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ScienceDirect
Procedia Engineering 69 (2014) 1541 – 1548
Procedia Engineering
www.elsevier.com/locate/procedia

24th DAAAM International Symposium on Intelligent Manufacturing and Automation, 2013

Influence of Shoulder Geometry and Coating of the Tool on the Friction Stir Welding of Aluminium Alloy Plates

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Abstract

Friction Stir Welding (FSW) has demonstrated a significant potential for joining low melting point non-ferrous metals in several joint configurations. During FSW metals are joined in the solid state due to the heat generated by the friction and flow of metal by the stirring action of a pinned tool.
This paper reports an experimental investigation on the effects of geometry and surface coating of the tool shoulder on the defectiveness, the microstructure and the microhardness of a 3 mm thick 5754H11 aluminium alloy butt weld.
During the experiments the diameter and slope of the shoulder varied. Moreover a tungsten carbide coated was tested. The pin geometry and dimensions were kept constant. Four different tools for shoulder geometry and coating condition were tested.
The weld was characterized in terms of the bead morphology and the grain size.
The weld microhardness profile was measured for all the microstructural zones of the friction stir welding process.
The obtained results provide a deeper knowledge of the effect of the tool shoulder geometry and surface condition on the aluminium alloy weldability.

Keywords: friction stir welding, tool shoulder geometry, 5754H11 aluminium, geometrical and microstructural characterisations, microhardness profile

1. Introduction

Friction Stir Welding (FSW) was developed and patented by The Welding Institute (TWI) of UK in 1991 [1]. Friction stir welding (FSW) was invented as a solid-state joining technique, and it was initially applied to aluminium alloys. The basic concept of FSW is that, after the weld edges are clamped, a non-consumable rotating tool is forced

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doi:10.1016/j.proeng.2014.03.153

between them and moved along the weld seam. The material is then essentially extruded around the tool before being forged by the shoulder. During FSW the metals are joined in the solid state due to the heat generated by the friction and flow of metal by the stirring action of a pinned tool.

The tool serves two primary functions: (a) to heat the workpiece, and (b) to produce of the material flow [2]. The tool pin is the weakest component of the tool due to severe stresses at high temperatures. Arora et al. [3] have addressed their attention to load bearing capacity of tool pin during friction stir welding. Nonetheless, the shoulder geometry has influence on thermal cycles, peak temperatures, power requirements, and torque. An optimum tool shoulder diameter was identified by Mehta et al. [4] using three-dimensional, heat transfer and materials flow analysis.

Pin tool proved to be more effective than pin-less tool at welding magnesium alloys [5].

FSW is also an effective mean to refining grain size of cast or wrought aluminium or magnesium based alloys via dynamic recrystallization [6].

Therefore, this technology has demonstrated a significant potential for joining low melting point non-ferrous metals in simple and complex geometries [7].

The drawbacks of FSW include the need for powerful fixtures to clamp the workpiece to the welding table, the high force needed to move the welding tool forward, the relatively high wear rate of the welding tool, and slow welding speed, which can lead to long process time [8].

The weld can be characterized in terms of nugget and thermal like pinhole, tunnel defect, piping defect, kissing bond, cracks. These defects are due to improper flow of metal and insufficient consolidation of metal in the FSP region, which depend on the plasticization condition [9].

Several solutions have been proposed. Among them it worth to remember the proposition of a Fiber Laser Assisted Friction Stir Welding (FLAFSW) process. LAFSW introduces additional local heating, without melting of the material, immediately ahead of the weld zone so that less mechanical energy, delivered through the tool, must be converted into heat. This reduces the tool forces, deflections in the machine and fixture, and may enable higher weld speeds. Several works have already addressed the subject [10, 11, 12].

In this paper, three-millimetre thick plates of aluminium of 5754H11 alloy were friction stir butt welded. The AA5754-H111 magnesium aluminium alloy is an high strength non-heat treatable aluminium alloy and it is optimal and extensively used for structural applications.

Four different tools were considered that differed for geometry and surface treatment of the shoulder. The welds were visually inspected. A qualitative analysis of crowns and roots was carried out. Then the microstructures of the cross-section was observed with the optical microscopy. Vickers microhardness and grain size measurements were carried out.

Nomenclature

θ	tool tilt
ω	tool rotation rate
v	tool traverse speed
h	target depth
p	v to ω ratio

2. Experimental procedure

2.1. Geometry of tools and materials adopted

The chemical compositions in mass percentage of base metal 5754H11 and tool steel are showed in table 1. Table 2 contains the properties of the MG18 carbide that were used for the tools.

Table 1. Chemical composition for tool steel and welded aluminium.

Wt %	Si	Fe	C	Cu	Mn	Mg	Mo	Cr	Zn	Ti	V	other	Al
AA5754	0.4	0.4	-	0.1	0.5	2.6-3.6		0.3	0.2	0.15	-	0.15	balance
Tool steel	0.30	balance	0.38	-	0.75	-	2.25	2.6	-	-	0.9	-	-

Table 2. Carbide properties.

Specific weight [g/cm3]	Young modulus [GPa]	Thermal coefficient of expansion [10-6/K]	Thermal conductivity [W/m•K]	Vickers hardness
14.45	580	5.5	85	1680

The following geometries of the tool were used.

- Tool 1 was made of Uddeholm QRO 90 Supreme tool steel, which has good hot hardness and strength. The tool had a 10 mm shoulder and a 7° conical edge. The pin was cylindrical with a 4 mm flat bottom and a 2,8 mm height. It is shown in figure 1.
- Tool 2 was made of the same steel of the conic shoulder tool but had a different shoulder size, which was flat and measured 10.32 mm as shown in figure 2.
- Tool 3 was produced in two parts, which were assembled by a mechanical lock. The working part of the tool was made of tungsten carbide (MG18 code ISO K20-40) while the support was made of C45 carbon steel. The shoulder dimension had a 25 mm diameter with a 7° concavity. The pin was trunk-conic with a flat bottom whose diameter was 8 mm long. The pin slope angle was 15° and the height 2.8 mm. Figure 3 shows its characteristics.
- Tool 4 was equal to the tool 3. It had an additional feature that was a hard coating made AlCrN. This coating improves the wear resistance and the thermal stability of the working part of the tool. It is presented in figure 4.

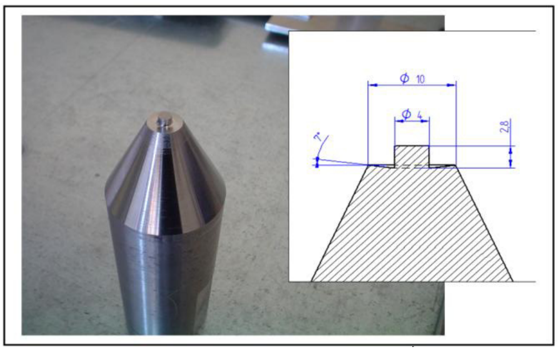

Fig.1. Tool 1 geometry: conic small shoulder.

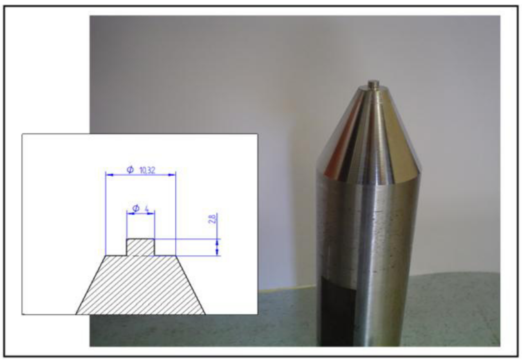

Fig. 2. Tool 2 geometry: flat small shoulder.

Figu. 3. Tool 3 geometry: carbide tool large shoulder.

Fig. 4. Tool 4 geometry: carbide tool large shoulder with coating.

2.2. Process parameters

Table 3 shows the experimental plan at a glance adopted to carry out the analysis.

Table 3: Experimental plan at-a-glance.

GEOMETRY	sample	p [mm/r]	ω [rpm]	v [mm/min]	h [mm]	θ
CONIC SMALL	1	0,32	1700	550	-1,7	0,2
SHOULDER	2	0,33	1500	500	-1,75	0,2
FLAT SMALL	3	0,38	1700	660	-1,6	2,5
SHOULDER	4	0,60	1000	600	-1,6	2,5
	5	0,42	700	300	-2,76	1,2
CARBIDE LARGE	6	0,50	600	300	-2,76	1,2
FLAT SHOULDER	7	0,60	500	300	-2,76	1,2
	8	0,80	500	400	-2,76	1,2
CARBIDE LARGE	9	0,50	600	300	-2,76	1,2
FLAT SHOULDER	10	0,60	500	300	-2,76	1,2
WITH COATING	11	0,80	500	400	-2,76	1,2

3. Risults and discussion

3.1. Weld appearance

The conic tool produced a regular joint with a complete circle around the exit hole. The qualitative analysis of crown and root has shown no defects. The bead obtained by this tool was characterized by a smooth surface and little flash.

The flat shoulder gave different welds for sample 3 and 4. The sample 3 was more regular and showed a smooth surface and almost no flash. Sample 4 had flash in the steady state welding condition and lack of penetration.

The large shoulder carbide tool generated a different weld appearance and quality. The weld had a large crown and presented side flash. The root of the weld was also large but there was lack of penetration for the lower p value The flash diminished with the p parameter while the overall quality of the weld improved for higher r values.

The large shoulder coated carbide with coating tool gave almost defect-free weld. Figure 5 shows the crown and root of the sample 11.

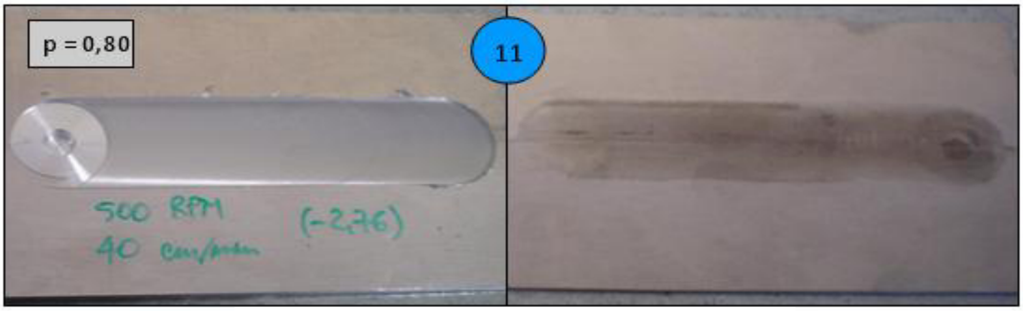

Fig. 5. Weld outlook for sample 11 (A crown, B root).

3.2. Cross section and microhardness

A number of investigations demonstrated that the change in hardness in the friction stir welds is different for precipitation-hardened and solid-solution- hardened aluminum alloys. It was suggested that such a softening is caused by coarsening and dissolution of strengthening precipitates during the thermal cycle of the FSW. The former creates a softened region around the weld center in a number of precipitation-hardened aluminum alloys.

The transition zone corresponds approximately to the edge of welding tool pin. In this zone no recrystallization was observed because the temperature derived from the friction stir processing is not high enough and deformation was not so severe to cause recrystallization.

Figures 6 through 9 show the cross section of the weld for some welding conditions. They show the typical hardness curves that were labeled by Sato et al. BM for the same hardness region as the base material, LOW for the region of lower hardness than base material, MIN for the minimum-hardness region, and SOF for the softened region [13]. In Fig. 6, the region adjacent to the TMAZ is the HAZ, where the grain size is similar to the base metal.

The nugget is approximately symmetric about the weld centreline and it is typically similar in diameter to the pin, which is the most prominent feature of the friction stir welded zone.

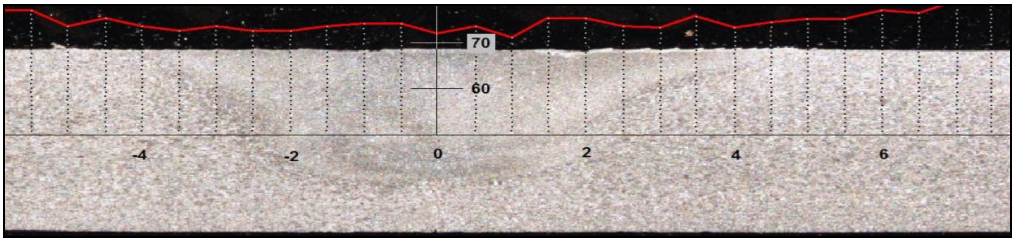

Fig. 6. Cross section and microhardness profile of sample 2.

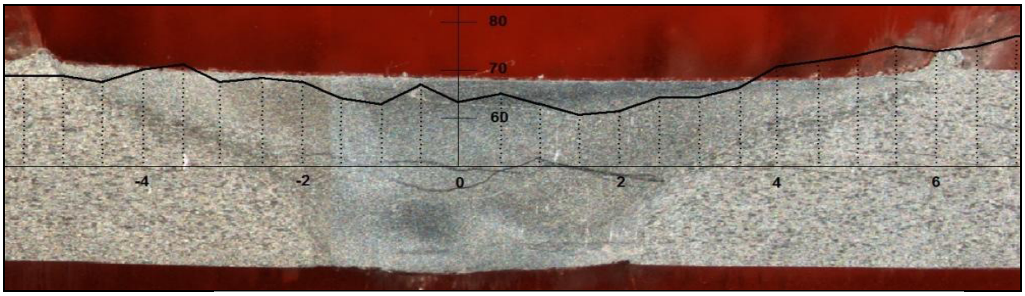

Fig. 7. Cross section and microhardness profile of sample 3.

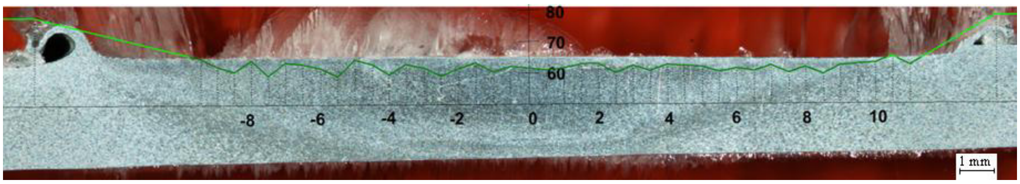

Fig.8. Cross section and microhardness profile of sample 8.

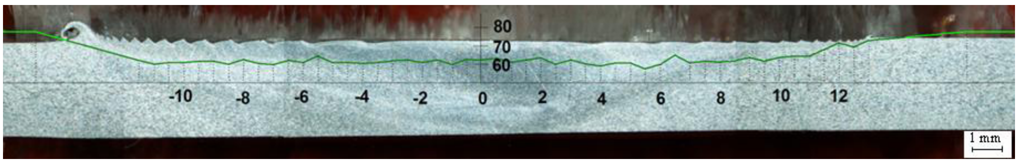

Fig.9. Cross section and microhardness profile of sample 11.

3.3. Grain size

The dynamic recrystallization typical of the FSW process resulted in the generation of a fine and equiaxed grain in the nugget zone. The size of the grain in the nugget varied in the range of 7-10 □ m and was unaffected by the tool geometry and surface condition. Figures 10 shows the grain size in different zones of the joint in the horizontal and vertical directions (which were defined with respect of the welding direction).

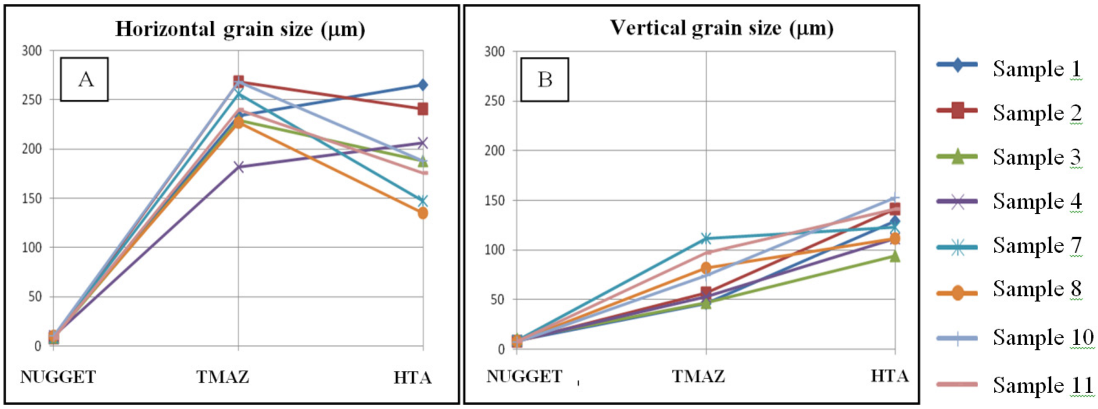

Fig. 10. Grain size: (A) horizontal size, (B) vertical size.

In the thermo-mechanical and heat affected zones (TMAZ and HAZ, respectively) the form of grain varied in the horizontal and vertical directions. Therefore in those zones the grains were oblong and their size was affected by the tool features. The TMAZ was characterized by a highly deformed structure for almost all the tools. The parent metal elongated grains were deformed in an upward flowing pattern around the nugget zone, which was proved by the larger horizontal grain size with respect to the HAZ. The vertical size did not vary significantly between the TMAZ and HAZ.

The use of the flat shoulder determined a larger grain deformation than the small shoulder.

4. Conclusion

In this study, the effects of the tool shape and surface condition on the microstructure, microhardness and grain size of a 3 mm thick 5754H11 aluminum alloy butt weld were studied. The following conclusions were achieved:

- The conic tool produced a regular joint with a smooth surface and little flash
- The flat shoulder showed sensitiveness to the process parameters since it gave different result for sample 3 and 4
- The large shoulder coated carbide with coating tool gave almost defect-free weld
- The shoulder size influenced the size of the microstructural zones and the hardness profile
- The grain size in the TMAZ was sensitive to the tool shoulder

As a future development of this work the large shoulder with the wear resistant coating will be tested for tool wear optimization.

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