Friction Stir Welding - Recent Developments in Tool and Process Technologies

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Friction stir welding (FSW) was invented by TWI in 1991[1] and substantial development has been conducted subsequently. It allows metals, including aluminium,[2-12] lead,[13] magnesium,[14] steel,[15] titanium,[16] zinc, copper,[17] and metal matrix composites[18,19] to be welded continuously. Many alloys, which are regarded as difficult to weld by fusion processes, may be welded by FSW. The basic principle of the FSW process is shown in Figure 1.

A non-consumable rotating tool is employed of various designs, which is manufactured from materials with superior high temperature properties to those of the materials to be joined. Essentially, the probe of the tool is applied to the abutting faces of the workpieces and rotated, thereby generating frictional heat, which creates a softened plasticized region (a third-body) around the immersed probe and at the interface between the shoulder of the tool and the workpiece. The shoulder provides additional frictional treatment to the workpiece, as well as preventing plasticized material from being expelled from the weld. The strength of the metal at the interface between the rotating tool and the workpiece falls to below the applied shear stress as the temperature rises, so that plasticized material is extruded from the leading side to the trailing side of the tool. The tool is then steadily moved along the joint line giving a continuous weld.

Although incipient melting during welding has been reported for some materials, FSW can be regarded as a solid state, autogenous keyhole joining technique. The weld metal is thus free from defects typically found when fusion welding, e.g., porosity. Furthermore, and unlike fusion welding, no consumable filler material or profiled edge preparation is normally necessary.

The process has already made a significant impact on the aluminium-producing and user industries worldwide and FSW is now a practical technique for welding aluminium rolled and extruded products, of thickness ranging from 0.5 to 75 mm. The present paper describes recent developments in FSW tool design, as this is the key to the successful application of the process.

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![Fig. 1. Principle of friction stir welding.](image1)

Tools and Techniques: Conventional Rotary Welds: Although FSW consistently gives high quality welds, proper use of the process and control of a number of parameters is needed to achieve this. A key factor in ensuring weld quality is the use of an appropriate tool and welding motion.

The importance of the tool is illustrated in the following recent example involving the lap welding of 6 mm 5083-O, aluminium alloy wrought sheet. In preliminary trials a conventional cylindrical threaded pin probe tool was used which gave a good as-welded appearance. A typical pin type probe is shown in Figure 2.

However, bend testing showed the weld to be weak due to excessive thinning of the top sheet and thickening of the bottom sheet caused by a pressure differential during welding (see Fig. 3).

The failure followed the original interfacial surface oxide layers, which in 5083-O condition aluminium alloy, are known to be particularly tenacious. The above problems were caused because, although the tool employed gave satisfactory welds when butt-welding plate components, its use when lap welding was inappropriate. Lap welding requires a modified tool to ensure full disruption of the interfacial oxide layers and a wider weld than is required when butt-welding.

A transverse macrosection taken from a weld produced with a pin type probe shows extreme plate thinning on the retreating side and a serious hook feature on the advancing side of the weld, whilst porosity is also clearly visible (see Fig. 4).

![Fig. 2. Cylindrical threaded pin type probe.](image2)
This example illustrates that good welding can only be achieved by the use of a tool appropriate to the application.\textsuperscript{38–22}

With regard to modification of the notch at the edge of the weld, special tools and techniques are under development, which will accomplish this, specifically the Flared-Triflute\textsuperscript{TM} probe Skew-stir\textsuperscript{TM}, and Re-stir\textsuperscript{TM}. The forms of the first two tools are shown in Figures 5 and 6 whilst detailed explana-

Fig. 6. Basic principle of skew-stir\textsuperscript{TM}.

tion of the Re-stir\textsuperscript{TM} technique is described later, and is illus-

Triflute type probes can be designed with any combination of neutral, left or right-handed flute, or ridge grooves to suit the material and joint geometry being welded. Moreover, Figure 5d shows that the individual ridges on the probe can be regarded as independent features. This effectively enables neutral, left or right hand inclined ridge grooves to deflect plasticized material and move the fragmented oxides upward or downward as required with every 120 degree part rotation of the probe.

Skew-stir\textsuperscript{TM} Lap Weld: The skew-stir\textsuperscript{TM} variant of FSW differs from the conventional method in that the axis of the tool is given a slight inclination (skew) to that of the machine spindle, as shown in Figure 6.

A lap joint made with a Flared-Triflute\textsuperscript{TM} probe is shown in Figure 7a. In this example, the width of the weld region is 190% of the plate thickness and little upper plate thinning is apparent. (The corresponding weld width achieved when using a conventional threaded pin probe is 110%). The notch at the edge of the weld achieved using this tool is shown in Figures 7b,c. It should be noted that the notch at the retreating side (Fig. 7b) does not lie in a direction perpendicular to the sheet interface as it does in a weld made with a conventional pin probe. The notch at the advancing side (Fig. 7c), however, turns in a direction perpendicular to the sheet interface, but this is much less pronounced than when a conventional pin is used.

Promising results have also been achieved with the A-Skew\textsuperscript{TM} tool.\textsuperscript{23} Figure 8 shows a weld made at the same conditions as Figure 7, but using this tool. Figures 8b,c show an improved orientation of the edge notch, even on the advancing side.

Reversal Stir Welding – Re-stir\textsuperscript{TM}: Introductory Remarks: The continuing development of friction stir welding (FSW) has led to a number of variants of the process. The following describes preliminary studies being carried out on Re-stir\textsuperscript{TM} welding at TWI. The salient features of the Re-stir\textsuperscript{TM} welding technique are illustrated in Figure 9. This illustration applies to both angular reciprocating, where reversal is imposed within one revolution, and rotary reversal, where reversal is imposed after one or more revolutions.

The use of the Re-stir\textsuperscript{TM} welding technique provides a cyclic and essentially symmetrical welding and processing treatment\textsuperscript{12,24,25} Most problems asso-
ciated with the inherent asymmetry of conventional rotary FSW are avoided.

The results from preliminary Re-stir™ welding trials with 6 mm thick 5083-O condition aluminium alloy show considerable promise. A transverse macrosection of a Re-stir™ butt weld made in this material using a conventional MX-Triflute™ probe is shown in Figure 10. The weld region is essentially symmetrical in shape tending to become narrower towards
Surface Appearance of Re-stir™ Butt and Lap Welds: Figure 11 shows the appearance of the weld surface that is formed beneath the tool shoulder produced at a welding travel speed of 1.6 mm/s (96 mm min⁻¹), using five revolutions per interval.

Figure 12 shows the detail of the surface of a weld made at 4 mm/s (240 mm min⁻¹) travel speed, using ten revolutions per interval. The fine surface ripples reveal the number of rotations and the extent of the interval, while the less frequent, coarser and wider surface ripples reveal the position of the change in rotation direction. For Re-stir™, the distance and time between each interval depends on the combination of rotational speed and the travel speed used.

Macrosections of a lap weld made by Re-stir™ are shown in Figures 13a–c. This weld was made in 5083-O condition aluminium alloy, using a Flared-Triflute™ type probe. Figure 13a shows a weld with detrimental plate thinning/hooking owing to the non-optimization of welding parameters, but does serve to illustrate the symmetrical nature of the weld produced by the Re-stir™ technique.

The longitudinal section shown in Figure 13b is taken at a position at the edge of the weld region and shows the effect of the change in the direction of rotation. The plan view of Figure 13c reveals a patterned weld region surrounded by a HAZ. There is some evidence that during the reversal stage some of the “Third-body” plasticized material close to the probe is “re-stirred” back in the opposite direction.

The Re-stir™ process requires further optimization to achieve welds of reproducibly high quality and freedom from defects, but early trials suggest benefits in terms of weld symmetry. Initial Re-stir™ work using an A-skew™ probe shows that only a slight down turn in the overlapping plate/weld interface occurs at the outer regions of the weld that should be beneficial in structural applications (cf. Fig. 4). Figures 14a–c illustrates this effect in a lap weld in 5083-O condition aluminium alloy.

This paper describes recent tool and process developments for FSW butt and lap welding, particularly when using a Flared-Triflute™ probe, and the Skew-stir™ and Re-stir™ techniques. The

the top of the plate. This is in marked contrast to conventional rotary friction stir welding in which an asymmetrically shaped weld is obtained. [8]
latter lap welding techniques gave an improvement in weld integrity; a reduction in upper plate thinning and an increased welding speed compared with the conventional pin type probe.

Although significant improvements have been achieved, additional tool development work is underway to further optimize integrity and appearance of FSW lap welds. Butt welds pro-
duced with Whorl™ and MX-Triflute™ frustum-shaped probes that gave acceptable weld quality are also described.

In addition, initial investigation of the Re-stir™ technique has demonstrated that it may offer significant benefit in generating essentially symmetrical welds and hence has the potential to overcome some of the problems associated with the asymmetry inherent in conventional rotary friction stir welds. Moreover, ongoing investigations are expected to establish the advantage of using Re-stir™ for the welding of dissimilar materials; by using more revolutions in one direction interval and less in the opposite direction interval to compensate for material with widely differing flow properties.

Although it is early days and much more development work is required before the technique can be used commercially, it seems possible that the Re-stir™ may well become the preferred option for certain butt and lap weld configurations, tailor welded blanks, compound lap, spot and welding, dissimilar materials and other material processing applications.

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**High Temperature Deformation Behavior of the Bond–Coat Alloy PWA 1370**

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The application of thermal barrier coatings (TBCs) is generally recognized as being essential to the development of high efficiency gas turbines, both for aeroplane engines and stationary use. A TBC system consists of the superalloy sub-

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