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Friction Stir Welds (FSW) of aluminium alloy AW6082-T6

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ABSTRACT

Purpose: Purpose of this paper is the investigation on the properties and microstructural changes in Friction Stir Welds in the aluminum alloy 6082-T6 in function of varying process parameters.
Design/methodology/approach: Tensile strength of the produced joints was tested and the correlation with process parameter was assessed. Microstructures of various zones of FSW welds are presented and analyzed by means of optical microscopy and microhardness measurements.
Findings: Mechanical resistance of test welds increased with the increase of travel (welding) speed with constant rotational speed. Softening of the material in weld nugget and heat affected zone was observed, of entity inferior that that of fusion welds. Origin of tunnel (worm hole) defects were found and analyzed.
Research limitations/implications: The test welds were produced with various combinations of process parameters without the possibility of controlling the downward force. Further extension of applicable parameters combinations could be examined.
Practical implications: The increase of mechanical resistance with increasing welding speed offers an immediate economic return, as the process efficiency is increased.
Originality/value: Information contained herein can be useful to further investigate on the possibility of improving the properties of FSW welds, as well as the efficiency of the process.
Keywords: Welding; FSW; Aluminum alloys

1. Introduction

In many industrial applications steels are readily replaced by non-ferrous alloys, in most cases by aluminum alloys. Some of these materials combine mechanical strength comparable with structural steels and low weight, allowing for a significant reduction of weight. While production of components of aluminum alloys is not very complex, joining of these materials can sometimes cause serious problems [1]. Lack of structural transformations in solid state and excellent thermal and electrical conductivity cause problems in fusion and resistance welding of aluminum alloys [2]. That led to the development of Friction Stir Welding [3] a solid state joining technique in which the joined material is plasticized by heat generated by friction between the surface of the plates and the contact surface of a special tool, composed of two main parts: shoulder and pin [4]. Shoulder is responsible for the generation of heat and for containing the plasticized material in the weld zone, while pin mixes the material of the components to be welded, thus creating a joint (Fig.1). This allows for producing defect-free welds characterized by good mechanical properties. This paper summarizes the results of an experimental campaign in which the aluminum alloy AW6082-T6 was FSWelded, using various combinations of process parameters (rotational and travel speed). Mechanical properties of the test welds were assessed by means of static tensile test, bending test. Macro and microstructure of the welds were examined by means of optical observations and Vickers hardness measurement.

2. Experimental

2.1. Production of joints

The experiments were conducted on the aluminum alloy AW-6082-T6, its chemical composition and principal mechanical properties are respectively presented in Tables 1 and 2. Given the Al-Mg-Si alloys are rather easily weldable even with conventional techniques, it was decided to verify weldability of the chosen alloy by the widest possible range of parameters.

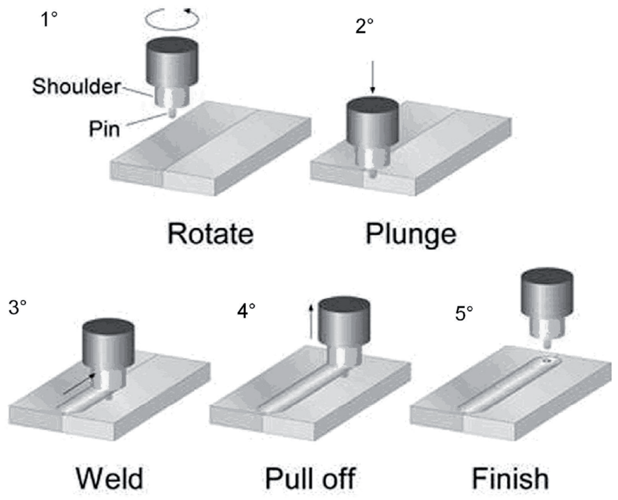

Fig.1. Schematic representation of FSW process

Table 1.
Chemical composition of AW-6082 (EN 573-3)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
0.70 1.30	0.50	0.10	0.40 1.00	0.60 1.20	0.25	0.20	0.10

Table 2.
Mechanical properties of AW-6082-T6 (EN 485-2)

Rm [MPa]	Rp0.2 [MPa]	A50 [%]	HB
≥310	≥260	10	94

The used welding station was a converted milling machine [5]. The following rotational and travel speed were chosen (Tab.3). Welds were made of laminated plates having the following dimensions: 300x150x5mm. The welding tool was made of a structural steel of resistance class 8.8. The diameter of the shoulder was 19mm, while the pin was a M6 bolt. The length of the pin was set at 4.8mm, which was slightly less than the thickness of welded plates. For all joints a 20 second preheat time was applied in order to increase the plasticity of the material and decrease the bending loads on the pin. The temperature of the welded plates was monitored during welding with thermocouples placed on both sides of the joint line, 15 mm from the weld axis.

2.2. Examination of joints

Visual inspection was performed on all welded samples in order to verify the presence of possible macroscopic external defects, such as surface irregularities, excessive flash, and lack of penetration or surface-open tunnels.

Temperature measurements showed a significant difference between the two sides of the welds: advancing and retreating. Tensile tests were performed on samples cut perpendicularly to the weld line. The tests were carried out at constant speed of 5mm/min.

Microhardness of the welds was measured with the test load of 200g. The indentations were made at midsection of the thickness of the plates across the joint.

Metallographic specimens were cut mechanically from the welds, embedded in resin and mechanically ground and polished using abrasive disks and cloths with water suspension of diamond particles. The chemical etchant was the Keller's reagent. The microstructures were observed on optical microscope.

Table 3.
FSW welding parameters for AW-6082-T6 alloy

Weld number	Rotation [rpm]	Travel [mm/min]	Weld number	Rotation [rpm]	Travel [mm/min]
FSW-01	230	115	FSW-07	880	170
FSW-22	330	115	FSW-13	880	260
FSW-21	330	170	FSW-14	880	390
FSW-04	460	115	FSW-15	880	585
FSW-09	460	170	FSW-03	1230	115
FSW-19	460	260	FSW-06	1230	170
FSW-05	630	115	FSW-10	1230	260
FSW-08	630	170	FSW-11	1230	390
FSW-17	630	260	FSW-12	1230	585
FSW-20	630	390	FSW-16	1700	390
FSW-02	880	115	FSW-18	1700	585

3. Discussion of results

3.1. Temperature acquisition and visual inspection

The temperature on advancing sides of weld was higher than on retreating side, with the average difference of 50°C. The difference is a result of asymmetry of the FSW process [6,7]: total linear velocities of the perimeter of the shoulder is higher on the advancing side than on the retreating side. Figure 2 represents the temperature diagram acquired during the execution of weld FSW-02.

Several types of defects were revealed. In case of the joint FSW-06 a surface-open tunnel was found as a result of insufficient downward pressure [8]. Excessive lateral flash was also observed in most of the welds, resulting from the outflow of the plasticized material from underneath of the shoulder (Fig. 3).

3.2. Tensile tests

In all cases the samples failed in HAZ of the advancing side, similarly as reported in [9]. The results are presented in Fig.4. It can be noticed that at constant rotational speed mechanical resistance of joints increases with increasing of the travel speed (Fig. 4). This can be attributed to the decreased heat input and relative limited softening of the HAZ.

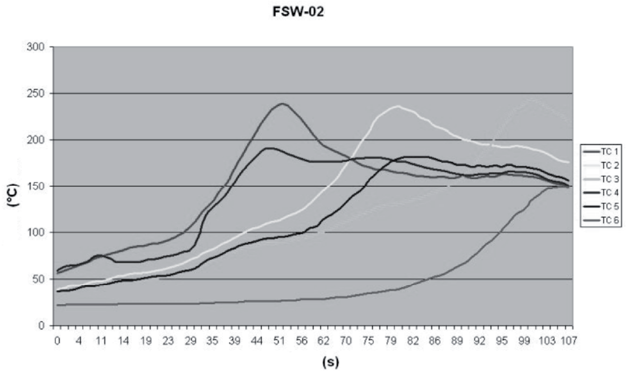

Fig. 2. Temperatures acquired in the weld FSW-02

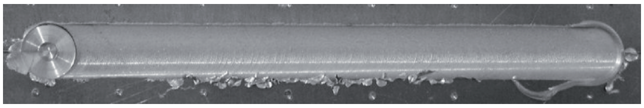

Fig. 3. Lateral flash in the joint FSW-18

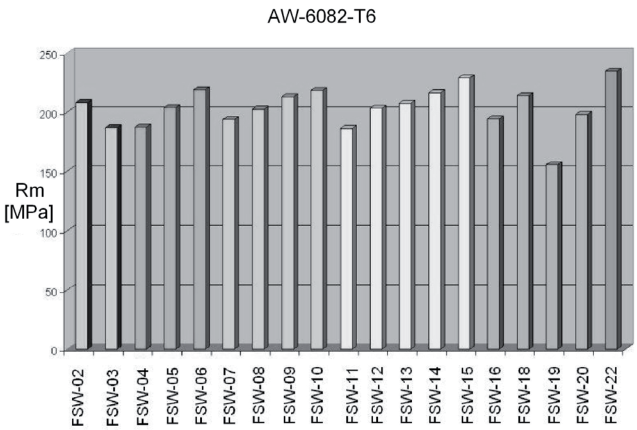

Fig. 4. Results of tensile tests

3.3. Microhardness

Figure 5 represents the hardness diagram of the joint FSW. The hardness of both the heat affected zone (HAZ) and the weld nugget (WN) is lower than that of base metal (BM), respectively by 15-20% and 7-10%. The difference between HAZ and WN is attributable to the grain refinement in WN, caused by intensive stirring. The softest points of the joints correspond to the failure locations in tensile tests.

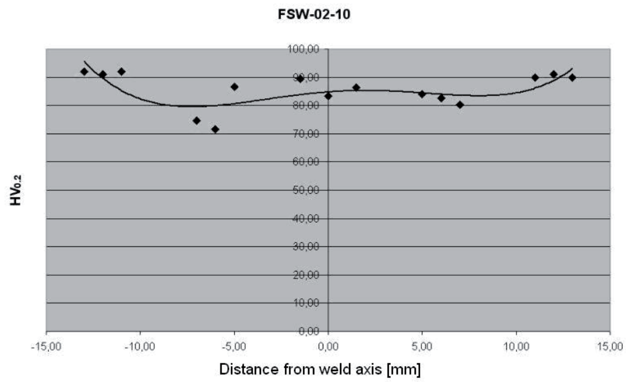

Fig. 5. Hardness profile of the weld FSW-10

3.4. Metallography

Microstructures of various zones if FSW joints, in particular case of the joint FSW- are presented in figure 6. Grains in BM are elongated with average dimensions LxH equal µm. In WN the grains are refined, equiaxed of average diameter 1-5µm. This refinement is the result of dynamic recrystallization [10,11,12], i.e. a combined action of high rate strain and elevated temperatures. Such recrystallized structure is characterized by a very low level of residual stresses, excellent ductility and mechanical properties superior to those of HAZ [13]. The concentric rings visible in WN, called "onion rings" are a typical feature of FSW process and document the complex mechanics of the process: combination of rotational, longitudinal and vertical movement of the plasticized material [14,15].

The WN is a part of a bigger zone, the Thermo-mechanically Affected Zone (TMAZ), in which grains are deformed, elongated and rotated due to the strain to which they were subjected. Moving away in the direction of BM, the successive zone is HAZ. The microstructure here is similar to that of BM, the grains are slightly overgrown as a result of the exposure to welding heat.

An interesting artifact was found in the sample FSW-03 (Fig.7). At the intersection of WN, TMAZ and flow arm (a band of material running from WN towards the joint edge on advancing side) the three distinct zones are starting to separate, giving origin to a tunnel defect. These defects are attributable to the combination of parameters: insufficient or excessive rotational speed combined with too low downward force. In such case the welded parts cannot be correctly stirred and mixed together and a tunnel (also called "worm hole") is created, running along the entire weld [16].

4. Conclusions

Mechanical properties of FSW welded aluminum alloy 6082-T6 change with changing of process parameters. Tensile strength of

FSW welds is directly proportional to the travel / welding speed. Hardness drop was observed in the weld region. That softening was most evident in the heat affected zone on the advancing side of the welds, that corresponded to the failure location in tensile tests. An initial stage of a tunnel defect was found at the intersection of weld nugget and thermo-mechanically affected zone.

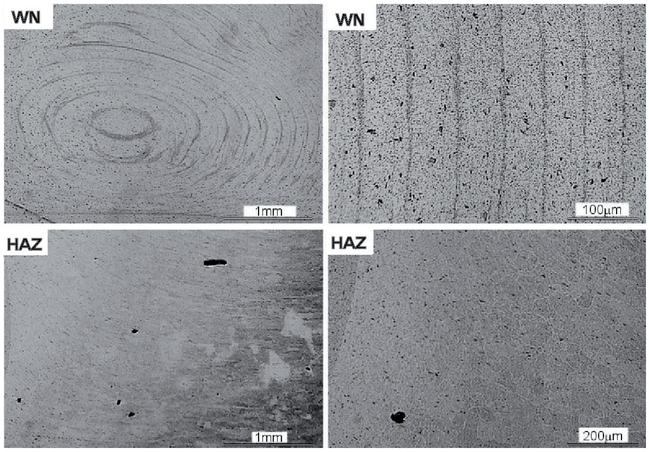

Fig.6 Microstructures in various zones of the weld FSW

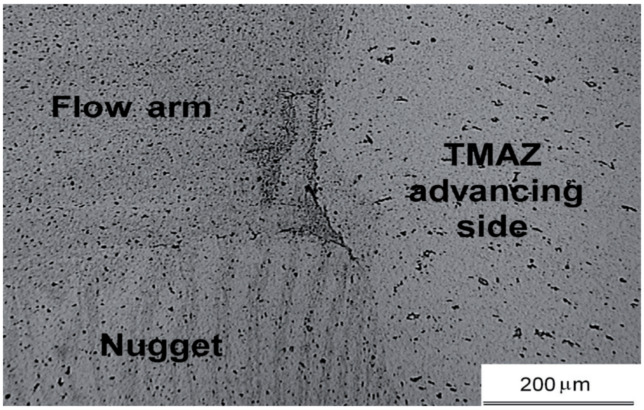

Fig. 7. Initial stage of tunnel defect in the weld FSW-03

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