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Micro- and Macro- Mechanical Properties of Pinless Friction Stir Welded Joints in AA5754 Aluminium Thin Sheets

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Abstract

The effect of process parameters, tool configuration and geometry on FSW of thin sheets in AA5754 aluminium alloy was widely investigated. Tools in “pin” and “pinless” configurations were used. It was shown that the “pinless” tool allows the obtaining of mechanical properties higher than those of the “pin” one. An investigation was also carried out in order to evaluate the microstructure of the joints. Welds obtained with the “pin” tool exhibit a more pronounced grain refinement than the one observed using the “pinless” one even though the presence of cavities and less homogeneity strongly affect the mechanical properties of joints.

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Keywords: Aluminium alloy; Friction stir welding; Thin sheet; Pinless tool; Tool configuration; Mechanical properties; Microstructure.

1. Introduction

Friction stir welding (FSW) is a promisingly ecologic and “green” technology that enables to reduce material waste and to avoid radiation and harmful gas emissions usually associated with the fusion welding processes [1]. As well known, FSW is a solid state process involving severe deformations; they are induced by the combined effect of rotation and translation of a cylindrical shouldered tool with a profiled pin inserted into the sheet edges to be welded. The softening mechanisms, such as dynamic recrystallisation, activated by the frictional heat generated at the tool–sheet interfaces, allow to accommodate the large deformations of the workpiece material and permit its complex mixing across the joint.

FSW has many technical advantages in joining soft materials, such as aluminium and magnesium alloys, that are very difficult to be welded using conventional fusion technologies due to the insurgence of many defects [1, 2].

Several authors have shown the influence of the process parameters and tool geometry on the mechanical properties, microstructure and material flow path, formability of similar and dissimilar friction stir welded joints in aluminium and magnesium alloys [3-7]. As a consequence, the process parameters and tool geometry have to be accurately chosen in order to obtain the desired micro- and macro-mechanical properties and to minimize the occurrence of defects.

Among the process parameters, the rotational (ω) and welding (v) speeds of the tool have a strong influence on the joint quality. In particular, the rotational speed results in stirring and mixing of material around the rotating pin whilst the tool translation moves the stirred material from the front to the back of the pin and finishes welding process [1, 2]. Higher tool rotational speed generates higher temperature because of higher friction heating and results in more intense stirring and mixing of material, as observed by Elangovan and Balasubramanian in [8] on friction stir processed zone in AA2219 aluminium alloy. It was clearly shown that the ω/v ratio is usually characterised by an optimal value that leads to the best mechanical properties of the FSWed joint [1, 3].

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Concerning the tool geometry, it strongly influences the heat generation during the FSW process; to this end, it was shown that the most relevant part of the heat flux generated can be attributed to the frictional forces at the tool shoulder–workpiece interface [1, 8]. Such result is confirmed by the low heat generation of the pin, quantified in less than 20% of the total heat generation [9, 10]. In addition, the maximum temperature in FSW performed using a "pinless" tool is very similar to the one taking place during the process performed using a "pin" tool under the same conditions, indicating the reduced influence of the pin on the heat generation [9]. As a consequence, friction stir welding can be also performed with a "pinless" tool even though the potential advantages offered in terms of simplified tool geometry, versatility since such tool is not dedicated to a specific sheet thickness, and microstructural homogeneity [11, 12], can be fully exploited only as thin sheets are welded; as a matter of fact, as the thickness increases, the shoulder influence becomes ever more localised to the top sheet surface. To this end, the analysis of the effect of the tool configuration on FSWed AZ31 magnesium alloy, with a sheet thickness of 1.5 mm, has proven the beneficial effect of the "pinless" tool on the mechanical properties of joints [11].

In this context, the present work aims at studying the influence of the process parameters and tool configuration on micro- and macro-mechanical properties of FSWed joints in thin AA5754 aluminium alloy sheets. To this purpose, FSW experiments were carried out, using "pin" and "pinless" tools, with different shoulder diameters, at different rotational and welding speeds values. A microstructural investigation has been also carried out in order to evaluate the microstructure covering all regions of the welded joints as a function of the tool configuration and welding conditions.

2. Materials and experimental procedures

2.1. Friction stir welding experiments

The material used in the present investigation was AA5754 aluminium alloy, supplied in form of 1 mm thick sheet, in the H111 temper state.

Friction stir welding was performed on a CNC machining center (Fig. 1). Two properly designed tools in H13 tool steel, with shoulder diameters (d_s) equal to 8 and 19 mm, were used; each of them was manufactured both in the "pin" and "pinless" tool configurations (Fig. 2) [11]. The profiled pin tool was characterised by cone base diameter and height equal to 2.5 and 0.7 mm, respectively, with a pin angle of 30°. The welding was carried out using a nuting angle of 2°. The blanks, 180 mm in length, 80 mm in width and 1 mm in thickness,

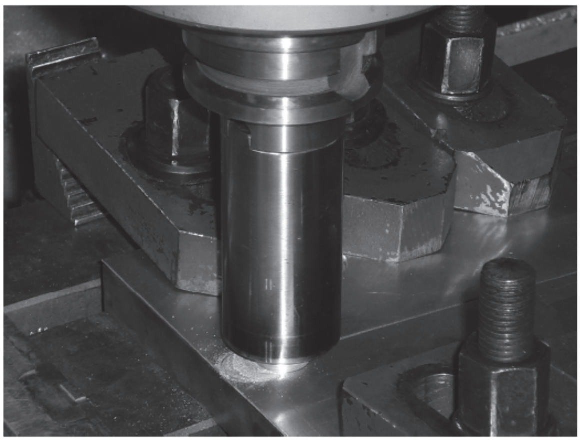


Fig. 1. Friction stir welding process of thin sheets using a "pinless" tool configuration (d_s=19 mm)

(a) (b)

Fig. 2. "Pin" and "pinless" tool configurations: (a) d_s =19 mm, (b) d_s = 8 mm

were joined with a welding line perpendicular to the rolling direction.

In order to investigate the effect of the process parameters, the experiments were carried out using constant values of rotational speed (ω) and welding speed (v), varying from 800 to 3000 rpm, and from 30 to 200 mm/min, respectively.

2.2. Tensile tests

Tensile tests were performed, at room temperature, in order to evaluate the mechanical properties of the welded joints and to compare them with that obtained on the base material (BM). To this purpose, specimens were machined from the FSWed blanks, with the loading direction perpendicular to the welding line, so that the welded area was located in the gage section of the sample.

The experimental results were plotted as nominal stress (s) vs. nominal strain (e) curves by which the ultimate values of tensile strength (UTS) and elongation in percentage (UE) were derived. At least three repetitions for each condition were performed.

2.3. Microstructural analysis

Polarized light optical microscopy (POM) was carried out on the FSWed joints in AA5754 aluminium alloy obtained using the different tool configurations and welding parameters; in particular, the microstructural analysis was performed in the nugget zone of the friction stir welded blank, in the transverse cross-section, in order to evaluate the microstructure as a function of the tool configuration, shoulder diameter and process conditions.

3. Results and discussion

Fig. 3 shows the typical flow curves of the friction stir welded joints in thin AA5754 blanks, obtained under different process parameters and shoulder diameters, using the "pinless" tool configuration. Such figure also shows the comparison between the s-e curves of the FSWed joints with the one of the BM that exhibits a relevant deformation before necking and an almost negligible post-necking strain. It can be seen that the friction stir welded joints show the same behaviour of the BM even though the post necking strain is almost negligible. Furthermore, the flow stress and the ductility values of the FSWed joints are always lower than those of the BM, according to the results obtained by Rodrigues et al. on thin friction stir welds in AA6016-T4 aluminium alloy [4]. The tensile strength and ductility of the joints are strongly improved by increasing the shoulder diameter from 8 to 19 mm and can be attributed to the increase in the workpiece temperature produced by an augment of the contact surface with rising the shoulder diameter [13]. A similar behaviour was also observed by the authors on AZ31 magnesium alloy [11].

The different plastic behaviour of BM and FSWed joints can be also analysed by comparing the fractured tension tested samples (Fig. 4). In the base alloy, a fracture surface at about 30° to the perpendicular to the loading direction can be observed, whilst the fracture surface in the welded sample is almost perpendicular to the loading direction.

Fig. 5 shows the ultimate values of tensile strength and elongation of FSWed joints, obtained using the "pinless" tool configuration, with the two different shoulder diameters investigated, as a function of the rotational/welding speed ratio. In general, the FSWed joints obtained using d_s=8 mm are characterised by UTS and UE values lower than those provided using d_s=19 mm. As far as the highest shoulder diameter is concerned, it appears that the UTS values are not significantly affected by the ω/v ratio whilst the UE values increase with rising ω/v ratio until a peak value, obtained at 25 rev/mm, followed by a slight decrease as ω/v further increases.

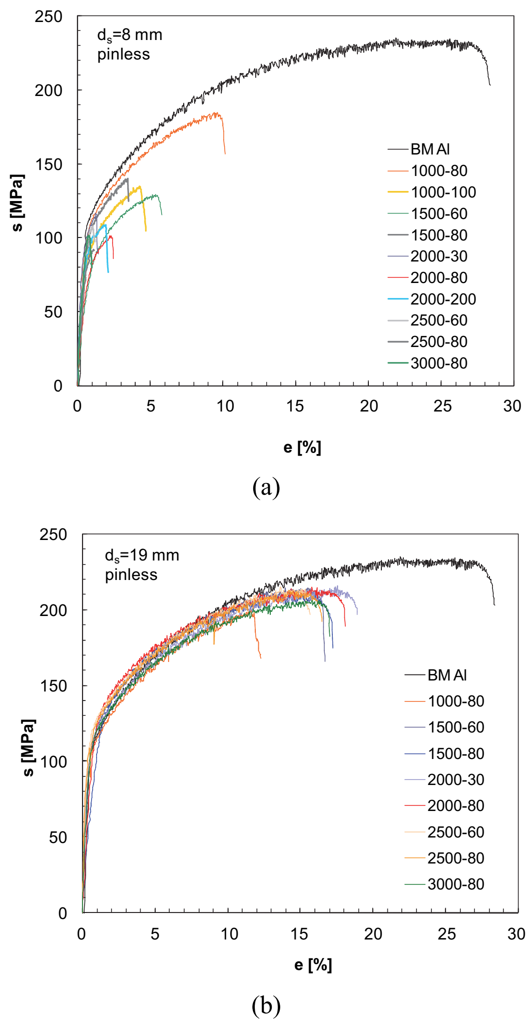


Fig. 3. Typical flow curves of friction stir welded AA5754 thin sheets using different welding parameters and tool geometries with the "pinless" tool configurations: (a) d_s = 8 mm; (b) d_s = 19 mm

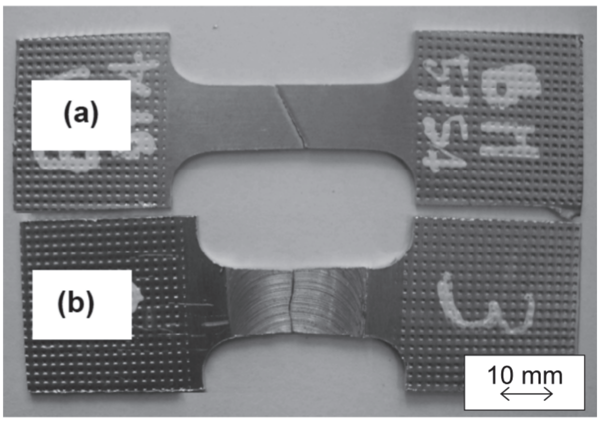
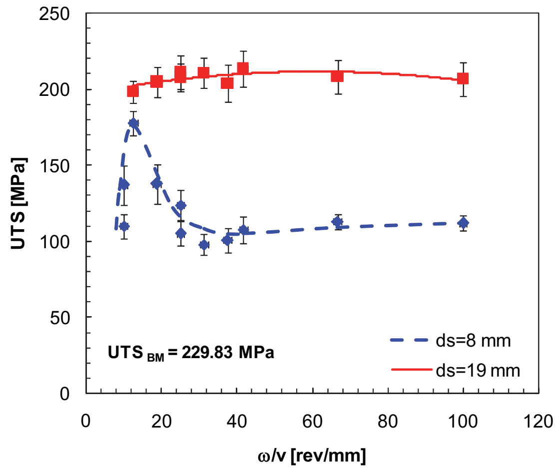
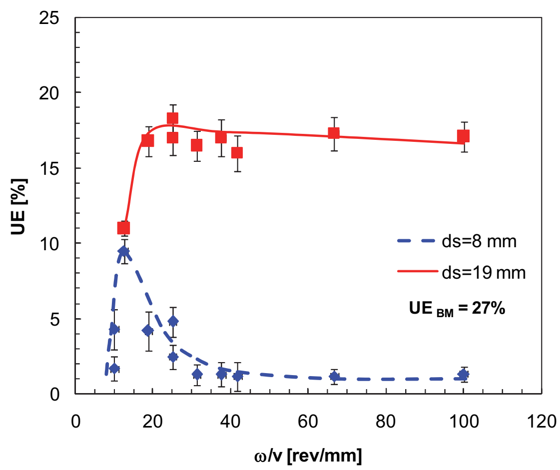


Fig. 4. Comparison between typical fractured tension tested samples: (a) BM; (b) FSWed joint

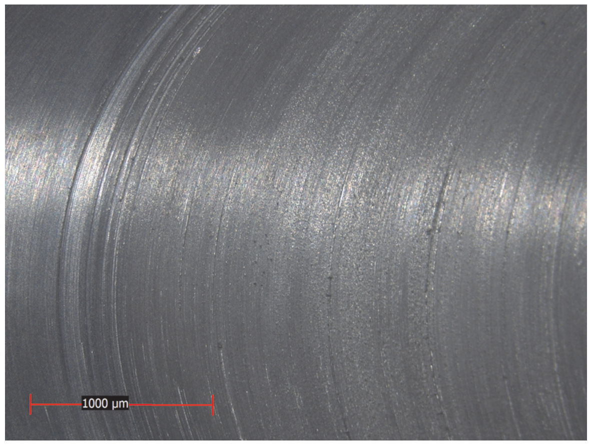


(a)

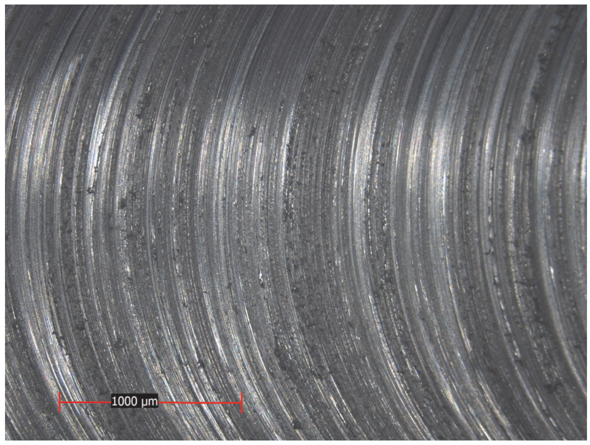


(b)

Fig. 5. (a) Ultimate tensile strength and (b) ultimate elongation provided by tensile tests at room temperature, performed on FSWed AA5754 joints obtained using different tool sizes as a function of the rotational/welding speed ratio



(a)



(b)

Fig. 6. Surface appearances of the FSWed joints obtained under different welding parameters: (a) 2000 rpm – 30 mm/min; (b) 3000 rpm – 80 mm/min (d_s =19 mm, "pinless" configuration)

The behaviour of UTS and UE versus ω/v ratio is related to the combined effect of rotational and welding speeds on joint formation. As shown also in [1, 2], ω and v values affect the temperature field, heat generation and cooling rate. In particular, the heat generation rate increases with rising ω/v ratio; such increase can be obtained both by increasing the ω value, which leads to higher temperatures and results in more intense mixing of material, and by decreasing the v value, which produces an increase in specific thermal contribution conferred to the joint so that more time is given to the heat to flow into the joint. However, in the experimental conditions of the present work, the heat flow towards the backing plate also plays a very important role in the thermal field due to the very small sheet thickness (1 mm); in particular, as welding speed decreases, the detrimental effect of the heat dissipation towards the backing plate on the temperature field becomes ever more important until it prevails on the beneficial effect produced by the increase in the heat generation rate. As a consequence, the mechanical properties of joints increase with increasing ω/v ratio up to a peak, and then decrease as ω/v further increases. The more marked decrease in the mechanical properties with increasing ω/v, observed using the 8 mm "pinless" tool, is related to the reduced heat generation produced by friction as the shoulder diameter decreases; consequently, the effect of heat dissipation towards the backing plate on UTS and UE becomes more marked with decreasing d_s.

The surface of welds is also affected by the process conditions, as it can be observed by the surface appearance of joints obtained using the "pinless" tool configuration, under different rotational and welding speeds (Fig. 6). In particular, as the ω/v decreases, the surface roughness increases and small depth striations are observable; such behaviour can be attributed to the

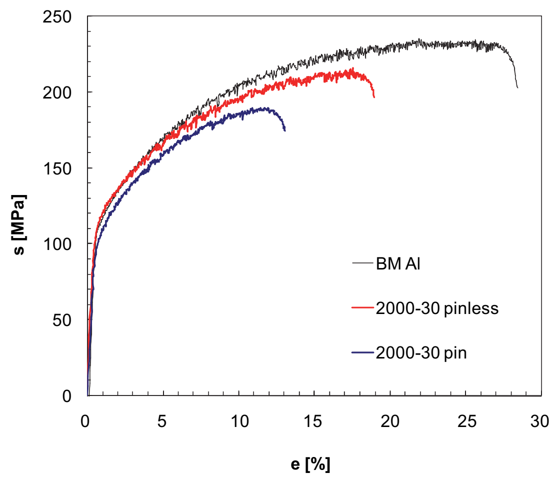


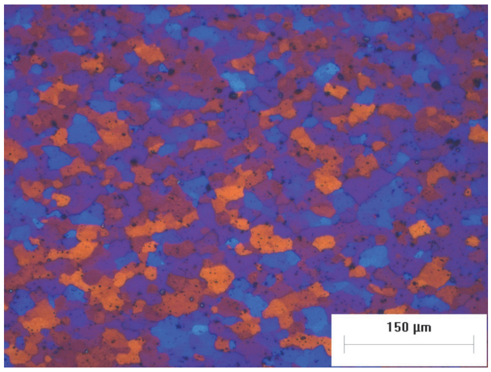
Fig. 7. Typical effect of the tool configuration on flow curves of FSWed AA5754 thin sheets (d_s = 19 mm)

increase, with decreasing ω/v ratio, in the welding speed that, as well known, causes a worsening in the surface roughness notwithstanding the beneficial effect on the surface finishing produced by the increase in the rotational speed.

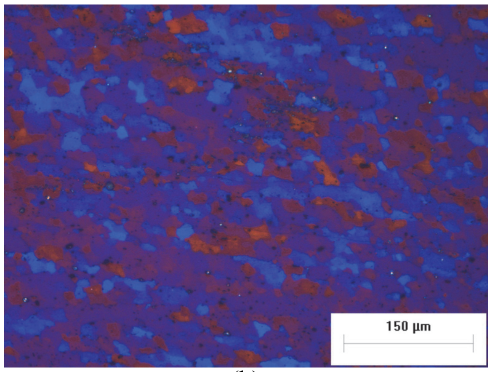
By focusing the attention on the FSW process performed using the tool with the shoulder diameter of 19 mm, Fig.7 allows to analyse the tool configuration effect on the mechanical properties of welded joints. It was shown that the "pinless" tool configuration allows the obtaining of the highest values of the tensile strength and ductility. Such results are in agreement with those obtained by authors on AZ31 magnesium alloy, 1 mm thick sheet [11].

In order to understand the different mechanical behaviour of the welded joints obtained using the "pin" and "pinless" tool configurations, the microstructure of the joints was analysed in different regions of the transverse cross-section of the welded blanks (Fig.s 8). In particular, Fig. 8a shows the microstructure of the parent material, characterised by a mean grain size of 18.62 μm.

A general grain refinement along the weld centerline of the joint is obtained (Fig.s 8b and 8c); furthermore, the stirring action of the pin leads to a finer grain structure (Fig. 8c), with a mean grains size of 10.05 μm, but less homogeneous than that obtained using the "pinless" tool configuration (Fig. 8b), characterized by a mean grains size of 12.22 μm. Such discrepancy was also observed by Buffa et al. in a friction stir processed aluminium alloy [14] and by authors in FSWed AZ31 magnesium sheets [11]. The mean grain size tends to be very similar to the base material one, shown in Fig. 8a, as the distance from the weld axis increases. However, notwithstanding the grain refinement, the FSWed joints obtained using the pin tool configuration are characterised



(a)



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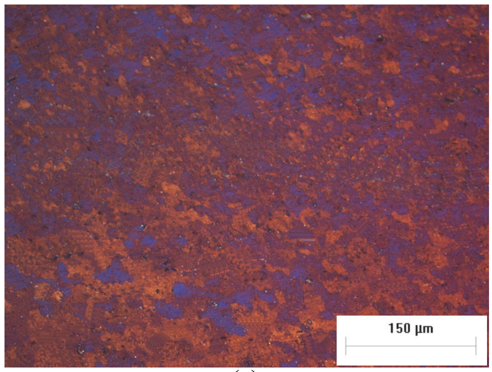

(c)

Fig. 8. Typical microstructure of FSWed joints obtained at 2000 rpm and 30 mm/min: a) parent material, b) weld centerline in pinless joint and (c) weld centerline in pin joint (sheet thickness: 1 mm)

by the presence of defects, such as cavities, with a high porosity level mainly localised near the top and bottom surfaces of the welded sheets (Fig. 9) that strongly reduce the mechanical properties as shown in Fig. 7.

4. Conclusions

The present paper aims at studying the effects of process parameters, tool geometry and sizes on the mechanical properties and microstructure of friction stir

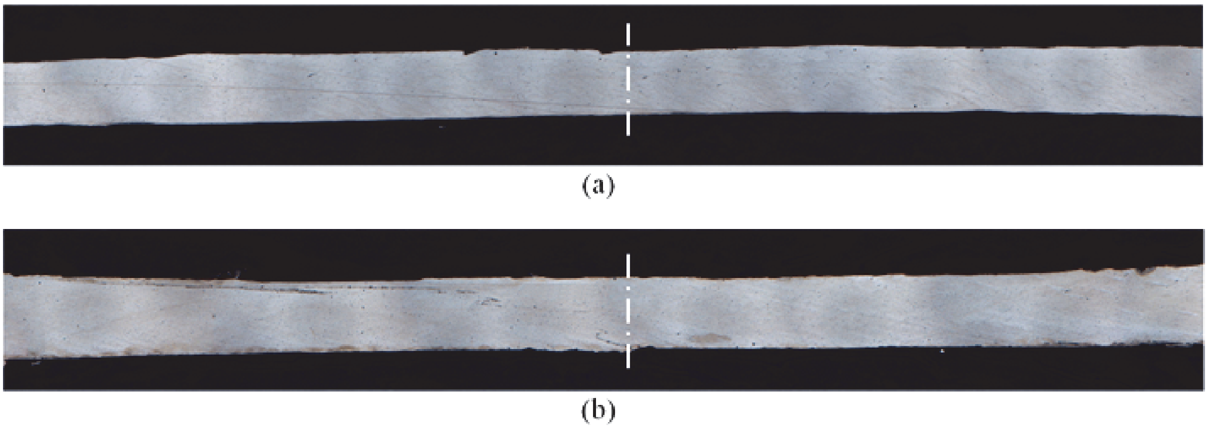

Fig. 9. Macrostructure in the cross-section perpendicular to the welding line of FSWed joint obtained at 2000 rpm and 30 mm/min with (a) "pinless" and (b) "pin" tool configurations

welded thin AA5754 aluminium alloy sheets. "Pin" and "pinless" tool configurations were taken into account; each of them was manufactured with different values of the shoulder diameter.

The experimental results can be summarised as follows:

- the ultimate values of tensile strength and elongation of FSWed joints obtained using the shoulder diameter of 8 mm, in the "pinless" tool configuration, are lower than those provided with the shoulder diameter of 19 mm; as far as the highest shoulder diameter is concerned, it appears that the UTS values are not significantly affected by the ω/v ratio whilst the UE values increase with rising ω/v ratio until a peak value followed by a slight decrease as ω/v further increases;
- the tensile strength and ductility values obtained with the "pinless" tool configuration are higher than those provided by the "pin" tool one, irrespective of the shoulder diameter and process parameters;
- a general grain refinement along the weld centerline of the joint is observed. Furthermore, the stirring action of the pin produces a more pronounced grain refinement than the one observed using the "pinless" tool; unfortunately, the FSWed joints obtained using the "pin" tool configuration are characterised by the presence of defects, such as cavities, with a high porosity level mainly localised near the top and bottom surfaces of the welded sheets.

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