Microstructure and Micro Hardness of Friction Stir Welded AA2024-T3 Joints

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ABSTRACT
Macrostructure, microstructure and micro hardness of friction stir welded AA2024-T3 joints was studied. The influence of tool pin profile on the microstructure and hardness of these joints was examined. Square, triflute and tapered cylinder pins were used in this study. Vickers micro hardness tests and grain size measurements were taken from the transverse plane of welded samples. Distinct zones in the macrostructure were evident. The zones were identified by transitions in the microstructure and hardness of weld samples.

KEYWORDS: Friction Stir Welding; Microstructure; Hardness

1. INTRODUCTION

The Welding Institute (TWI) developed Friction Stir Welding (FSW) in 1991[1] and it is considered to be one of the most significant developments in metal joining in recent times. It is a solid-state welding technique used for joining aluminium alloys (as shown in Fig.1). This technique is currently being applied to the aerospace, automotive, and shipbuilding industries [2,3].

Due to its solid state nature FSW has many benefits over fusion welding techniques. However, one of its main advantages is its ability to weld all series of aluminium alloys, in particular the 2xxx series alloys [4]. These alloys are used extensively within the aerospace industry for applications such as fuselage and wing skin panels due to their high strength to weight ratio. However, these alloys are mostly non-weldable using fusion welding methods due to problems with oxidisation, solidification, shrinkage, sensitivity to cracking, hydrogen solubility and the resultant porosity problems [5].

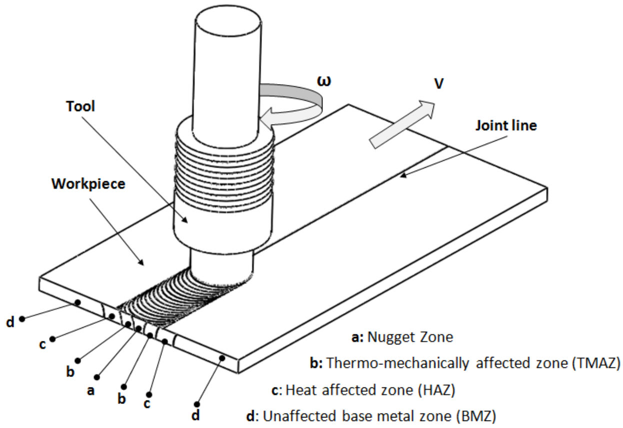

Fig. 1 Friction Stir Welding schematic

FSW involves the translation of a tool along the joint line between two plates. The tool rotates at high speeds during the process. The tool is made up of a profiled pin and a shoulder which utilise frictional heat to soften the workpiece material either side of the joint line and mix the workpiece materials together. The FSW tool is not consumed in the process and is crucial to the

welding process. The shoulder generates the largest component of heat in the process. The pin causes localised heating and plastic deformation of the material around the pin.
The macrostructure of a FSW joint consists of three distinct zones; the central nugget zone (NZ), the Thermomechanically affected zone (TMAZ) and the heat affected zone (HAZ). The zonal microstructure of a FSW joint is shown in Fig. 1 and Fig.2. The objective of this work was to determine the variation in hardness across a FSW joint and determine the correlation between microstructure and hardness. The effect of pin profile on the microstructure and hardness of FSW joints was examined.

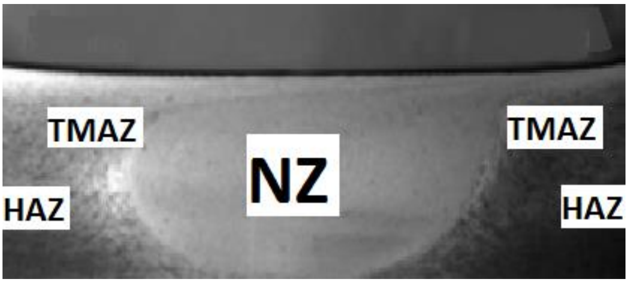

Fig. 2 Zonal microstructure of FSW (Adapted from [1])

2 EXPERIMENTAL PROCEDURE

A Corea F3UE vertical milling machine was modified for use in this experiment. Fig. 3 gives details of the FSW tooling. Aluminium alloy AA2024-T3 plates (4.8mm thick) were butt welded using three different pin profiles: tapered cylinder, square and triflute. All pins were 4.6mm in length. The swept diameter of the square pin was 7mm. The swept diameter of the tapered cylinder and triflute pins tapered from 7mm (at the shoulder) to 2.69mm. A scrolled shoulder was used in this investigation (no tilt angle was required). Rotational and translational speeds were 450rpm and 180 mm/min respectively.

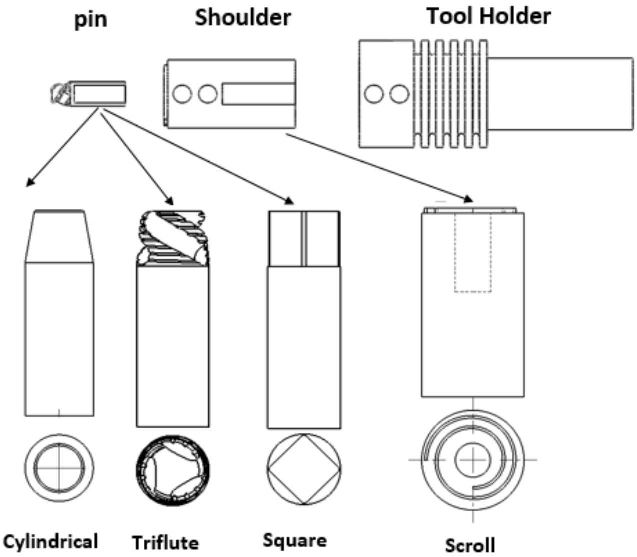

Fig. 3 The three pin profiles used, shoulder with scroll, and tool holder

Samples were cut from the cross-section of each FSW joint and prepared for post weld analysis. Samples were polished to remove all tool marks and scratches. The samples were then etched using Keller's reagent to reveal the microstructure. Samples were viewed using a Leica DM LM microscope and ImageJ software was used to measure grain size. Vickers microhardness tests were carried out using a Mitutoyo MVK-H1 micro hardness machine. Four rows and twenty five columns of indents were made across the weld samples with 1mm horizontal spacing was maintained between columns. The indent rows were positioned 1, 2, 3.25 and 4.5 mm from the base of the sample.

Fig. 4 shows the outline of the indentation point gridlines. Each diamond point represents a hardness test location.

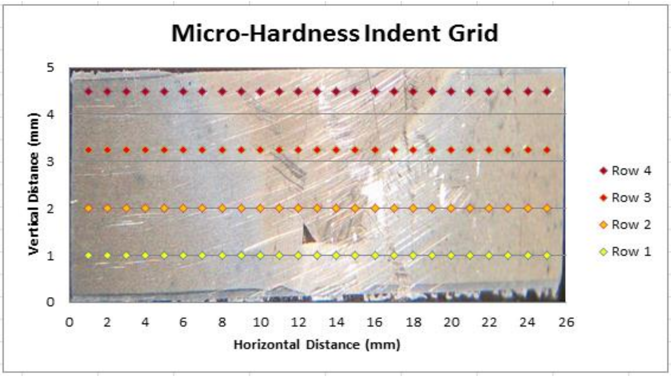

Fig. 4 Position of indents on tapered cylinder weld sample

3. RESULTS AND DISCUSSION

Microstructural analysis revealed a complex microstructure in the FSW zone. On a macrostructural level the weld zone was found to be trapezoidal in shape for each pin. Table 1 shows the results of macrostructural analysis for the three pin profiles. By comparing the swept diameter of each pin to the width of the nugget zone for each pin it is clear that tool geometry is directly linked to the shape of the FSW zone. Despite having the same swept diameter, it can be seen that the NZ of the triflute pin does not narrow with depth from the workpiece surface as drastically as that of the tapered cylinder pin. This was due to increased mixing action resulting from the flutes in the pin surface. The greater mixing action of the square and triflute pins resulted in a larger NZ when compared to the tapered cylinder pin.

A tunnel defect (an internal void) was observed in the welds performed by tapered cylinder pin. This defect was observed in the transition region between the NZ and the TMAZ at a depth similar to the plunge depth of the pin and on one side only. This is because the cylindrical pin produces less plastic deformation and stirring of the workpiece and plasticised material is simply allowed to extrude along the sides of the pin which can lead to the formation of tunnel defects along the interface of the NZ and TMAZ

Table 1 Macrostructural data for three pin profiles

Pin Profile	Macrostructure	Size of Nugget Zone (mm)		Shape of FSW Zone	Defects
		W	H		
Tapered Cylinder		13.40 4.59 2.64	4.8	Trapezoidal	1. Tunnel defect at plunge depth of pin. 2. Remnants of joint line at base
Square		13.67 7.37 5.51	4.8	Trapezoidal	None
Triflute		13.01 5.72 3.57	4.8	Trapezoidal	None

The HAZ, TMAZ and NZ were defined by different microstructural features. Fig. 5 shows examples of the typical grain structures found in the distinct zones. Fig. 5(a) shows the microstructure of the parent material. This microstructure is typical of the alloy, which was tempered (T3) and rolled. Fig. 5(b) shows the microstructure of the HAZ. The HAZ and parent material were found to have similar microstructures as no deformational action from the tool is felt in this zone. Fig. 5(c) shows the plastically strained microstructure of the TMAZ. This was due to plastic strain induced by the mechanical action of the tool. Average grain size in the TMAZ was found to be similar to the parent material however a wider range of grain size was apparent throughout the TMAZ. Fig. 5(d) shows the fine equiaxed grain structure of the NZ.

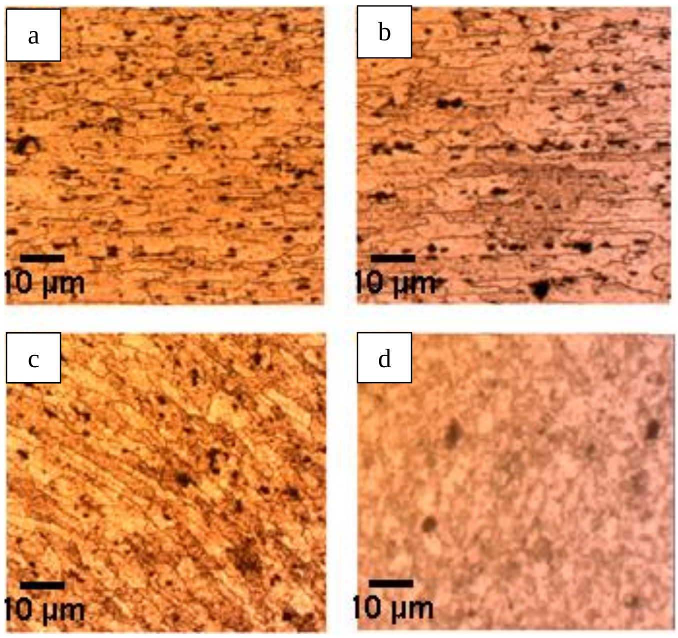

Fig. 5 Grain morphology at 50× magnification of a) Parent material b) HAZ c) TMAZ d) NZ

The grain morphologies found in the various weld zones were qualitatively similar the same regardless of the pin used. Grain size in the NZ seemed to vary slightly as a result of pin profile (Table 2). The average grain size in the NZ for the square, tapered cylinder and triflute pins was calculated as 2.19, 2.3 and 2.23µm respectively. The differences in NZ grain size may have been as a result of the increased plastic deformation and stirring generated by the flutes in the triflute design and the flat faces of the square pin design.

Table 2 Variation in grain size in the nugget zone

	Location in Nugget Zone	Grain Size (µm) Min	Max	Average
Square	Top	1.60	3.47	2.23
	Right of Centre	1.60	4.29	2.20
	Centre	1.62	3.42	2.24
	Left of Centre	1.64	3.42	2.09
	Bottom	1.60	3.50	2.16
Tapered Cylinder	Top	1.61	3.66	2.17
	Right of Centre	1.61	5.00	2.46
	Centre	1.60	4.00	2.18
	Left of Centre	1.64	5.43	2.43
	Bottom	1.60	3.36	2.24
Triflute	Top	1.60	3.36	2.23
	Right of Centre	-	-	-
	Centre	1.60	3.46	2.17
	Left of Centre	1.60	5.01	2.35
	Bottom	1.61	3.85	2.17

Figures 6, 7, and 8 show the measured hardness values recorded on the grid for the three tools in question. The measured hardness across each of the weld zones is below that of the parent material. This suggests that the strength of the weld will be lower than the parent material strength.

Hardness decreases from the parent material into the HAZ and increases from the HAZ into the NZ. Relatively constant hardness is found across the NZ.

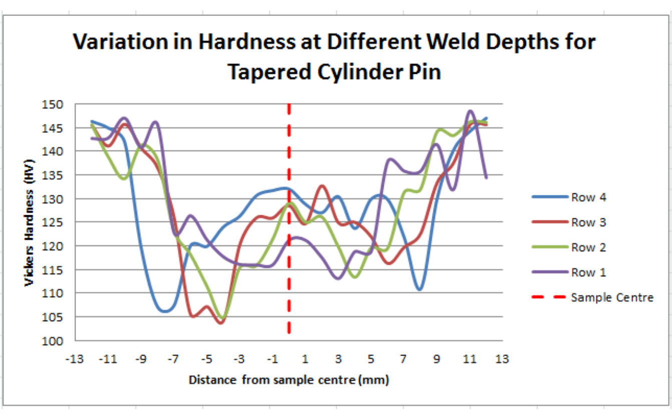

Fig. 6 Tapered cylinder hardness data at different heights in the weld thickness

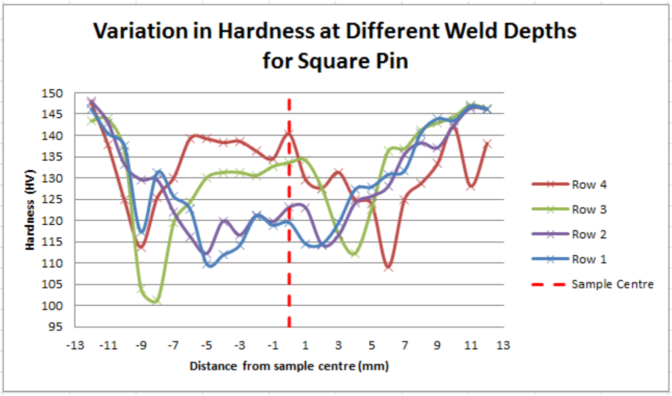

Fig. 7 Square hardness data at different heights in the weld thickness

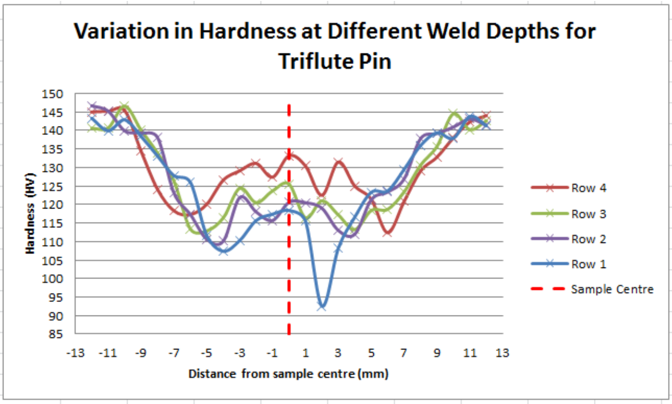

Fig. 8 Triflute hardness data at different heights in the weld thickness

4 CONCLUSION

Flat plates of AA2024-T3 (4.8 mm thick) were butt welded using Friction Stir Welding. Three pairs of plates were welded under the same operating conditions but with differing pin profiles. The pin profiles used were tapered cylindrical, square and tri-flute. A scroll shoulder element was used for each case.

In summary, the main conclusions drawn from this work are:

1. The microstructure analysis showed a zonal transition from the unaffected parent material to a HAZ, a TMAZ, and a NZ in the centre of the weld.
2. Measured hardness varied through each FSW zone. The hardness in each zone was below that of the parent material.
3. The HAZ had the lowest hardness across the weld profile for each pin type tested.
4. The cylindrical pin produced a tunnel defect due to a lack of plastic deformation. Pin profiles with flats and flute produced a more consolidated joint.

5 REFERENCES

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