FSW JOINT MICROSTRUCTURE OF TWO HIGH STRENGTH ALUMINUM ALLOYS: A 2024 / A 7050

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Abstract
The process of friction stir welding (FSW) has been employed primarily for joining aluminum sheets without melting. The present work relates the results of microstructural investigations of the joint produced by friction stir welding of two high strength heat treatable aluminum alloys in a lap joint of a sheet with an extruded profile. The joint microstructure showed a characteristic mixture pattern of the two alloys. It exhibited a more or less regular pattern of elongated stripes on the advancing side and a turbulent pattern on the retreating side of the joint. These stripes maintained the difference in their appearance, hardness values and chemical composition.

Keywords: friction stir welding, lap joint, joint microstructure

1 Introduction

The process of friction stir welding developed in 1991 by The Welding Institute, Cambridge, is a joining method for metals in the solid state without using filler material [1]. The welded joint is the result both of friction heating and mechanical mixing of the material by means of a rotating tool.

FSW since its discovery has became a routinely applied process for joining aluminum alloy components, especially in the aerospace industry, being most appropriate for straight flat components such as plates and panels of high strength alloys [2-5]. It has been proved that the joints produced by FSW have good strength and ductility also in alloys with difficulties in conventional welding methods.

Various thermo-mechanical processes interact in FSW, such as plastic deformation, flow, recrystallization, heating and cooling, which determine the integrity of the joint. Being a relatively new process, research and development efforts are concentrated on the role of the materials, welding parameters, tool design on the microstructure and properties of the welded joint. Since in aeronautical applications the necessity of joining two dissimilar aluminum alloys is of top interest the microstructure of a FSW joint between a 2024 sheet and a 7075 extruded profile was examined in this contribution.

FSW process description

In FSW a cylindrical tool with a shoulder and a threaded pin at its extremity moves along the contact line of the plates to be welded at a constant velocity and simultaneously rotates around its axis, see **Figure 1**. The plates have to be fixed rigidly since the shoulder is in firm contact with their upper surface during its motion. Sufficient heat has to be generated by friction and

plastic deformation in the workpiece in order to soften the material. During the translation of the tool severe plastic deformation and flow occurs in the plasticized material. The rotational movement results in material transport from the front of the tool to the trailing edge where it is forged into the joint due a slight backward inclination of the tool.

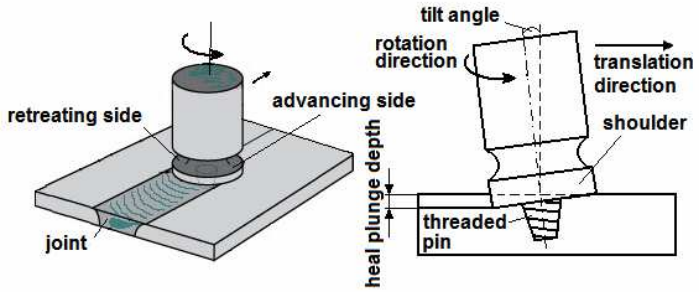


Fig.1 Schematic representation of the FSW process

The side of the joint where the rotation direction and the translation direction coincide is designated as *advancing side* and the other side as *retreating side*. This difference in the motion leads to differences in heat transfer and material flow what is reflected in the inherent asymmetry of the joint structure. **Fig.2**. represents schematically the metallurgical structure of a FSW joint.

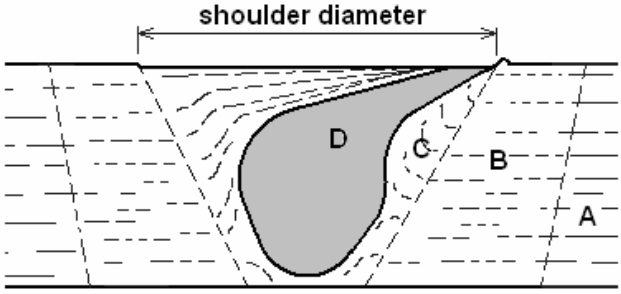


Fig.2 Scheme of the transversal section of a FSW joint. A – base metal, B – heat affected zone, C – thermomecanically affected zone, D – stirred zone (nugget).

Four different regions can be found in a FSW joint: base material (BM), heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ) and the stirred zone (SZ) or nugget.

FSW process variables

The principal process variables include the tool translation and rotation speed, the vertically applied stress, the tilt angle of the tool and the tool design. The peak temperature increases with increasing rotation speed and with increase of the axial pressure, but decreases slightly with increasing translation speed. Due to the increase of heat generation with the increasing rotation speed the torque decreases as the material flows more easily at high temperatures and high strain rates. The slight increase of the torque with the increase of the translation speed is due to the fact that the material flow is more difficult at a lower temperature. The torque itself depends on the tool design, the tilt angle, the vertically applied stress, as well as on the conditions in the contact area with the material defined by the friction coefficient, shear stress. [6, 7]

Low vertical pressure produces insufficient heating leading to voids. Excessively high pressure on the other hand can result in overheating and thinning of the joint area as well as in tool erosion and/or tool fracture.
Different tool geometries [8,9] influence heat generation, plastic flow, the power required and the quality of the joint. The shoulder of the tool in the contact with the material generates the heat and maintains the plasticized material in the process area, while both the shoulder and the pin produce the material flow. An exhaustive study of the tool geometry was carried out by Colegrove and Shercliff [10,11] with an objective of a quantitative approach to the material flow. They found that the tool design practically does not influence the heat input and the required power.

Joint microstructure

The heat generated during the process as well as the plastic flow affects the microstructure of the joint. In this regard two types of aluminum alloys have to be considered – heat treatable or precipitation strengthened and non heat treatable alloys.
In the heat treatable alloys precipitate dissolution and re-precipitation has to be considered during the thermal cycle. Depending on the peak temperature in a given distance from the tool axis complete dissolution followed by re-precipitation may occur in the nearest areas, while in the more distant regions precipitate coarsening accompanied by the reduction of their number can be expected. The competition between these two effects results in a continuous change in hardness with a minimum in the heat affected zone [12]. In not heat treatable alloys the strength in the joint region will depend on the grain size.
Joining two dissimilar alloys a more complicated situation emerges. Moreira et al. [13] reports a mixed microstructure of the two alloys in the nugget area of a butt weld. Mroczka et al. [14] found that the nugget was predominantly formed in butt weld by the alloy positioned on the advancing side of the tool.

2 Materials and experiments

Two high strength precipitation hardenable alloys were used for the FSW joint: 2024 and 7075. The composition of the alloys is in the **Table 1**.

Table 1 Composition of the alloys used for the FSW joint

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Other each	Other total	Al
2024	max. 0.5	max. 0.5	3.8-4.9	0.3-0.9	1.2-1.8	max. 0.1	max. 0.25	max. 0.15	max. 0.05	max. 0.15	bal.
7075	max. 0.4	max. 0.5	1.2-2.0	max. 0.3	2.1-2.9	0.18-0.28	5.1-6.1	max. 0.2	max. 0.5	max. 0.5	Bal.

The sheet of the 2024 alloy was in the condition T3 - solution heat-treated, cold worked, and naturally aged. The extruded Z profile of the 7075 alloy was in the condition T7 651 – solution heat treated and artificially aged, stress relieved by stretching. The seam of the FSW joint was produced in the lap position, see **Fig. 3**.
Keller´s etch was used to reveal the microstructure by optical microscopy. EDS microanalyses were carried out in the nugget by means of a scanning electron microscope in order to map the extension of the mixing of the two alloys. The impact of the changes of the microstructure upon the mechanical properties was evaluated by means of microhardness measurements in the mixed region of the FSW joint.

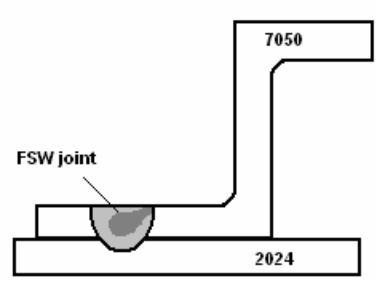


Fig.3 Scheme of the FSW lap joint

3 Results and discussion

Fig. 4 shows the macrostructure of the FSW lap joint in a section perpendicular to the translation direction.

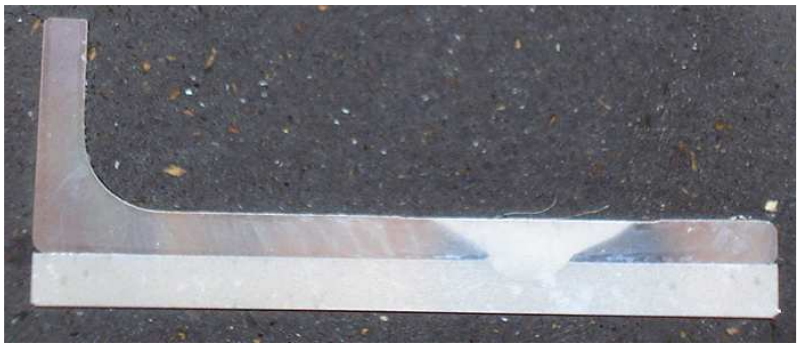


Fig.4 Macrostructure of the joint. The lines indentify the microhardness measurement loci.

While the upper part joint - the 7075 profile - suffered a complete mixing up, the lower alloy – the 2024 sheet - was mechanically affected only partially. The total depth of the mixed area was 2.27 mm.

A small magnification view of the joint microstructure is presented on **Fig 5**. , revealing the mixture of the two alloys by different coloration. The darker coloration belongs to the 2024 alloy. The pattern of mixing does not show the onion ring structure frequently observed in butt joints [15, 16]. Nevertheless, on the advancing side a regular line-up of striations can be observed which can be seen in detail on **Fig 6**. A significant difference in the microhardness values between the clear and dark areas reveal the different strength levels of the two alloys. The hardness values are marked in the respective areas in **Fig.7a**.

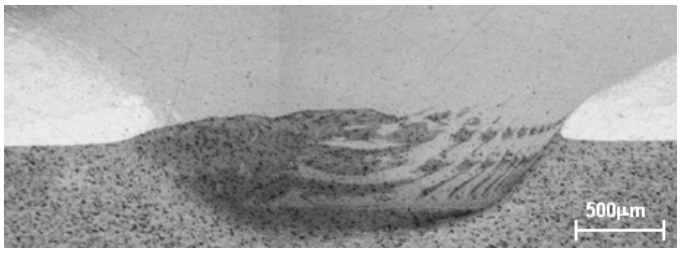


Fig.5 A low magnification view of the joint microstructure

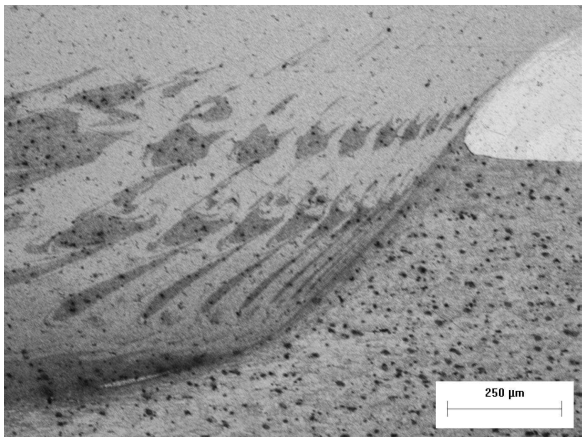
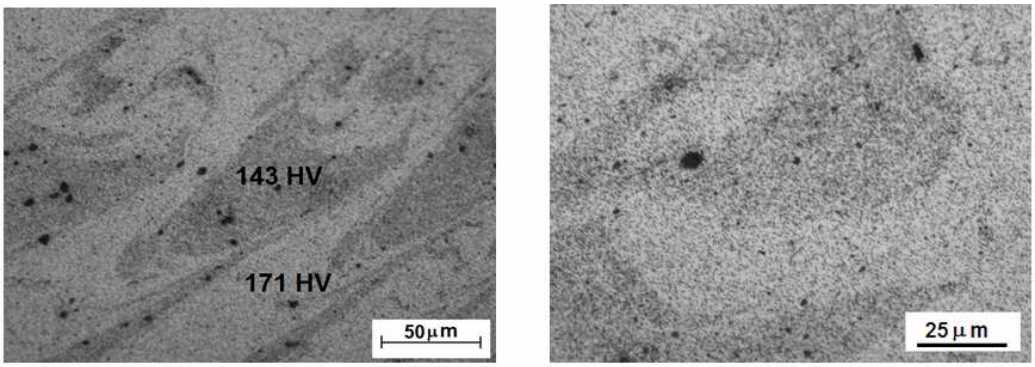


Fig.6 The microstructure of the advancing side in a closer view



a b

Fig.7 Detailed view of the striated region with microhardness values of the clear and dark regions (a), as well as with a zoom (b)

The striations on the retreating side had a different pattern of mixture, showing a certain degree of “turbulence” when compared to the regular sequence of “stripes” of the advancing side, **Fig 8**.

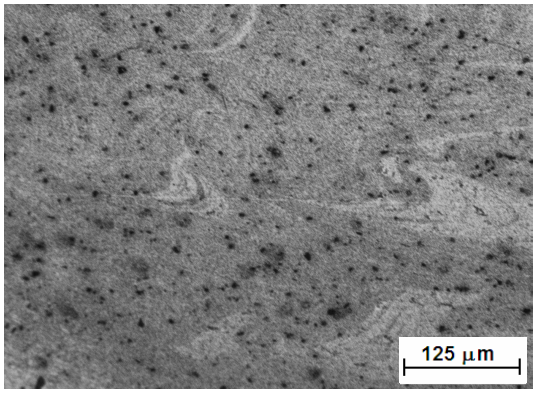


Fig.8 Striation pattern on the retreating side

The digital mapping of the alloying element distribution did not reveal detectable interdiffusion between the two alloys, the zinc and copper distributions coincided by the dark and light areas of the optical microscopy.

4 Conclusions

Microstructural analysis was carried out in a FSW joint of two high strength aluminum alloys in a lap joint of a sheet with an extruded profile .The joint microstructure showed a mixture pattern of the two alloys characterized by a more or less regular pattern of stripes on the advancing side and a turbulent pattern on the retreating side, while maintaining the difference in their hardness values. No detectable interdiffusion of the alloying elements was found.

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