A STUDY ON INTERNAL DEFECTS IN FRICTION STIR WELDING OF ALUMINIUM ALLOYS

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ABSTRACT

Friction Stir Welding (FSW) is a solid state welding process that offers advantages over the conventional techniques. As it is a solid state process, re-solidification defects like porosity and cracks are greatly reduced. The aim of the research undertaken was to examine weld quality of FSW joints using destructive and non-destructive methods. Welds were produced in Al 5052 and Al 2024 plates using a tapered cylinder pin profile. X-ray imaging was used to determine the weld quality of the Al 5052 joints. Cross-sectional analysis was undertaken on weld samples of Al 2024 joints. In both cases, a tunnel defect (internal defect) was found running parallel to the advancing side of each weld. This defect was located at the depth of pin penetration in the 2024 joints. It was found that the size of the defect could be reduced by altering operating parameters and weld path. Tests undertaken on the Al 2024 plates showed that that defect free welds can be produced by using pin profiles which encourage greater plastic deformation.

KEYWORDS: Friction Stir Welding; Weld Quality; Internal Defects

1) INTRODUCTION

FSW was developed by the Welding Technology Institute in the UK in 1991 for use on materials which were previously classified as being non-weldable by conventional fusion welding [1]. Such materials include non-ferrous materials like aluminium and magnesium alloys, and copper [2]. Traditional methods of welding produce poor quality welds in these materials. Oxide layers can form on the workpiece surface while cracks and porosity can develop in the fusion zone during the solidification process [3-5]. These defects are considerably reduced in FSW as it is a solid state process i.e. the melting temperature of the material is never reached.

FSW presents advantages in quality, costs and processing facility. This allows for applications in the automotive, structural and aeronautics industries when the conventional welding process are unattractive [6-9].As no melting occurs in FSW, the energy required to weld is considerably smaller than conventional methods. Furthermore, the heat affected zone and residual stresses associated with welding are reduced. As a result, the quality and reliability of the weld joint increases [10].

Figure 1 shows a schematic drawing of the FSW process.

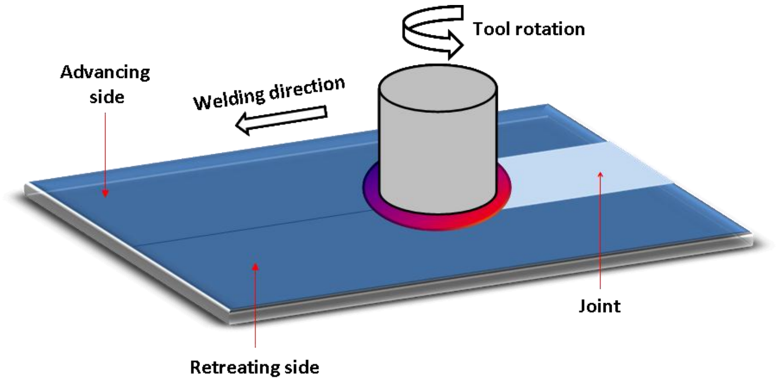


Fig. 1 Schematic of FSW process

The FSW tool is made up of a profiled pin and shoulder and is not consumed in the process. During the process the tool is rotated at high speeds and plunged into the joint line of the sheets to be welded. Friction at the tool-sheet interface produces localized heating that softens the material around the tool. The rotational action of the tool mixes the softened material together as it advances along the joint line, thus producing a consolidated weld.

This paper describes research undertaken into FSW in Trinity College Dublin (TCD) and the CEFCON lab of the Federal University of Rio de Janeiro (UFRJ) in Brazil. Research in UFRJ was undertaken into non-destructive testing of weld quality in Al 5052 joints. Research in TCD focused on microstructural analysis of weld cross sections with varying pin profiles. The aims of this research were to:

1) Observe the influence of operating parameters on weld quality.
2) Observe the influence of weld path on weld quality.
3) Determine the effect of tool pin on weld quality.

2) EXPERIMENTAL PROCEDURE

2.1 Aluminium alloy 5052

FSW was conducted on aluminium alloy 5052 plates using an adapted CNC milling machine. The shoulder diameter was 12.5 mm. Both the diameter and total length of the pin were 4.5 mm. A tapered cylinder pin with a cone angle of 30˚ and a height of 0.9 mm was used. Simple linear and linear reverse weld paths (see Table 1) were performed. For each weld path two welds were produced using different operating parameters. The first welds were produced at rotational and translational speeds of 1000 rpm and 75 mm/mm respectively (OP1). The second welds were produced at rotational and translational speeds of 1500 rpm and 150 mm/min respectively (OP2). X-ray images were used to evaluate the influence the weld path and the operating parameters have on the weld quality.

Table 1 Weld paths

Simple linear	Linear reverse
←	↔

2.2 Aluminium alloy 2024

A Corea F3UE vertical milling machine was modified for FSW applications. Aluminium alloy AA2024-T3 plates were butt welded using three different tool pin profiles: tapered cylinder, triflute and square. Each pin was 4.6mm in length. The swept diameter of the tapered cylinder and triflute pins tapered from 7mm (at the shoulder) to 2.69mm. The swept diameter of the square pin was 7mm. A scrolled shoulder was used in this investigation as no tilt angle was required. Rotational and translational speeds were 450rpm and 180 mm/min respectively. Samples were cut from the cross-section of each FSW joint. Samples were polished to remove all tool marks and scratches. The samples were then etched using Keller’s reagent. Samples were viewed using a Leica DM LM microscope.

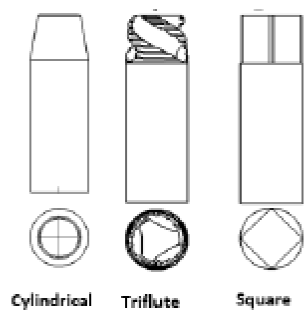


Fig. 2 Tapered cylinder, triflute and square pin profiles

3) RESULTS

3.1 Aluminium alloy 5052

The x-ray images of the two weld paths can be seen in Table 2. The letters A and R in the images identifies the advancing and retreating side respectively. In the images of linear reverse path the direction and the advancing and retreating side correspond to the last passage.

Table 2 X-ray images of welds produced by simple linear and linear reverse welding

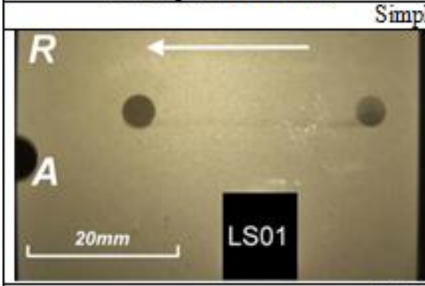
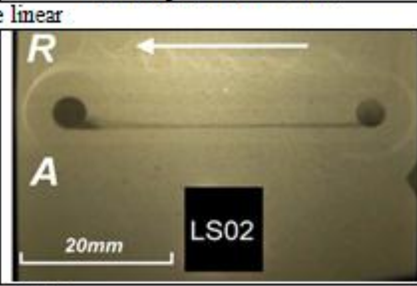
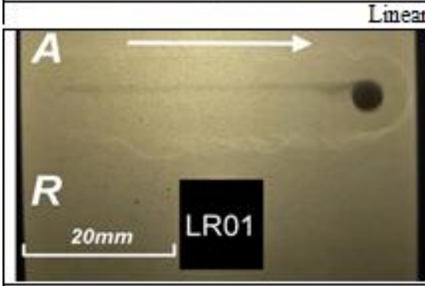
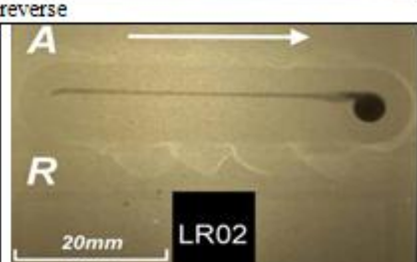
Operating Parameters 1 (OP1) (1000 rpm, 75 mm/min)	Operating Parameters 2 (OP2) (1500 rpm, 150 mm/min)
Simple linear	
	
Linear reverse	
	

Table 2 shows an internal defect running along the length of the weld for each weld path. The defect is also apparent for both sets of operating parameters.

3.2 Aluminium alloy 2024

Images of the cross-sections corresponding to each pin can be seen in Table 3. Images of a defects found in the weld produced by the tapered cylinder pin can be seen in Fig. 3&4.

Table 3 Weld cross-sections produced by each pin profile

Pin Profile	Macrostructure
Tapered Cylinder	
Triflute	
Square	

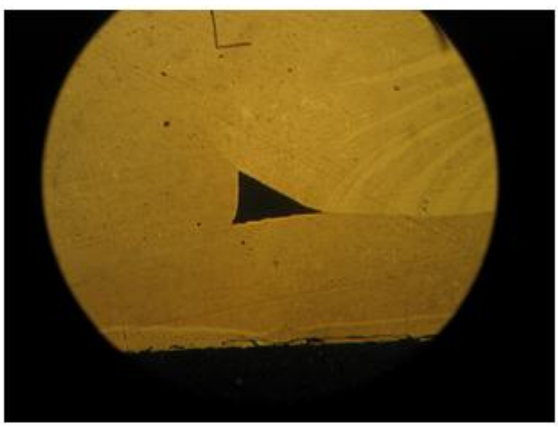


Fig. 3 Tunnel defect at depth of pin penetration produced by tapered cylinder pin at ×50 magnification.

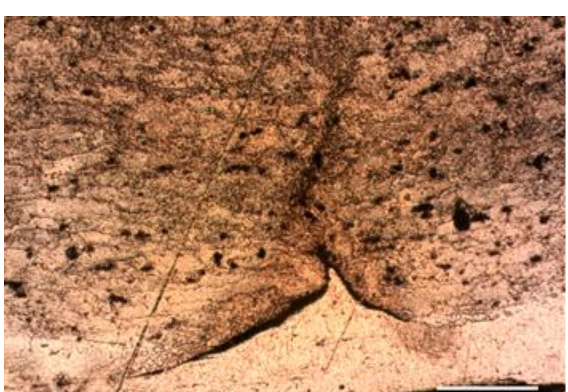


Fig. 4 Remnants of joint line at the bottom of the weld produced by tapered cylinder

4) DISCUSSION

4.1 Aluminium alloy 5052

X-ray images in Table 2 show an internal void running along the length of each weld. The void appears on the advancing side of the tool in both cases. The linear reverse weld path involves a second pass of the tool along the joint line. In the second run however the tool translates the joint line in the opposite direction. Since the direction of tool rotation does not change between the first and second pass, the advancing and retreating sides of the tool are switched in the reverse direction. This explains why the void is found at the top of the image for linear reverse and on the bottom of the image for simple linear. One advantage of the linear reverse weld path is that it removes one of the keyholes left behind by the tool pin. These keyholes can be seen at the end of the welds in Table 2.

When using OP1, the tunnel defect is reduced in size when compared with using OP2. This is true for both the simple linear and linear reverse weld paths. Heat input into the FSW zone is greater for lower rather than higher translational speeds. At high speeds insufficient heating and mixing of the material can cause internal voids [11-12]. Kim *et a.l* [12] describe this as an abnormal flux/deformation of the material by the temperature gradient between the top and the bottom of the weld.

4.2 Aluminium alloy 2024

On observation of weld samples, the square and triflute pins produced defect free welds. As mentioned previously, the weld produced by the tapered cylinder pin contained a defect. This defect is located where the pin reached maximum penetration into the plate depth and can be seen in Table 3 and Fig. 3.This defect was observed in both samples cut from the weld; indicating that it is a tunnel defect running through the weld. This defect was also observed in the research conducted on the Al 5052 (See Table 2).

Defects such as these are attributed to inadequate mixing and material deformation. Fig. 4 shows that, in addition to tunnel defects, remnants of the joint line can be seen in the Tapered cylinder weld sample. This defect is again a result of inadequate material deformation due to the smooth surface area of the tapered cylinder pin.

Welds produced by the square and triflute pins were found to be defect free. This is because, unlike the square and triflute pins, the tapered cylinder pin has a smooth rounded surface. The pulsation action of the square pin as it rotates ensures sufficient mixing of softened material. The flutes in the Triflute design serve the same purpose. Macrostructural images of the weld cross-sections produced by each pin can be seen in Table 3.

5) CONCLUSION

In relation to the aims of this research and based on observed results; the following conclusions were drawn:

1) Tunnel defects were found on the advancing side of welds produced by a tapered cylinder pin in both Al 5052 and Al 2024 joints. Furthermore joint line defects were also observed in the Al 2024 cross section.

2) Regardless of the path the weld takes a tunnel defect is found on the advancing side of the welds produced by the tapered cylinder pin.
3) By varying the operating parameters the size of the defect was reduced but not eliminated.
4) Defect free welds were produced by changing the profile of the pin.

6) ACKNOWLEDGEMENTS

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7) REFERENCES

[1] W. M. Thomas, E. D Nicholas, J. C. Needham, M. G. Murch, P. Temple-Smith and C. J. Dawes: ‘Friction stir butt welding’, Int. Pat. Application no. PCT/GB92/02203; UK Pat. Application no. 9125978.8, 1991; US Pat. 5460317, US Patent Office, Alexandria, VA, 1995.

[2] Soundararajan V, Zekovic S, Kovacevic R. Thermo-mechanical model with adaptive boundary conditions for friction stir welding of Al 6061. Em: International Journal of Machine Tools and Manufacture, V45, 1577–1587p, 2005.

[3] P. Thornton, A. Krause, R. Davies. Aluminium spot weld. En: Weld Journal. Vol. 75, 1996, p101-108.

[4] A. Gean, S. Westgate, J. Kucza, J. Ehrstorm. Static and fatigue behavior of spot welded 5182-0 aluminium alloy sheet. En: Weld Journal. Vol. 75, 1999, p. 80-86.

[5] Dehghani M, Amadeh A, Akbari S. Investigations on the effects of friction stir welding parameters on intermetallic and defect formation in joining aluminum alloy to mild steel. Materials and Design, V49, 433–441p, 2013.

[6] Long T, Tang w, Reynolds A. Process response parameter relationships in aluminium alloy friction stir welds. Science and Technology of Welding and Joining. V12, N4, 311-317p, 2007.

[7] Kumar R, Singh K, Pandey S. Process forces and heat input as function of process parameters in AA5083 friction stir welds. Em: Transactions of Nonferrous Metals Society of China, V22, 288-298p,
2012.

[8] T. Iwashita, “Method and apparatus for joining”. Patente 6601751 B2, US, 2003.

[91] Nandan R, DebRoy T, Bhadeshia H. Recent advances in friction-stir welding – Process, weldment structure and properties. Progress in Materials Science. V53, 980–1023p, 2008.

[10] Colegrove P.A, Shercliff H. R. Experimental and numerical analysis of aluminium alloy 7075-T7351 friction stir welds. Science and Technology of Welding and Joining, V.8, No. 5, 360-368p, 2003.

[11] Russel M J. Development of improved tool design and parameters for the friction stir butt welding of 1.2, 6 and 25mm thickness aluminum alloy, England: TWI Rep. n 801, 2004

[12] Kim Y.G, Fujii H, Tsumura T, Komazaki T, Nakata K. Three defect types in friction stir welding of aluminum die casting alloy. Materials Science and Engineering A 415, pp 250–254, 2006