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FSW characterization of 6082 aluminium alloys sheets

K. Mroczka [a,*], A. Pietras [b]

[a] Institute of Technology, Pedagogical University of Cracow, ul. Podchorążych 2, 30-084 Kraków, Poland

[b] Institute of Welding, ul. Bł. Czesława 16/18, 44-100 Gliwice, Poland

* Corresponding author: E-mail address: kmrocz@gmail.com

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ABSTRACT

Purpose: The purpose of the investigations was to elaborate a set of FSW parameters for connecting 6082 aluminium alloy sheets allowing to produce welds of highest strength.

Design/methodology/approach: The FSW was tried at different speeds and at additional cooling. The welds microstructure was studied using optical and scanning electron microscopes. The mechanical properties of produced connections are discussed regarding their tensile test and microhardness measurements.

Findings: The FSW welds, aside some zigzag lines connected probably with the incorporation of the surface oxides, were found to be devoid of any macro defects. The weld microstructure showed strong grain refining with the smallest of ~14 µm located in their centre. The highest ultimate tensile strength of such connections of ~230 MPa was obtained for experiments performed at a linear velocity of 710 rpm, rate of rotation 560 mm/min and applied intensive cooling of the joined plates. The welds showed lowest hardness in the centre rising by ~20% at its sides. The friction stir welding connections retain plastic properties of 6082 aluminium alloy presenting ductile fracture.

Research limitations/implications: In the further studies bending tests and transmission electron microscopy investigations are planned. Additionally, the stability of microstructure of the welds at higher temperature will be analysed.

Practical implications: The elaborated parameters for FSW of 6082 welding can be applied as starting data for industry FSW tests for such alloy.

Originality/value: The results of present experiments are adding new information on FSW of the aluminium alloys, especially 6082 type. The applied welding parameters provide good quality of welds.

Keywords: Friction Stir Welding; 6082 aluminium alloy; Hardness; Microstructure

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Friction stir welding (FSW) technology help joining aluminium sheets, without material preheating. The welding process takes place by a rotating FSW tool. The tool works within welded materials moving along their edges. The scheme of conventional friction stir butt welding is presented in Fig. 1. Plastic deformation and raised temperature sometimes up to ~450°C results in forming characteristic macro-structure of weld nugget area for FSW in the centre, thermomechanically affected zone, heat affected zone followed by parent material. The weld nugget is frequently surrounded by rings known as an "onion rings" microstructure, but welds of the same aluminium alloys are devoid of such patterns [1]. The microstructure and properties of particular zones depend strongly on the welding parameters [2, 3] and the type of the welding tool (pin and shoulder – Fig. 1) [4-8]. The FSW technology is applied presently for welding aluminium and magnesium alloys as well as copper, steel, composites and dissimilar materials [9-14]. Welds between aluminium alloy sheets and especially between 6xxx formed by FSW [15] are much better then high temperature welding methods like Gas Metal Arc Welding method [16, 17].

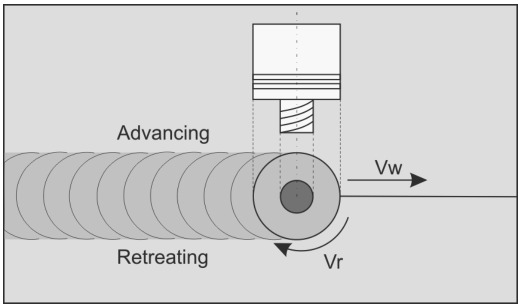

Fig. 1. A FSW scheme (butt-welding)

Description of FSW weld formation mechanisms is hard due to the complexity of the material flow directions and processes proceeding in the microstructure. The different studies of the aluminium alloys in FSW connections show various dislocation densities [18, 19]. The grain size within the weld nugget was found strongly depending on the linear velocity of the tool [19]. As a result, hardness in a region of the weld can change in many ways [2, 11, 20-22] in relation to the original material. Therefore, the better understanding of the FSW process needs more experiments in which mechanical measurements are combined with microstructure observations.

The 6xxx series alloys are frequently used in construction of building and ships [23]. One of a more popular alloy of this series is 6082 applied in the form of sheets or extruded elements. FSW may help to retain the high mechanical properties of the alloy in a final product as it was signalled in papers by Larsson *et al.* [23] and Adamowski *et al.* [24]. The wide application perspective of this type of construction elements joining of 6082 alloy causes that more information on it is needed.

Therefore, the aim of the present paper was to analyze the effect of wider set of FSW parameters including intensive cooling of the welded parts on the microstructure and properties of the joined sheets of 6082 alloy.

2. Experimental method

The 6 mm thick 6082-T6 alloys sheets containing up to 0.08% Cu, 0.6% Mn, 1.0% Mg, 0.8% Si, 0.4% Fe (all in wt %) were friction stir welded using different settings. Butt welds were made parallel to the rolling direction at 710 rpm and linear velocities of the tool at 224, 560 and 900 mm/min. The welding process was performed with a conventional tool: pin 8 mm diameter, shoulder 25 mm diameter, an angle between tool shoulder and surface of the welded sheets was 1.5°. The welding was carried out at room temperature. In some cases intensive cooling the sheets down to ~249 K (-10^{o}C) was tried. It was performed by pouring granulated dry ice (CO_2) on the sheet surface. The samples were stored at 243 K (-30^{o}C). Hardness (μHV0.1) profiles of welds cross-section were obtained at a distance of 3 mm from the face of the weld. The ultimate tensile strength was estimated during tension test. The microstructure investigations were conducted using an optical microscope OLYMPUS GX51 with Nomarski differential interference contrast and a scanning electron microscope (SEM) - Philips 525M. The microscopic observations at the optical microscope were performed on the cross-sections that were ground and polished mechanically, and then etched in 4% NaOH, H_2O solution. The SEM studies were conducted on the fracture surfaces obtained from tensile tests.

3. Results and discussion

Fig. 2 presents the results of tensile test of the samples welded using the following parameters: 710 rpm at 224, 560 and 900 mm/min. Intensive cooling was applied for samples 224L, 560L and 900L. The best result of ultimate tensile strength – 230 MPa is observed for 710/560L sample. Comparable results were achieved for samples 560, 900 and 900L (about 190 MPa) and welds obtained by Adamowski *et al.* [24]. The tested samples broke usually close to the heat affected zone what is shown in Fig. 3. Locations of the crack within this part of the weld were also observed at other aluminium alloys joined using FSW technique [25].

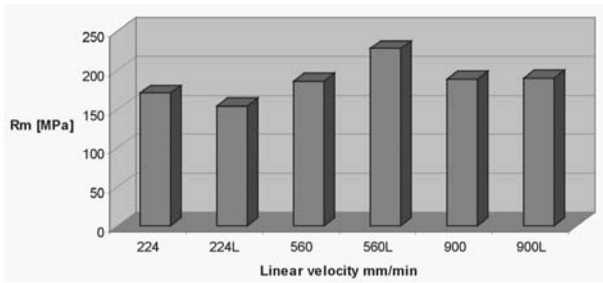

Fig. 2. Ultimate tensile strength of welds

The microhardness measured across the welds is presented in Figs. 4-6. All variants of the welding process resulted in similar profile of the microhardness curves. At the distance of about 12 mm from the welding line (on both sides), hardness decreases. At the same time, the region of the lower hardness is widest for the weld formed at the least linear velocity (244 mm/min). The smallest hardness is present at the ends of the mentioned region, *i.e.* in heat affected zone. Such hardness profile correlates with the point of rupture of the samples in the tensile test (Fig. 3). Hardness of welds obtained at RT is presented in Fig. 4. It is significant that hardness in the heat affected zone increases at the welding linear velocity. On the contrary, hardness of the weld central part is the same independently on the applied welding parameters.

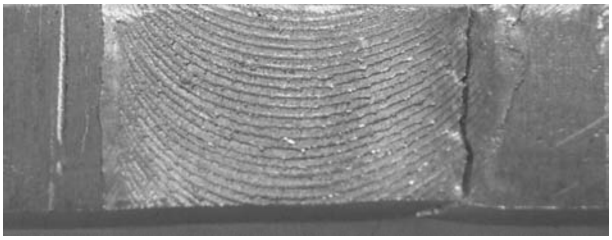

Fig. 3. Broken tensile tested sample 710/560L

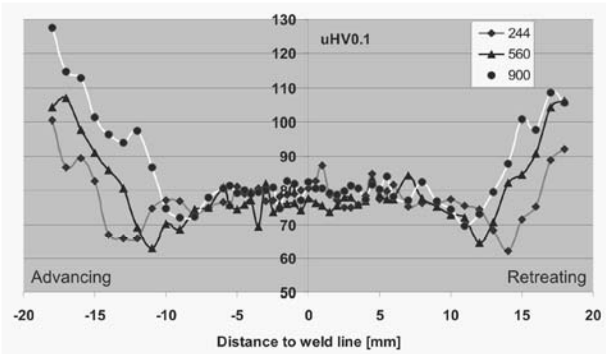

Fig. 4. Microhardness across the weld: 710 rpm, 244, 560 and 900 mm/min

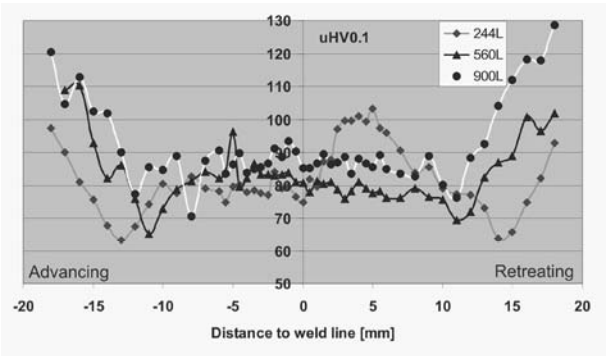

Fig. 5. Microhardness across the weld: 710 rpm, 244, 560 and 900 mm/min, (L – means with cooling)

The analysis of results of the samples welded at the intensive cooling shows that hardness of the heat affected zone also increases at the linear velocity of the welding. On the contrary, hardness in the central region of the weld is strongly dependent on the linear velocity of welding (Fig. 5). The curve for the weld 900 is located at the highest level on a diagram presented in the Fig. 5. However, in case of 244L weld on the retreating side at the distance of 2–7 mm of the welding line, significant increase of hardness up to about 100 HV0.1 should be noted. At the next Figure (Fig. 6) curves for the samples 560 (welded without cooling) and 560L (welded with cooling) are presented together. These welds are characterized by the highest strength. Both hardness profiles are very alike, whereas hardness of the 560L weld on the attack (advancing) side is slightly higher. The analyzed hardness distribution corresponds to the results presented in [24], where properties of 6082 alloy FSW welds for different parameters are described. They are also similar to hardness profiles obtained for welds made on 6013 alloy sheets [26, 10].

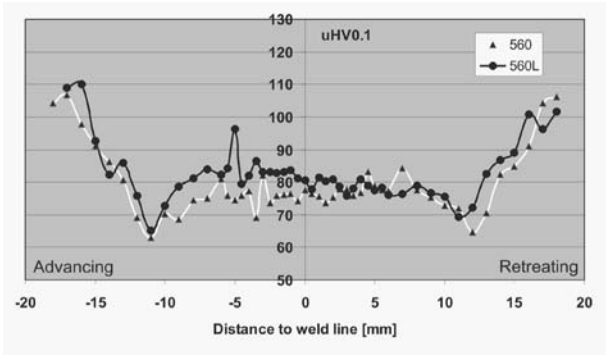

Fig. 6. Microhardness across the weld at: 710 rpm, 560 mm/min (L – means with cooling)

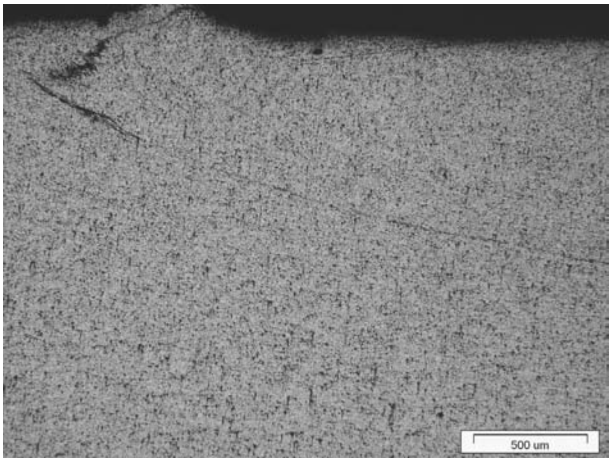

Fig. 7. Microstructure of the weld 710/560L, close to the face of the weld

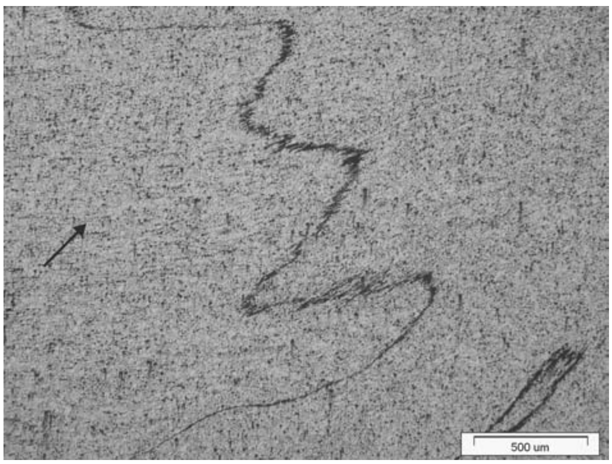

Fig. 8. Microstructure of the 710/560L weld centre

The fine grains and string of precipitates in 710/560L weld revealed by etching are visible in Figs. 7 to 9. Additionally, darker zigzag lines are present in this area. Such microstructure is characteristic for the friction welded aluminium alloys. Similar zigzag lines found in 2024 alloys were determined as agglomeration of Al_2O_3 particles [27]. The average grain size at the weld centre was estimated at ~14 μm (Fig. 9). The bands containing finer grains were observed in the lower part of the weld, below the region that directly interacted with a tool. Similar bands with much finer grains located at the bottom of the weld between the surface and weld nugget were observed in other welds of aluminium alloys e.g. 2017A, 6013. In the 710/560 weld a weak zigzag line was also observed (Fig. 10). The analysis of the grain size in the weld (at same area as in case of 710/560L) showed that it is also of ~ 12 μm. The centre of FSW obtained at the welding parameters 710/244 and 900 (with and without cooling), are characterized by equiaxial grains. It is probably due to dynamic recrystallization proceeding during FSW process as suggested by Scialpi *et al.* and Elangovan *at al.* [6, 28]. The presently studied welds show absence of so called “onion rings microstructure”, what is common in many 6082 alloy FSW welds [24].

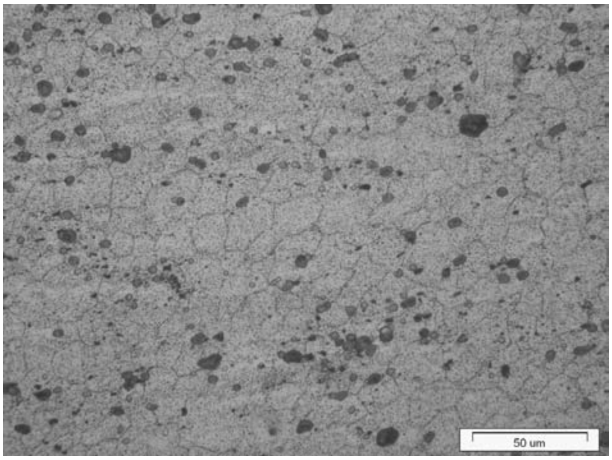

Fig. 9. Microstructure of the 710/560L weld centre

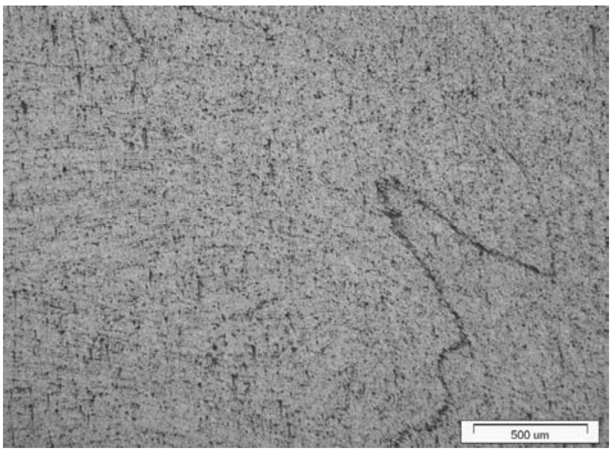

Fig. 10. Microstructure of the 710/560 weld centre

Fig. 11 presents fracture of the 710/560L weld central part analyzed by means of SEM method. This area shows characteristic dimples usually attributed to ductile fracture. It is also possible to observe cleavage surfaces on brittle particles with a size of few micrometers partially submerged in the plastic matrix (Fig. 12). The EDS (Energy Dispersive X-ray Spectroscopy) chemical composition analysis indicated that they were probably the Al_3Fe phase precipitates.

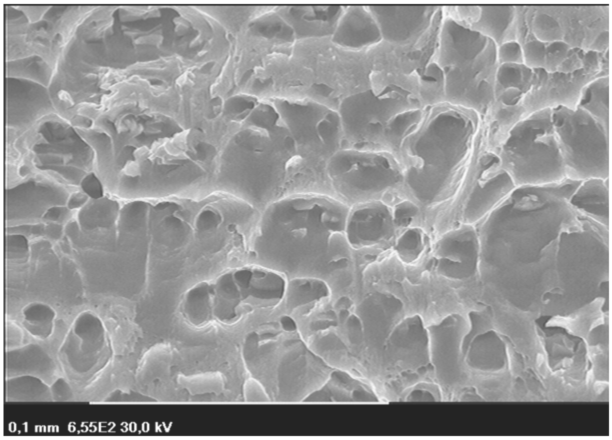

Fig. 11. Ductile fracture of 710/560L samples after tensile test – the weld centre

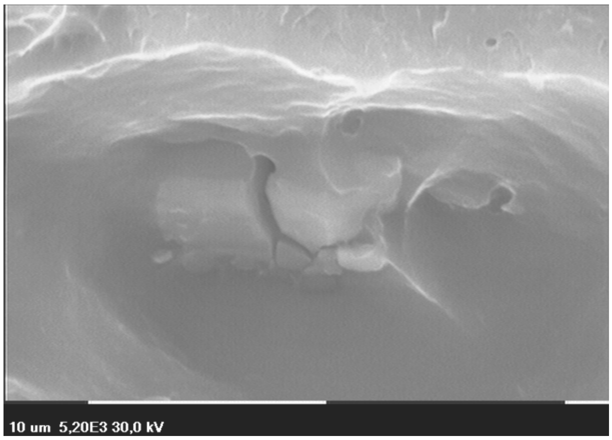

Fig. 12. Fractured brittle precipitate in the710/560L weld centre

Moreover, particles composed of Al, Si, and Fe were also observed. Such phases are typical for the alloys of 6xxxx series, *i.e.* α-$Al_{12}Fe_3Si$ or β-$Al_9Fe_2Si_2$ [29]. The ductile fracture was observed also in the welds produced at different welding parameters 710 rpm and 244, 244L, 560, 900 and 900L mm/min. The image of such material failure with visible slip bands in case of the 710/900 weld is presented in Fig. 13. The homogeneous microstructure of the fracture is most probably a result of relatively high plasticity of all 6xxxx series alloys. The fractures of the FSW welds characterized by higher hardness and strength, for example alloys for 7xxxx [22] or 2xxx [30] series, show much more diversified fracture in regions of a weld nugget, thermomechanically affected zone or close to the face of the weld, most often.

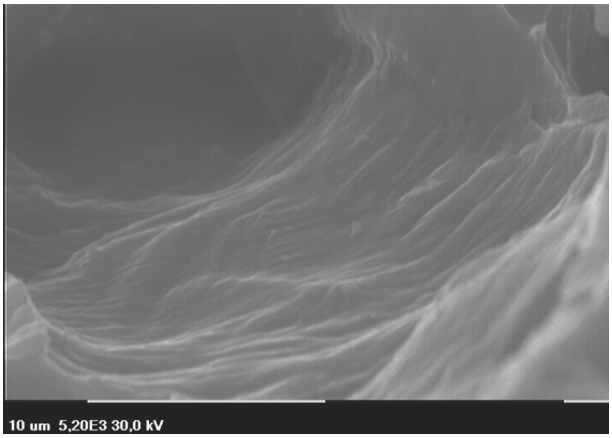

Fig. 13. Bands of plastic deformation on the surface of 710/900 weld fracture

4. Conclusions

The investigations performed in present project helped to show that:

1. The application of the FSW technology allows to obtain good-quality welds of the 6082-T6 aluminium alloy at 710 rpm and 244 – 900 mm/min;
2. The specified above FSW parameters helped to produce defect free – apart from some zigzag lines - high strength weld;
3. The FSW process caused generally refinement of grains in the weld area, the strongest one in the weld centre;
4. The highest ultimate tensile strength of the weld (230 MPa) was obtained applying the following parameters: 710 rpm, 560 mm/min while intensive cooling;
5. The microhardness measured across the welds was found typical for FSW welds of the alloys 6xxx series with a distinct drop in the heat affected region (about 12 – 14 mm from the welding line);
6. The welds obtained by FSW for 6082-T6 aluminium alloy retain plastic properties of matrix material as confirmed by ductile fracture of tensile broken samples.

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