements such as Cu, Mg etc. which adversely affect the corrosion resistance of the alloy [4, 5].

Not long ago, riveting and fastening procedures were the main joining technologies for components made of high strength aluminium alloys because of their poor weldability [6, 7]. However, this problem has been overcome with implementation of the Friction Stir Welding (FSW) technique developed by the TWI-institute [8]. As presented by da Silva et al [9], Zimmer et al [10], Avettand-Fenoel et al [11] and Ahmed et al [12], there are three main magnitudes influencing the quality of FSW-joints: (i) tool geometry; (ii) welding parameters and (iii) joint construction. A peculiar feature of FSW-joints is the complex microstructure which significantly depends on the structural tool design, the rotation speed, the welding speed, the pressure of the tool on the plates along the vertical axis, the angle under which the tool acts on the material and the characteristics of the material being welded. As described by Ouyang et al [13] and Balokhonov et al [14], the following zones can be identified in the microstructure of the FSW-joints: the heat-affected zone (HAZ), the thermo-mechanical zone (TMZ), the stir zone (SZ) and the zone of base material. From that aspect it is very important to choose the right combination of welding parameters in order to obtain a welded joint of the corresponding quality without defects [15].

In last two decades, many authors have published comprehensive investigations where different influencing parameters on the mechanical, structural and corrosion properties of FSW-joints of aluminium alloys are studied in details. Vidal et al. [16] analysed the improvement of FSW-joints of
the aerospace aluminum alloy AA2024-T351 using the Taguchi method and statistical analyses to obtain the optimal welding parameters. Perović et al. [17] analysed the influence of the rotation speed and welding speed on the impact strength, microstructure and cross-section micro-hardness of FSW-joints of Al-Zn-Mg-Cu high strength aluminum alloy. The combined effect of a small difference in pin geometry and rotation and welding speed on the weldability, mechanical and structural properties of FSW 2024-T351 Al plates was studied by Radisavljević et al [18]. Hussain [19] conducted a study to determine and evaluate the influence of main welding parameters on the Vickers hardness, tensile strength and microstructure of FSW-joints of AA6351 aluminum alloy. Gupta et al [20] analysed the process parameters (tool rotational speed between 300 to 1000 rpm and welding speed of 50 mm/min) and energy input on the microstructure, hardness, tensile strength and corrosion property of 7475 aluminum FSW-joints. The similar work has also been proposed by Su J Q et al [21] who investigated the grain structure, dislocation density and second phase particles in various regions (dynamically recrystallized zone- DXZ, thermo-mechanically affected zone- TMAZ and heat affected zone- HAZ) of FSW aluminum alloy 7050-T651.

As described above, numerous researches have been carried out in the past to study the mechanical properties of FSW-AA2xxx-joints and their dependence on the tool geometry and welding parameters. On the other hand, the comprehensive investigations of the fatigue behaviour of FSW-AA2xxx-joints dated in the last decade. Aydin et al [22] studied the influence of the rotating speed and translation welding velocity on the fatigue behaviour of FSW-AA2014-T6 alloy. Authors concluded that the highest fatigue strength corresponds to the rotating speed of 1520 rpm and translation velocity 80 mm/min. Lemmmt et al [23, 24] investigated the influence of welding orientation and residual stresses on the fatigue crack initiation. Authors concluded that the influence of residual stresses is significant when the welding orientation is parallel to the applied load. Ilman et al [25] and Milan et al [26] investigated the fatigue crack propagation of FSW-AA2024-T3-joint. Their experimental results have shown that the FSW-joint is more resistant to the longitudinal crack growth due to beneficial influence of compressive residual stresses in this direction. As shown by Hatamleh et al [27], the fatigue behaviour of FSW-AAxxxx-joints could be improved with additional shot or laser peening. In last period, the numerical modelling was sometimes performed (Nikfam et al [28], Kraedegh et al [29], Đurđević et al [30], Živojinović et al [31]) to simulate the fatigue crack initiation and growth in the critical areas of FSW-joints. In [32], Neto et al presented a literature review of the numerical modelling of friction stir welding process. They concluded that FSW-modelling helps to visualize the fundamental behaviour of the welded materials and allows to analyse the influence of different welding parameters (including tool design) and boundary conditions, without performing costly experiments. The comprehensive numerical simulation of material flow in FSW of AA7075-T6 aluminium butt joints has also been done by Fratini et al [33], who proposed the experimental verification of numerical results.

The main objective of these research is to determine the influence of welding speed on the mechanical properties and fatigue behaviour of FSW-joints made of aluminium alloy AA 2024 T351. When studying the fatigue behaviour of treated FSW-joints, the special attention is destined to both, low cycle fatigue (LCF) and high cycle fatigue (HCF). Namely, it is assumed that the fatigue behaviour may be significantly dependent on the expected fatigue life of treated FSW-joint.

2. Material and welded joint characterization

The experimental testing has been performed on the high strength aluminium alloy AA2024-T351 with the chemical composition and mechanical properties given in Table 1. Two plates 500 mm × 65 mm × 6 mm were welded using FSW welding machine (see Figure 1) where the final length of the weld was 400 mm.

There are a large number of input parameters required for the production of friction stir welded joints, such as tool rotation speed, welding speed, axial force, tool pitch, geometry of tool etc. The microstructure and the mechanical properties of the welded joint are most influenced by the tool rotation speed and welding speed. The microstructure of FSW welded joint is characterized by 3 zones: the heat-affected zone (HAZ), the thermo-mechanical zone (TMZ) and the stir zone (SZ) (Fig. 2).
Figure 1. FSW welding machine (left) and welding tool (right).

Figure 2. Schematic illustration of FSW.

In the conducted researches, the samples were welded with a constant tool rotation speed \( n = 750 \) rpm and three different welding speeds as presented in Table 2. After the welding process was completed, the visual control as well as the radiographic control of welded samples on the weld face and root of the seam were performed. No defects were detected (visually, touch or magnifier).

Table 1: Chemical composition and mechanical properties of AA2024-T351.

| Chemical composition [%] | Mechanical properties |
|-------------------------|-----------------------|
| Cu  | Mg  | Mn  | Fe  | Si  | Zn  | Ti  | Yield strength \( R_e \) [MPa] | UTS \( R_m \) [MPa] | Elongation \( A_5 \) [%] | Hardness \( HV \) |
| 4.70 | 1.56 | 0.65 | 0.17 | 0.046 | 0.11 | 0.032 | 370 | 481 | 17.9 | 137 |

Table 2. Friction stir welding parameters.

| Sample designation | Rotation speed \( n \) [rpm] | Welding speed \( v \) [mm/min] | Ratio \( n/v \) [rev/mm] |
|--------------------|-------------------------------|-------------------------------|-------------------------|
| A – I              | 750                           | 73                            | 10.27                   |
| B – II             |                               | 116                           | 6.47                    |
| C – III            |                               | 150                           | 5                       |

Metallographic observation was carried out by optical microscopy using Leica M205A optical microscope. The specimen for optical microscopy was ground, polished and etched using Tucker’s (45 ml HCl, 15 ml HNO₃, 5 ml HF and 25 ml H₂O) reagent. Figure 3 shows four microstructures which correspond to the base material (BM) and welded joints for different welding speeds (A-I, B-II, C-III) as already presented and appropriate designated in Table 2. In general, the microstructure is dependent on the amount of the heat input during the welding process. From that respect, the maximum heat input will appear by the lowest welding speed (the case A-I) and vice versa. Therefore, the fine microstructure corresponds to the welding regime C-III and coarse microstructure to the regime A-I.
3. Experimental testing

Specimens for the further mechanical and fatigue testing were manufactured from FSW-samples. As shown on Figure 4, two types of specimens were provided: specimen for tensile test and specimen for fatigue test. Tensile tests were carried out at room-temperature under strain rate of $3.3 \times 10^{-3}$ s$^{-1}$ according to the ASTM E8M standard. Two tensile specimens were tested for each welding regime (A-I, B-II and C-III) and average values have then been considered when determining the mechanical properties of FSW-joints (see section 4). Fatigue tests were carried out on a servo-hydraulic fatigue testing machine (Shimadzu Servopulser E100kN, Shimadzu Co.) at room-temperature under the stress ratio $R=0.1$ and loading frequency of 35 Hz. For each welding regime, the fatigue tests have been performed at different stress levels. Based on the obtained experimental results, the S-N curves were constructed as presented in section 4.

![Figure 3. Microstructures of base material (BM) and welded joints for different welding speeds.](image)

![Figure 4. Specimens locations in FSW-welded joint (a), specimen for tensile test (b) and specimen for fatigue test (c).](image)
4. Results and discussion

Figure 5 shows the mechanical properties (ultimate strength $R_m$, yield stress $R_{p0.2}$ and elongation $EL$) of welded joints for different welding regimes (A-I, B-II and C-III). It is evident, that the best mechanical properties correspond to the welding regime B-II with the middle welding speed $v = 116$ mm/min. This welded joint also shows a relative good ductility with elongation at breakage about 7.43 %. On the other hand, a very brittle behaviour (small difference between $R_m$ and $R_{p0.2}$ and extremely short elongation at breakage) under quasy static loading can be observed for welding regime C-III, where the welding speed was the highest ($v = 150$ mm/min). For welding regime A-I with the lowest welding speed ($v = 73$ mm/min), the mechanical properties of welded joint can be found in the between of the properties for B-II and C-III.

![Figure 5. Mechanical properties of welded joints for different welding regimes.](image)

| Regime | $R_{p0.2}$ [MPa] | $R_m$ [MPa] | $EL$ [%] |
|--------|----------------|-------------|-----------|
| A-I    | 281.9         | 371.00      | 2.29      |
| B-II   | 330.9         | 469.06      | 7.43      |
| C-III  | 337.6         | 352.03      | 0.33      |

Figure 6 shows the S-N curves (relations between amplitude stress $\sigma_a$ and number of cycles until failure $N$) for different welding regimes. When creating the S-N curves the fatigue limit of about $10^7$ was assumed. It is evident, that the highest fatigue strength corresponds to the welding regime B-II where the welding speed was $v = 116$ mm/min. For this case, the fatigue limit at $10^7$ loading cycles is approximately 68 MPa. The S-N curve for welding regime C-III (the highest welding speed) shows a relative high fatigue strength in the area $N < 10^5$. It can be explained with the fact that the yield stress $R_{p0.2}$ is the highest for welding regime C-III which results in the high fatigue strength in this area. On the other hand, the fatigue strength is for the welding regime C-III significantly decreasing with increase of $N$. The latter can be explained on the assumption that the hard and brittle material which corresponds to the regime C-III is very sensitive to the high cycle fatigue regime.

![Figure 6. S-N curves for different welding regimes.](image)
5. Conclusions
In the presented work, the mechanical and fatigue behaviour of the alloyed aluminium alloy AA-2024 welded by the Friction Stir Welded (FSW) process were studied. The FSW-process was performed by using a vertical milling machine for constant rotation speed of welding tool 750 rpm and three different welding speeds: 73, 116 and 150 mm/min. Based on the obtained experimental results the following conclusions can be made:

- As expected, the minimum heat input due to friction between welding tool and welding plates has been obtained for the highest welding speed 150 mm/min (welding regime C-III) and the maximum heat input has been obtained for the lowest welding speed 73 mm/min (welding regime A-I).
- The welding speed and consequently the heat input have a significant influence on the microstructure of welded joints. Because the maximum heat input appears by the lowest welding speed (the case A-I), the relative coarse microstructure has been detected in this case. The finest microstructure (the smallest grain size) corresponds to the welding regime C-III (the highest welding speed).
- The experimental results of the static tensile tests have shown that the best mechanical properties (ultimate strength, yield stress) correspond to the welding regime B-II with the middle welding speed 116 mm/min, which at the same time assure a relative good ductility (elongation at breakage is about 7.43 %). On the other hand, a very brittle behaviour (extremely short elongation at breakage) has been obtained for welding regime C-III, where the welding speed was the highest.
- The experimental results of the fatigue tests have shown that the highest fatigue strength corresponds to the welding regime B-II (welding speed 116 mm/min) for both, LCF and HCF area. The fatigue behavior for welding regime C-III (the highest welding speed) shows a relative high fatigue strength in LCF-area ($N < 10^5$) and low fatigue strength in HCF-area ($N > 10^5$). It can be explained with the fact that the hard and brittle structure which appears by high welding speed is very sensitive to the high cycle fatigue regime.

For future work the influence of the residual stresses on fatigue life of FSW-joint may be addressed. Namely, the higher heat input in the case of low welding speed could induces greater residual stresses which are in high cycle fatigue regime usually not relaxed and may significantly influence the fatigue life of treated FSW-components.

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