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MATERIAL FLOW BEHAVIOUR AND MICROSTRUCTURAL INTEGRITY OF FRICTION STIR BUTT WELDMENTS

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Abstract

The present investigation is concerned with basic studies of the plasticised weld formation and microstructural development in the heat affected zone (HAZ) of friction stir butt welded Al-Mg-Si and Al-Cu alloys. For these experiments, a commercial AA6060-alloy was welded to an Al-1.8wt%Cu alloy. The materials were received in the form of 3mm gauge extrusions and were welded in the as-extruded T4 condition. The friction stir welds were then etched to reveal the material flow pattern for different stir tool geometries and welding conditions.

In addition, similar friction stir welds were carried out on commercial 3mm gauge AA6082-alloy flat bar extrusions in the T4- and T5-temper condition. The welds were subsequently subjected to heat treatment, metallograpic examination and mechanical testing. The results from the optical microscope examination revealed that the plastic deformation occurring during the welding operation strongly alters the weld formation. The subsequent Vickers hardness measurements of the weld HAZ showed that the width is interrelated to the stir tool diameter and the welding speed. It follows that the resulting HAZ strength level is mainly controlled by the dissolution and precipitation reactions taking place in the material during the weld thermal cycle. Consequently, the as-welded HAZ tensile strength depends on the initial metal temper condition. A 90% HAZ strength recovery in materials welded in the T4-temper condition can be achieved by the use of an appropriate post weld ageing treatment, which involves artificially ageing at 185°C for 5 hours.

The observed material flow pattern can be linked to the weld formation which occurs in extrusion dies. The friction stir concept is therefore proposed as a method to study weld formation in aluminium alloys that are difficult to extrude through port-hole dies.

Introduction

Friction stir welding is a joining method that produces solid-phase, low distortion, welds which are achieved with relatively low costs, and on simple and energy efficient mechanical equipment (e.g. a milling machine). The technique offer new design and production welding opportunities.

This solid state welding process is not constrained by need for filler wire, shielding gas or expensive power supply requirements and can be performed on equipment already existing today. The formation of the friction stir welds have many similarities with extrusion seam and charge welds generated in the weld chamber of an extrusion die. An increased understanding of the friction stir process technology can therefore be gained through investigation of the weld formation in extrusion dies for production of aluminium profiles. On the other hand, the welding process can be used as a tool for studying the weld formation in alloys that are difficult to extrude through port hole dies.

Friction Stir Welding

Friction stir welding is a solid-state welding process that produces coalescence by the heat developed from a mechanically induced rubbing motion through plasticisation and consolidation of the material about the butt joint line [1]. The friction stir tooling consists of a butt-end rod of large diameter, or so-called shoulder, and a pin which is connected to it. The operation is achieved by inserting the rotating pin of hard metal at the start of the joint, equal to the joint depth required. When the pin and shoulder is rotated, it friction heats an annular region of the aluminium alloy, rapidly producing a tubular shaft of plasticised metal around the pin. As the pin is moved in the direction of welding, the pressure provided by the shoulder and the leading face of the pin forces plasticised material to the back of the pin, where it consolidates and cools. Filler material, flux or shielding gas are not required by this process. A schematic illustration of the friction stir process and the tooling applied, is shown in Figure 1.

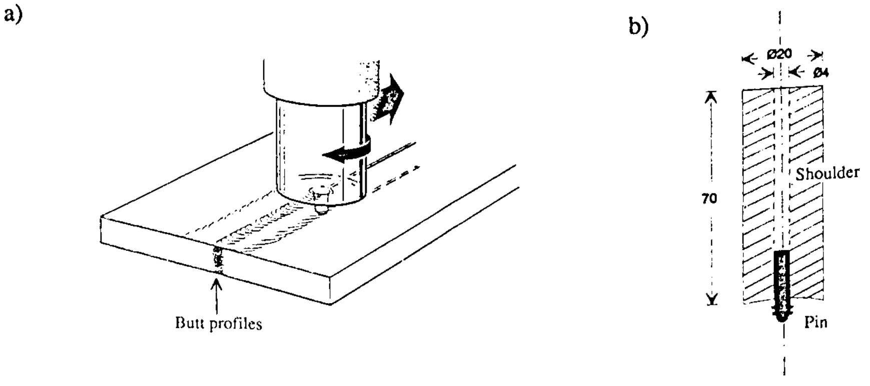

Figure 1. A schematic illustration of a) the friction stir process for joining of flat bar extrusions and b) the tooling applied.

Materials and Experimental Procedure

A summary of materials and experimental procedures used in this investigation is given below.

Contrast Material

For evaluation of the material flow in the friction stir weld zone, an Al-1.8wt%Cu alloy was welded to an AA6060 alloy extrusion. Both these alloys are known to have similar flow stress characteristics at extrusion temperature.

The AA6082-alloy

The AA6082 alloys were received in the form of extruded 3mm gauge flat bar. The materials were welded in both the as-extruded and artificially aged condition (i.e. T4 and T5- temper, respectively). Mechanical data for the base material is given in Table I.

Table I. Mechanical properties of 6082-alloys in the as-extruded and artificially aged condition [2].

Material	Temper	$R_{p0.2}$ [MPa]	R_m [MPa]	A_5 [%]
6082.50	T4	130	200	16
	T5 (T6)	255 (285)	295 (310)	8

Friction Stir Welding Equipment and Tooling

Rotation of the tooling was achieved by means of a 1.5kW (2HP) *Bridgeport* milling machine. The tooling used during this investigation is shown in Figure 1.b) and consists of a shoulder of Ø20mm high-strength die steel (H13) with a bowing on the friction face. The different pins used were Ø4mm (HSS) and had circumferencial fins projecting radially from the outer diameter.

Microstructure Characterisation

The experimental welds carried out on A6082 alloys were sectioned normal to the welding direction for conventional microstructure analysis in an optical microscope. In addition, friction stir welds carried out with the contrast material were subsequently etched with a macro etchant ($1/3HCl+1/3HNO_3+1/3H_2O$) to reveal the flow paths for different welding parameters applied.

Mechanical Testing

Quantitative information about the heat affected zone strength distribution, both prior and subsequent to the post weld ageing treatment (PWAT) was obtained from a series of Vickers hardness measurements (5kg load) carried out over the cross section area. Three point bend tests (Ø9mm) and tensile tests were also carried out in both T4- and T5-temper conditions on selected welds to achieve comparable data for the HAZ yield and tensile strength.

Experimental Results and Discussions

Surface appearance of Friction Stir Welds

In Figures 2. a-b) a typical surface appearance of the top and bottom of a friction stir weld is shown, respectively. As can be seen the surface appearance at the top is very smooth compared to conventional welds made on the same type of material, whereas the surface appearance at the bottom is similar to typical laser weldments where narrow weld pools are achieved.

a) Top surface of friction stir weld

b) Bottom surface of friction stir weld

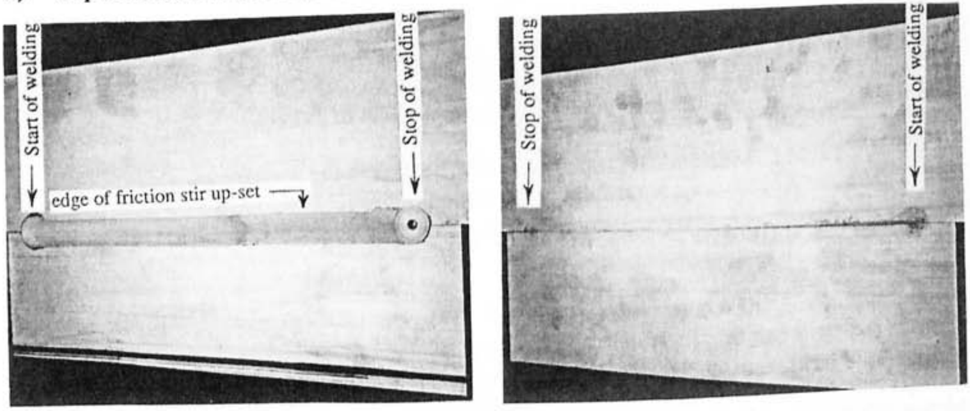

Figure 2. Typical surface appearance of a friction stir weld a) top of weld, b) bottom of weld.

Material Flow during Friction Stir Welding

The optical microstructure investigation of the friction stir welded contrast material to the AA6060 alloy revealed a marked change in the material flow as the welding speed increased. The change in etching response between the two welded components showed that the flow of material, forced by the fin-shaped pin, generates a self-clamping effect between the two previous butt edges involved. This is shown respectively in Figures 3. a) and b).

a) Pin movement : 0.8mm/revolution

1mm

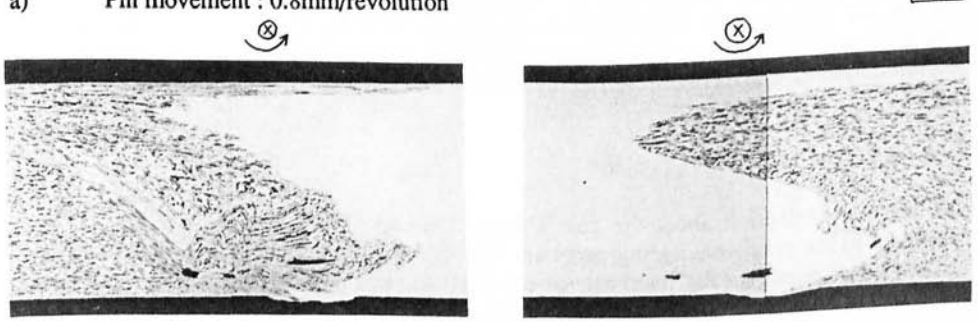

Figure 3.a). Friction stir weld formation in a AA6060 to Al-1.8wt%Cu weldment, at welding speed w=0.8m/min at rotational speed n=1000revolutions/min .

The left micrograph in Figure 3.a) shows the shear flow of the contrast material in the highly deformed part of the HAZ compared to the rotational movement, whereas the right micrograph shows the down-flow of the contrast material in the less deformed right hand-side part of the HAZ. In both cases the welding direction is down in the paper-plane. Figure 3.a) also shows the presence of small unwelded grooves in the bottom of the weld bead, which are typical in high speed friction stir welds. Figure 3.b) shows the same material combination welded at a lower speed, when a sound weld with no grooves is achieved.

b) Pin movement : 0.3mm/revolution 1mm

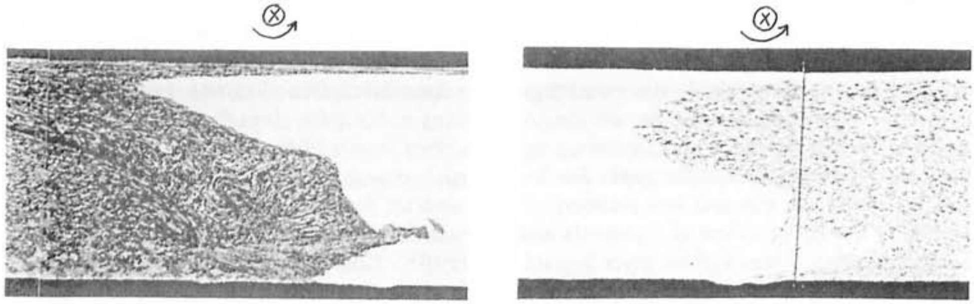

Figure 3.b). Friction stir weld formation in a AA6060 to Al-1.8wt%Cu weldment, at welding speed w=0.3m/min at rotational speed n=1000revolutions/min .

Microstructure in AA6082-alloy

Similar experiments were carried out with AA6082-alloys. The optical micrographs revealed the presence of a recovered fine-grained microstructure in the weld bead. The typical grain size is 3-6µm. However, the distribution of alloying elements is not altered during the welding operation, since no fusion takes place. The weld microstructure from the optical examination is shown in Figure 4.a), together with a schematic illustration of the different reaction zones in the HAZ.

a)

b)

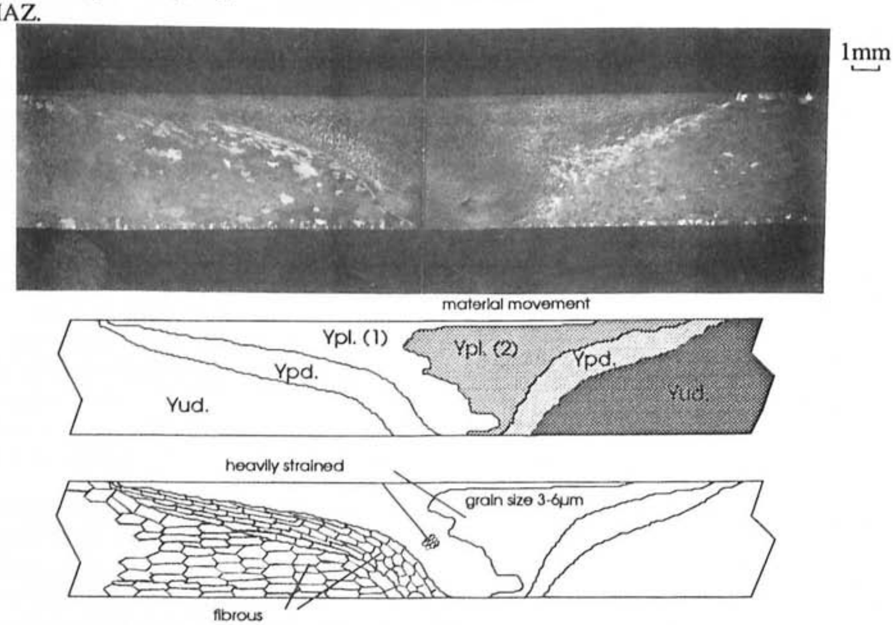

Figure 4. a) Optical micrograph and b) a schematic illustration of the different reaction zones in the HAZ of friction stir welded AA6082-alloys ; $Y_{pl.(1-2)}$: fully plasticised fine-grained region in extrusion (1) and (2) respectively, Y_{pd} : partly deformed coarser grained region, and Y_{ud} : undeformed HAZ.

Comparison with Extrusion Welds in Hollow Aluminium Profiles

Since friction stir welding is a solid state welding process that essentially means bringing two identically clean metallic surfaces to a distance of the order of the interatomic spacing, the grain boundaries in the highly deformed region can form when free electrons can jump across the interface. When surface layers are present, pressure welding involves the following stages : matching of surface asperities, splitting up of surface layers, formation of ligaments and extrusion of base metal into the gaps. For friction stir welding, the latter implies stirring of the material round the pin and compression of the material forced by the friction face of the shoulder. The area fraction of ligaments will increase during further deformation (i.e. at slow welding speeds), if the surface layer is hard and brittle. Conversely a soft and ductile layer tends to increase its own area fraction at the expense of the ligaments.

According to *Akeret* [3], extrusion welding is a kind of a solid state bonding process. The criterion for creating a successful weld is therefore, as for friction stir welding, an interface distance, between the two bodies to be joined, in the order of the interatomic distance. Interatomic forces will then create a perfect metallic bond. This mean that there is neither a requirement to obtain high enough temperatures so that the material melts, nor a time requirement for diffusion welding to take place.

Since the only requirement for a perfect bond is to obtain good contact between the metal surfaces, the pressure (e.g. deformation strain rate) is the primary parameter. The temperature is then only a secondary, indirect parameter since the flow stress reduces with increasing temperature. The required pressure will consequently decrease accordingly. The duration of the pressure on the surfaces is also an indirect parameter. However, the plastic deformation of the base material is time dependent at typical extrusion temperatures, meaning that there will be an indirect minimum required contact time for weld formation. Figure 5. shows the different deformation zones in a typical aluminium extrusion charge weld. By comparison with Figure 4.b) the different reaction zones seems to be present in both cases.

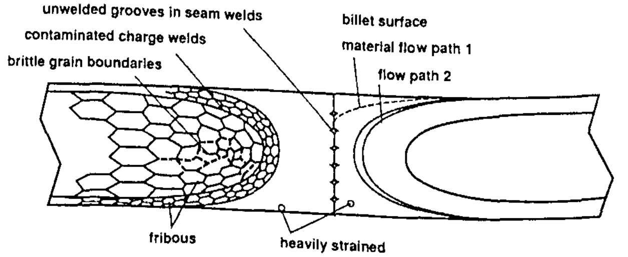

Figure 5. Different reaction zones in an aluminium extrusion weld.

The observed material flow pattern can therefore be linked to the extrusion weld formation which occurs in dies. As seen from the tensile tests, measurements of the HAZ strength distribution in AA6082-T4 friction stir weldments followed by artificial ageing, show that 90% of the base material strength can be achieved. The same %-wise reduction in yield and tensile strength is also experienced near the apex of an extrusion charge weld, at a distance from the die stop in extrusion of aluminium alloys [3]. However, the marked decrease in elongation experienced with charge welds is not present in friction stir weldements. This is due to a fine distribution of surface oxide particles in a fiction stir weld but also due to the rapid thermal heating and cooling cycles that takes place.

HAZ Hardness Distribution in AA6082-alloys

In friction stir welding of 6xxx-alloys, dissolution of Mg_2Si-precipitates will occur to an increasing extent in the peak temperature range from about 250°C to 500°C. This results in a continuous decrease in the HAZ hardness for the T5 temper material, as seen in Figure 6. During the rapid cooling of the friction stir weld, some external plastic straining may occur by generation of dislocations in the weld bead. This strain hardening contribution is however too small to compensate for the observed strength loss associated with dissolution of hardening Mg_2Si precipitates in the weld bead.

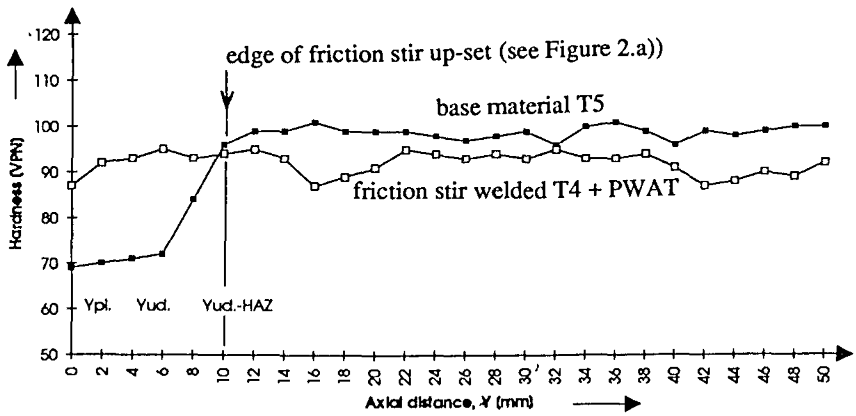

Figure 6. Measured HAZ top bead hardness distribution in friction stir welded components of the AA6082-alloy in the T5-temper condition and the T4-temper (followed by a post weld ageing treatment) condition.

HAZ Strength Distribution in AA6082-alloys

A full HAZ strength recovery can be achieved by the use of an appropriate post weld heat treatment procedure, which involves solution heat treatment at 585°C for 3 hours followed by artificially ageing at 185°C for 5 hours. This means that the observed strength reduction is not permanent. This is also in agreement with previous investigations with continuous drive friction welding experiments carried out on round bars of an AA6082 alloy and Al-SiC metal matrix composites [4].

However, in production of welded aluminium composite structures it is usually not possible to carry out a full post weld heat treatment. On the other hand, pre-fabrication of aluminium sections during the storage time prior to ageing in an extrusion processing line is possible. The bend and tensile strength data presented in Table II show that a 90% HAZ strength recovery in materials welded in the T4-temper condition can be achieved by the use of an appropriate post weld ageing treatment (PWAT), i.e. only artificially ageing at 185°C for 5 hours. The mean value of three tensile tests are given in Table II.

Table II. : Mechanical properties of friction stir welded components and base material.

Temper condition	$R_{p0.2}$ [MPa]	R_m [MPa]	A_5 [%]	Bend testing (Ø9mm)
Friction stir welded (T5)	124.6	195.8	9.8*	180° - no fracture
Friction stir welded (T4)	81.7	166.8	23.4*	180° - no fracture
Friction stir welded (T4) +PWAT	227.0	249.8	7.6*	60° - fract. in w.
Base metal (T5)	258.8	280.6	12.4	60° - fracture

* : All welded extrusions failed in the HAZ outside the edge of the friction stirred zone.

Conclusions

The basic conclusions that can be drawn from this investigation are the following :

The friction stir welding process has proved to be a useful method for solid state joining of 6xxx-alloy extrusions at high welding speeds.

In general, the local plastic deformation occurring during the welding operation strongly alters the material flow in the weld bead, resulting in a fine-grained microstructure.

The characteristic microstructural zones of friction stir weldments correspond to the different deformation zones observed in extrusion charge welds of aluminium alloys. The observed material flow pattern can therefore be linked to the weld formation which occurs in extrusion dies.

The resulting HAZ strength reduction is mainly controlled by dissolution and re-precipitation reactions taking place in the material during the weld thermal cycle. As a result, a 90% HAZ strength recovery can be achieved by the use of an appropriate post weld artificial ageing treatment at 185°C for 5 hours.

Acknowledgements

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