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Mechanical properties and microstructure of joints in AZ31 thin sheets obtained by friction stir welding using "pin" and "pinless" tool configurations

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ABSTRACT

The effect of process parameters, tool geometry and size on friction stir welding of thin sheets in AZ31 magnesium alloy was widely investigated. In particular, two properly designed tools, with different values of the shoulder diameter, were used; each of them was manufactured both in the "pin" and "pinless" tool configurations. It was shown that at the lowest shoulder diameter investigated (8 mm), the pin tool configuration leads to the obtaining of ultimate tensile strength and ductility values higher than those provided by the "pinless" one. By increasing the shoulder diameter (19 mm), a strong beneficial effect on both ductility and strength of the joint is obtained even though the welding performed using the "pin" tool configuration is critically affected by the process parameters. An investigation has been also carried out in order to evaluate the micro-hardness and microstructure covering all regions of the welded joints. A different metal flow can be clearly observed depending on the presence/absence of pin. Finally, a more homogeneous microstructure is obtained using the "pinless" tool configuration.

1. Introduction

Friction stir welding (FSW) is considered to be the most significant development in the last years in metal joining techniques. FSW is a solid state process in which a specially designed rotating tool, composed by a shoulder and a pin, is inserted into the edges of the sheets to be welded, with a proper tilt angle, until the shoulder gets in contact with the top surface of the sheets; then the rotating tool is moved along the welding line [1–3]. The combined effect of tool rotation and translation involves heat generation by friction between tool and sheets, and induces a strong plastic deformation of the workpiece material promoting its complex mixing across the joint. The weld is asymmetric since the advancing side (AS) is characterised by a resultant velocity vector higher than that in the retreating side (RS). A detailed observation of microstructure in the joint section has shown the occurrence of an area located at the core of the weld, called nugget, in which the original grains are replaced with fine equiaxed recrystallised grains [1–11].

The energy efficiency, environment friendliness and versatility make the friction stir welding a promisingly ecologic and "green" technology. Actually, as compared to the fusion welding processes, FSW consumes less energy and leads to a decrease in material waste and to the avoidance of radiation and dangerous fumes [1]. Moreover, FSW is able to produce a strong metallurgical bonding and has many technical advantages for joining soft materials, such as aluminium and magnesium alloys, that are very difficult to be welded or even "unweldable" using fusion technologies due to the insurgence of defects such as inclusions, voids or ineffective metallurgical structures [1–3].

An accurate choice of the process parameters (rotational speed, welding speed, tilt angle and sinking) and tool geometry (pin and shoulder geometry and size) is required in friction stir welding in order to obtain the desired microstructural and mechanical properties and to minimize the occurrence of defects. Defects in FSWed joints can be classified as geometric-related and flow-related [12]. The former are usually attributed to an insufficient pin penetration depth and/or improper seam tracking whilst the latter include flash formation, surface galling, lack of fill, wormholes and lack of consolidation [5–14]. Several studies were performed in order to investigate the influence of the most relevant process parameters on the material flow and weld quality [1–24]. In particular, the authors investigated the effects of the process parameters and sheet thickness on the mechanical properties and post-welding formability of FSWed joints in magnesium alloy [15–20]. Also the sinking and the force superimposed on the tool play a significant role in friction stir welding since they affect the amount of the heat generation during the welding [1–3,25,26].

As far as the tool geometry is concerned, it strongly influences both the metal flow and heat generation; Schimidt et al. [27] showed that the most relevant part of the heat flux generated during FSW can be attributed to the frictional force at the tool

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shoulder–workpiece interface. The effect of the pin on the heat generation is generally considered to be low, quantified in less than 20% of the total heat generation [21,22,28]. In addition, Tang et al. [29] demonstrated that, using a ''pinless'' tool, the maximum temperature occurring during FSW undergoes to a reduction equal to about 4% as compared to that taking place during the process performed using a ''pin'' tool under the same conditions; such result is indicative of the reduced influence of the pin on the heat input. Furthermore, Buffa et al. [30], in order to compare the results obtained using a traditional ''pin'' tool in friction stir processing of aluminium alloys with those obtained using a ''pinless'' tool, demonstrated that the pin action on the mechanical stirring is negligible as far as the longitudinal residual stresses are concerned. Finally, it should be noted that the ''pinless'' tool is associated to a easy fabrication process and it is not dedicated to a specific sheet thickness.

The potential advantages offered by the ''pinless'' tool configuration can be fully exploited only as thin sheets are welded since, as the thickness increases, the shoulder influence becomes ever more localised to the top sheet surface. On the other hand, most of studies on FSW available in literature deals with sheet thicknesses ranging from 3 to 6 mm using the ''pin'' tool configuration whilst only very few investigations are focused on thin sheets, less than 2 mm thick, due to the difficulties associated to the small thicknesses [25].

In this context, the present investigation aims at studying the effect of the process parameters, tool geometry and size on macro- and micro-mechanical properties of FSWed joints in thin AZ31 magnesium alloy sheets (1.5 mm in thickness). In particular, two properly designed tools, with shoulder diameters equal to 8 and 19 mm, were used; each of them was manufactured in the ''pin'' and ''pinless'' tool configurations. Finally, a microstructural analysis was carried out on the welded joints in order to evaluate the microstructural evolution as a function of the tool configuration and process conditions.

2. Experimental procedures

2.1. Material

The material used in the present investigation was AZ31 magnesium alloy, 1.5 mm in thickness, commonly used in stamping processes for the obtaining of components for aerospace, automotive and electronic industries [31,32]. The alloy, provided in the as-received condition, was characterised by an initial mean grain size of 29.95 μm (Fig. 1) and a micro-hardness value equal to 68 HV.

2.2. Friction stir welding experiments

AZ31 magnesium alloy sheets were friction stir welded using the computer numerical control machining centre described in [15]. A detail of the FSW operation is shown in Fig. 2. Different tool geometries and sizes were investigated. In particular, two properly designed tools in H13 tool steel (HRC = 52), with shoulder diameters (d_s) equal to 8 and 19 mm, were used; each of them was manufactured both with and without the pin, as shown in Fig. 3 (''pin'' and ''pinless'' tool configurations). The conical ''pin'' tool was characterised by cone base diameter and height equal to 3 and 1.3 mm, respectively, with a pin angle of 30°. In order to investigate the effect of the process parameters, the experiments were carried out using constant rotational speed (ω) and welding speed (v), varying in the ranges from 2000 to 3000 rpm, and from 30 to 70 mm/min, respectively. The welding was carried out using a nuting angle of 2°.

The blanks were 180 mm in length and 80 mm in width. The welding line was perpendicular to the rolling direction.

2.3. Macro- and micro-mechanical tests

The macro-mechanical properties of the welded joints were evaluated by means of tensile tests performed at room temperature on specimens, machined from the welded blanks, with the loading direction perpendicular to the welding line. The obtained results were plotted as nominal stress (s) vs. nominal strain (e) curves by which the ultimate tensile strength (UTS) and ultimate elongation (UE) were derived.

Micro-mechanical investigations were also carried out in order to evaluate the micro-hardness distributions into the welded joints. To this purpose, micro-hardness tests were performed on the section perpendicular to the welding line, considering different points across the welding joint at different depth values from the top surface of the sheet facing the shoulder.

2.4. Microstructural analysis

Light optical microscopy investigations were carried out on the FSWed joints obtained using the different tool configurations and welding conditions; in particular, the microstructural analyses were performed at different depths from the top to the bottom surface of the sheet, in close proximity to the weld axis and both in the advancing side and retreating side. The microstructural evolution

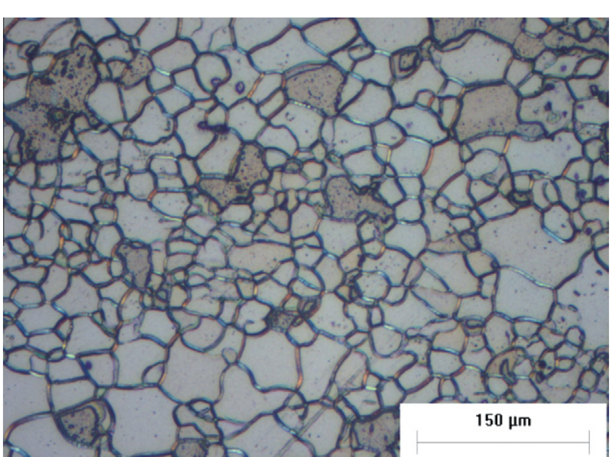

Fig. 1. Microstructure of the AZ31 magnesium alloy sheet in the as received condition, obtained in the cross section perpendicular to the rolling direction.

Fig. 2. Friction stir welding process.