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Microstructure and mechanical properties of friction stir welded joints made from ultrafine grained aluminium 1050

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ABSTRACT

In order to obtain ultrafine grained structure, commercially pure aluminium (Al 1050) plates were subjected up to 8 passes of Incremental Equal Channel Angular Pressing (IECAP) following route C. Plates in different stages of IECAP were joined using Friction Stir Welding (FSW). All welded samples were investigated to determine their mechanical properties and structure evolution in the joint zone. The joining process reduced mechanical strength of material in the nugget zone, which was explained by the grain growth resulting from temperature rise during FSW. Nevertheless, the obtained results are promising in comparison to other methods of joining aluminium.

1. Introduction

Nowadays, materials with ultrafine grained (UFG) structure are becoming more and more attractive for many industrial applications. The major advantage of these materials is their enhanced mechanical strength at ambient temperature due to increased amount of grain boundaries acting as obstacles for moving dislocations [1]. At elevated temperatures, the creep resistance decreases as documented for pure aluminium [2,3]. However, creep resistance is strongly influenced by the character of grain boundaries, i.e. creep ability increases for higher amount of high angle grain boundaries. The creep resistance can be even improved for the grain structure containing the majority of low-angle grain boundaries.

The extraordinary mechanical strength of UFG metals stimulated the development of their production methods. Today, UFG metals can be efficiently produced by different variants of the severe plastic deformation (SPD) method. However, the major restriction in wide industrial application of UFG metals is the lack of a reliable welding process, which unlike riveting would give material continuity in the joint. There is also a requirement to weld UFG materials without losing their properties governed by the nanoscale structure. In this context, traditional welding processes based on melting, such as brazing or arc welding, are not applicable because they occur at high temperature causing a total change of structure leading to structure discontinuity and considerable decrease in mechanical strength along the joining line. In this work, Friction Stir Welding (FSW) [4] was chosen as an innovative bonding technology to weld aluminium. FSW takes place in the solid state without reaching the melting temperature of the base material [5]. Stable connection is obtained by mixing the friction-heated, plasticized and deformed metal along the contact line of welded elements. It can be performed by moving a rotating tool (a pin with a shoulder) along a joining line. The key factor for obtaining a consistent joint is large plastic deformation at elevated temperature. It results in bringing-up atoms to a distance which allows creation of a metallic bond. Accompanied by increased density of lattice defects, the final microstructure in different joint areas is mainly dependent on dynamic recrystallization and/or recovery [6] what is common for materials such as aluminium, which is characterized by high stacking fault energy.

Compared to other joining techniques, FSW exhibits a number of advantages. The rise in temperature cannot be higher than a melting point. On account of that, problems related with resolidification, such as porosity, embrittlement and formation of second phase are not present. Additionally, distortion and residual stresses, which are seen in FSW joints, are lower than those observed for other methods, based on melting of the base material and a filler [5]. Parameters of the FSW process are crucial for quality and properties of obtained joints. For example, many papers were devoted to shoulder diameter [7,8], which appears

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to be one of the most influential factors. Other parameters such as pin profile [9,10], tool travel and rotation speeds [11,12], depth of pin's penetration were investigated too. Structural features, e.g. initial grain size, were also taken into consideration [13,14].

Joining UFG aluminium and its alloys was also a subject of numerous investigations. Plates with refined structure, obtained during accumulated roll bonding (ARB) [14] or constrained groove pressing (CGP) [15,16] were joined using FSW. In each case, authors attempted maximizing mechanical properties and preventing grain growth in the joint zone. Relying on the improved properties in coarse grained materials, materials with refined structure were taken into similar investigation. When the initial material is annealed and characterized by coarse grained structure, subsequent FSW leads to the creation of new, equiaxial grains with much smaller size than the initial one. As a result the improvement in mechanical properties is observed [13]. In the case of materials with already refined structure, the FSW process leads to grain growth in the joint zone, which seems to be extremely difficult to overcome. As was shown for aluminium 1050 [16], which is the same material as in this study, annealed samples subjected to FSW exhibited a very fine grain structure in the joint, which was formed by dynamic recrystallization. In the same investigation, materials with the initial refined structure revealed an intense reduction of microhardness in the stir zone, which was explained by the grain growth. It was caused by thermal instability resulting from high stored energy during severe plastic deformation. The samples after ARB were also annealed [13], which enabled achieving the best compromise between grain size and hardness. Unfortunately, joining immediately after ARB caused a decrease in mechanical properties of the stir zone. The conclusion from this work was that regardless of the initial grain size or shape, samples revealed equiaxial grains in the stir zone. Nevertheless, for base materials with UFG structure, there was a grain growth observed in the joints.

The aim of the present work was to join technically pure aluminium plates with ultrafine grained structure produced by Incremental Equal Channel Angular Pressing (IECAP) using FSW process and then determine the relationship between microstructure and mechanical properties in the base materials and joints.

2. Material and methods

The investigated material was technically pure aluminium (99.5 wt.%) EN AW-1050A-H24 supplied by the Konin Aluminium plant in the form of 3 mm thick rolled sheets. The exact chemical composition is presented in Table 1.

The samples with dimensions of 3 × 62 × 105 mm were processed using IECAP [17] to obtain UFG structure. The main idea of this method is to apply plastic strain in a series of small deformation increments [18], which are based on simple shear. Separation of feeding and deformation steps reduces friction during feeding, which enables processing of very long or continuous billets. As conventional ECAP, this method has the ability to pass the ingot via different routes. With square plates, there is a possibility of employing deformation route based on rotation about the normal to the plate (Z axis), which in the case of aluminium led to a homogenous UFG structure [19] with a large number of high angle boundaries [20]. In this study the applied deformation route was based on the rotation of plates about their longitudinal axis by 180° between passes (so called route C). The plates were investigated in an initial state (0 passes), after 4 and 8 passes of IECAP, which corresponds to true strains of 0, 4.6 and 9.2, respectively. To simplify the sample description, they were described as sample '0', '4' and '8', depending on the number of applied passes.

Table 1
Chemical composition of aluminium 1050.

	Si	Fe	Cu	Mn	Mg	Zn	Al
Content [%]	0.25	0.40	0.05	0.05	0.05	0.07	balance

The plates of the same type (i.e. subjected to the same processing path) were joined together using FSW, with the tool shoulder diameter of 17 mm and pin diameter of 5.5 mm. Samples were butt welded along Y plane, which means that joints were made along a longer edge of the rectangular plate. Rotational and linear speeds (Table 2) were different for materials with different number of IECAP passes, which comes from their structural differences.

To reveal the microstructure of the joints, different techniques were implemented. Anodized metallographic specimens were observed in a light microscope using a polarized light beam. For detailed microstructure investigations, Focused Ion Beam (FIB) and Transmission Electron Microscope (TEM) JEOL JEM 1200 with accelerating voltage of 120 kV were used. Samples for FIB and TEM observations were cut out in the X plane, which is perpendicular to the welding line and also perpendicular to IECAP direction. Thin foils were prepared using a wire saw, ground down to 150 μm and electropolished using Struers Tenupol-5 system operating at a voltage of 35 V at a temperature of 278 K. The solution containing ethanol, perchloric acid, butyl glycol and distilled water was used. Microstructure observations were taken together with the Selected Area Electron Diffraction (SAED) patterns with an aperture of effective diameter about 4 μm. Grain size was determined by calculating the equivalent diameter (d_2), which means the diameter of a circle with equal area as the investigated grain [21].

In order to characterize mechanical properties, tensile tests and microhardness measurements were carried out. In the case of tensile test, flat mini samples with a thickness of 0.6 mm (Fig. 1) were used. Tensile samples were perpendicular to the direction of the welding line marked also as the joining direction. Digital Image Correlation (DIC) has been used for accurate strain determination. Stir zone and base material were investigated separately in order to reveal differences between these two areas. For each zone 5 specimens were investigated. Microhardness measurements were carried out in the X plane of samples under a load of 200 g for 15 s. For each sample, 120 measurements were done in 3 parallel lines with 1 mm spacing along width and 0.5 mm along thickness of the butt welded rectangular plate.

3. Results

3.1. Microstructure

Microstructures of base materials together with histograms of grain size distribution are presented in Fig. 2. Sample '0' (in initial state) features a typical cold rolled structure with elongated grains of several microns in length. The average grain/subgrain size was about 2 μm. IECAP brought about significant microstructure refinement. After 4 passes, the grain size was reduced to about 655 nm. Further processing (up to 8 passes) only slightly affected the grain size which average value decreased to 630 nm. Histograms look comparable which is an evidence for similar structure of these two materials. The quantitative data regarding the microstructures is summarized in Table 3. Apart from equivalent diameter (d_2) and standard deviation (S.D.), grain elongation factor (d_{max}/d_2) and grain boundary development factor ($p/d_2\,\pi$), where p is perimeter) were determined. The sample '0' exhibits the highest value of grain elongation factor which is a clear evidence for elongated grains. With increasing number of IECAP passes, the grains become more equiaxial, which is reflected in lower value of this factor.

Table 2
Values of rotational and linear speed used in FSW process.

Sample	Rotational speed n [rpm]	Linear speed V_z [mm/min]
0	450	224
4	560	355
8	560	224