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Friction stir welding for the transportation industries

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This paper will focus on the relatively new joining technology—friction stir welding (FSW). Like all friction welding variants, the FSW process is carried out in the solid-phase. Generically solid-phase welding is one of the oldest forms of metallurgical joining processes known to man. Friction stir welding is a continuous hot shear autogenous process involving a non-consumable rotating probe of harder material than the substrate itself. In addition, FSW produces solid-phase, low distortion, good appearance welds at relatively low cost. Essentially, a portion of a specially shaped rotating tool is plunged between the abutting faces of the joint. Once entered into the weld, relative motion between the rotating tool and the substrate generates frictional heat that creates a plasticised region around the immersed portion of the tool. The contacting surface of the shouldered region of the tool and the workpiece top contacting surface also generates frictional heat. The shouldered region provides additional friction treatment to the weld region as well as preventing plasticised material being expelled. The tool is then translated with respect to the workpiece along the joint line, with the plasticised material coalescing behind the tool to form a solid-phase joint as the tool moves forward. Although the workpiece does heat up during FSW, the temperature does not reach the melting point. Friction stir welding can be used to join most aluminium alloys, and surface oxide presents no difficulty to the process. Trials undertaken up to the present time show that a number of light weight materials suitable for the automotive, rail, marine, and aerospace transportation industries can be fabricated by FSW.

Keywords: friction stir welding; transportation; solid phase

Introduction

Recently, a novel friction welding process for non-ferrous materials has captured the attention of the fabrication industry. This relatively new process called Friction Stir Welding (FSW) is a solid-phase process giving good quality butt and lap joints[1–4]. The FSW process has proved to be ideal for creating high quality welds in a number of materials, including those which are extremely difficult to weld by conventional fusion processes[5].

The basic principle of the process is illustrated in *Figure 1*. The process operates by generating frictional heat between a rotating tool of harder material than the workpiece being welded, in such a manner as to thermally condition the abutting weld region in the softer material. The tool is shaped with a larger diameter shoulder and a smaller diameter, specially profiled probe. The probe first makes contact as it is plunged into the joint region. This initial plunging friction contact heats a cylindrical column of metal around the probe as well as a small region of material underneath the probe. The depth of penetration is controlled by the length of the probe below the shoulder of the tool. The contacting shoulder applies additional frictional heat to the weld region and prevents highly plasticised material from being expelled during the welding operation. Once the shoulder makes contact the adjacent thermally softened region takes up a frustum shape corresponding to that of the overall tool geometry. The thermally softened region appears much wider at the top surface in contact with the shoulder, tapering down to the probe diameter. The combined frictional heat from the probe and the shoulder creates a plasticised almost hydrostatic condition around the immersed probe and the contacting surface of the shouldered region of the workpiece top surface. Material flows around the tool and coalesces behind the tool as relative traverse between substrate and the rotating tool takes place. Friction stir welding can be regarded as a autogenous keyhole joining technique. The consolidated welds are solid-phase in nature and do not show fusion welding defects. No consumable filler material, shielding gas, or edge preparation is normally necessary. The distortion is significantly less than that caused by any fusion welding technique.

Exploratory development work has encompassed aluminium materials from 1 to 75 mm thick.

FSW welding trials

Early exploratory development trials were carried out

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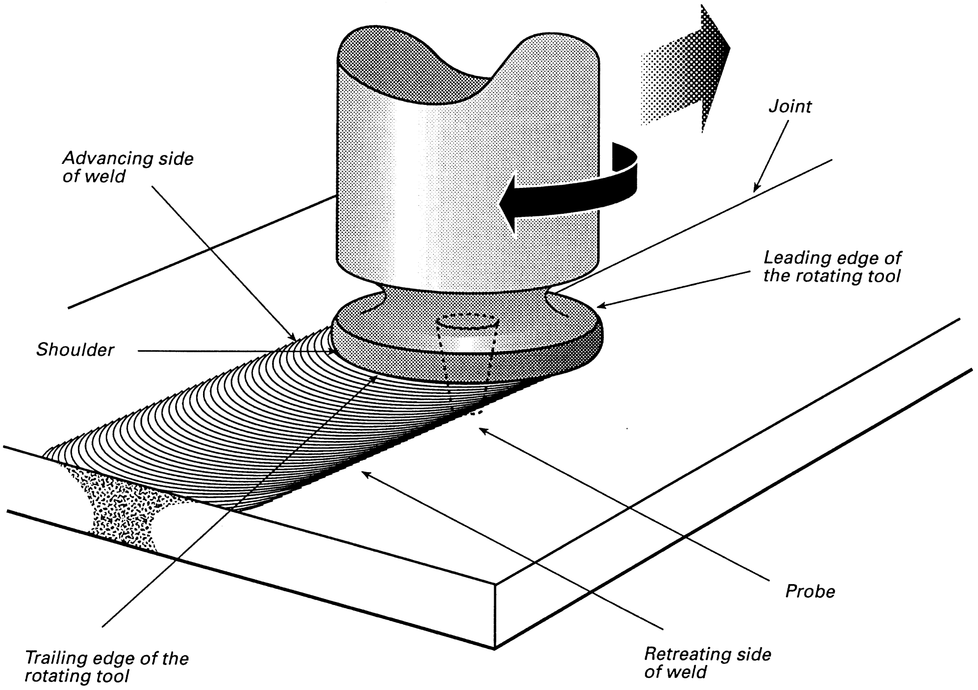


Figure 1 Friction stir welding technique

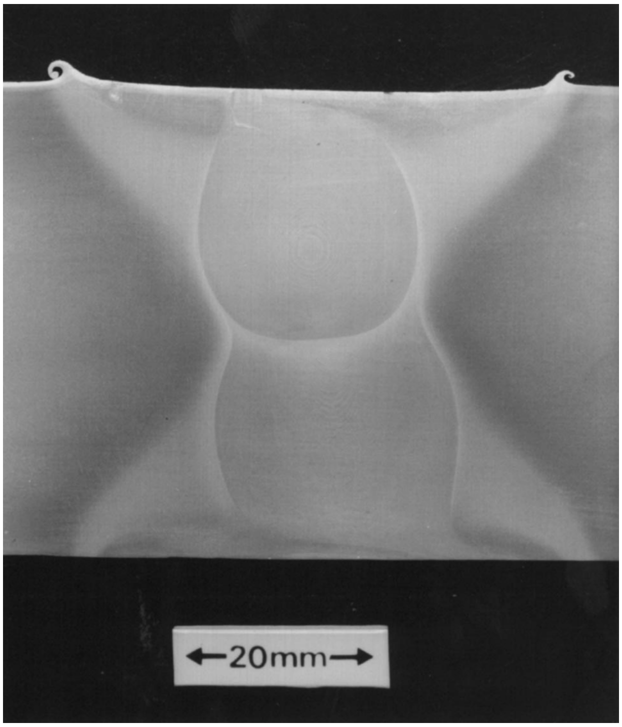


Figure 2 Transverse macrosection of 50 mm thick 6082 T6 aluminium alloy. Plate material welded from both sides, showing weld nugget profile and flow contours

with 6082 T6 aluminium alloy material in thicknesses ranging from 1.6 to 12.7 mm. Recent trials have extended the thickness range upwards to 75 mm in two passes.

Metallographic examination

A series of 50 and 75 mm thick welds in 6082 T6 condition aluminium alloy, which demonstrate the possibilities for the process for thick plate are shown in *Figures 2–4*. The macrosections from these welds are characterised by well defined weld nuggets and flow contours, almost spherical in shape, these contours are dependant on the tool design and the welding parameters and process conditions used. For heat treatable materials a well-defined heat affected zone surrounds the weld nugget region and extends to the shoulder diameter of the weld at the plate surface. The weld nugget itself is the region, where full dynamic re-crystallisation occurs that comprises of a fine equiaxed grain structure. The measured grain size is in the order of 2–4 μm in diameter. Typically the parent metal chemistry is retained, without any segregation of alloying elements. A hardness traverse taken from 50 mm thick test weld recorded the following values:

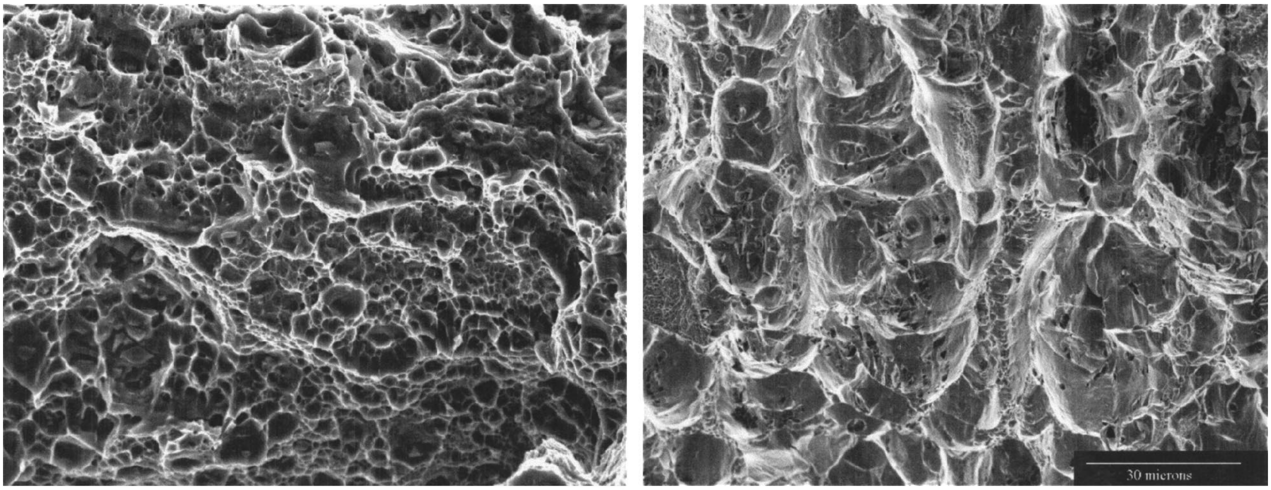
- Parent metal 100 HV$_{2.5}$
- Weld nugget 65 HV$_{2.5}$
- HAZ region 52 HV$_{2.5}$

Fractography

Samples of welded 50 mm thick 6082 T6 plate were notched in the parent material, and the weld nugget region and then fractured by bending. The fracture surfaces were examined using scanning electron microscopy. Both the weld nugget and the parent material failed in a ductile manner by the microvoid coalescence mechanism as shown in *Figure 3*. However, there was an absence of relatively large microvoids in the weld nugget sample and this may be a consequence of the break up of the primary constituent particles during stir welding.

Mechanical integrity

For plate thickness up to 50 mm thick, transverse



70599
a)

70595
b)

Figure 3 Fractography comparison between weld nugget and parent metal in 50 mm thick 6082 T6 aluminium alloy plate. (a) Fracture in weld nugget. Scanning microscopy of nick break bend, fracture face. (b) Fracture in parent metal. Scanning microscopy of nick break bend, fracture face

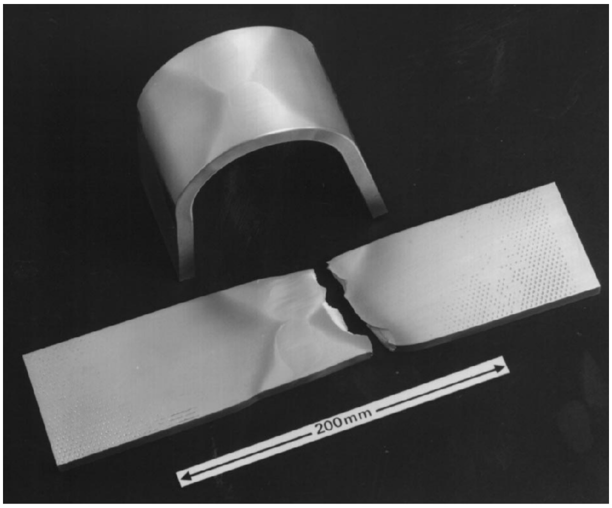


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Figure 4 Three point bend and tensile test in 75 mm thick 6082 T6 aluminium alloy FSW plate

sections were hammer bend tested to 180°. While transverse sections taken from 75 mm thick plate were three point bend tested as shown in *Figure 4*. A number of tensile tests were carried out with failure typically occurring in the HAZ region at 175 N mm^2 as shown in *Figure 4*. The localised reduction in specimen thickness during the tensile testing corresponds with regions of reduction in hardness.

Process characteristics

Experimental research work is being carried our at TWI to evaluate a range of materials and develop other FSW tools designed to improve the flow of plasticised material around the probe itself and to enable substantially thicker plates to be joined and enable relatively high traverse rates to be achieved.

Figure 5 illustrates the natural dynamic orbit inherently associated with every type of rotary machine. This eccentricity must to a greater or lesser extent be part of the friction stir welding process characteristics. Eccentricity allows hydromechanically incompressible plasticised material to flow more easily around the probe. It follows that a nominal bias off-centre or non-circular probe will also allow plasticised material to pass around the probe. Essentially it is the relationship between the greater volume of the ‘dynamic orbit’ of the probe and the volume of the static displacement of the probe, that helps provide a path for the flow of plasticised material from the leading edge to the trailing edge of the rotating tool.

A number of tool geometries and tool attitude for different materials have been reported in the literature[3,6,7]. For tools positioned perpendicular to the workpiece the leading edge of the rotation tool provides a frictional preheat effect heat and subsequent thermal softening of the workpiece in front of the probe. This preheat can be of advantage when dealing with harder or difficult to weld materials. The greater the area of the shouldered region of the rotating tool making contact with the joint surface the greater the frictional heat available. Increasing the diameter of the shouldered region, however, has practical limitations and tends to produce side flash on the weld surface.

Potential for the FSW process in the transportation industry

The potential scope for FSW initially lies with joining materials like aluminium, copper, copper alloys, lead, titanium, zinc etc. The applications range from the following:

- Airframes, fuel tanks, and thin alloy skins in the aerospace

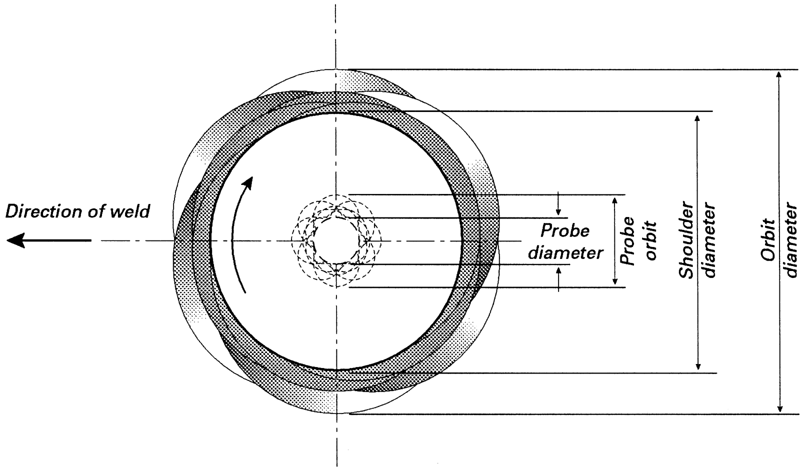

Figure 5 Dynamic orbit—plan view of rotating tool and probe

- Sheet bodywork and engine support frames for the automotive industry
- Railway wagon and coachwork, and bulk carrier tanks for the transportation industry
- Hulls, decks, and internal structures for high speed ferries and LPG storage vessels for the shipbuilding industry

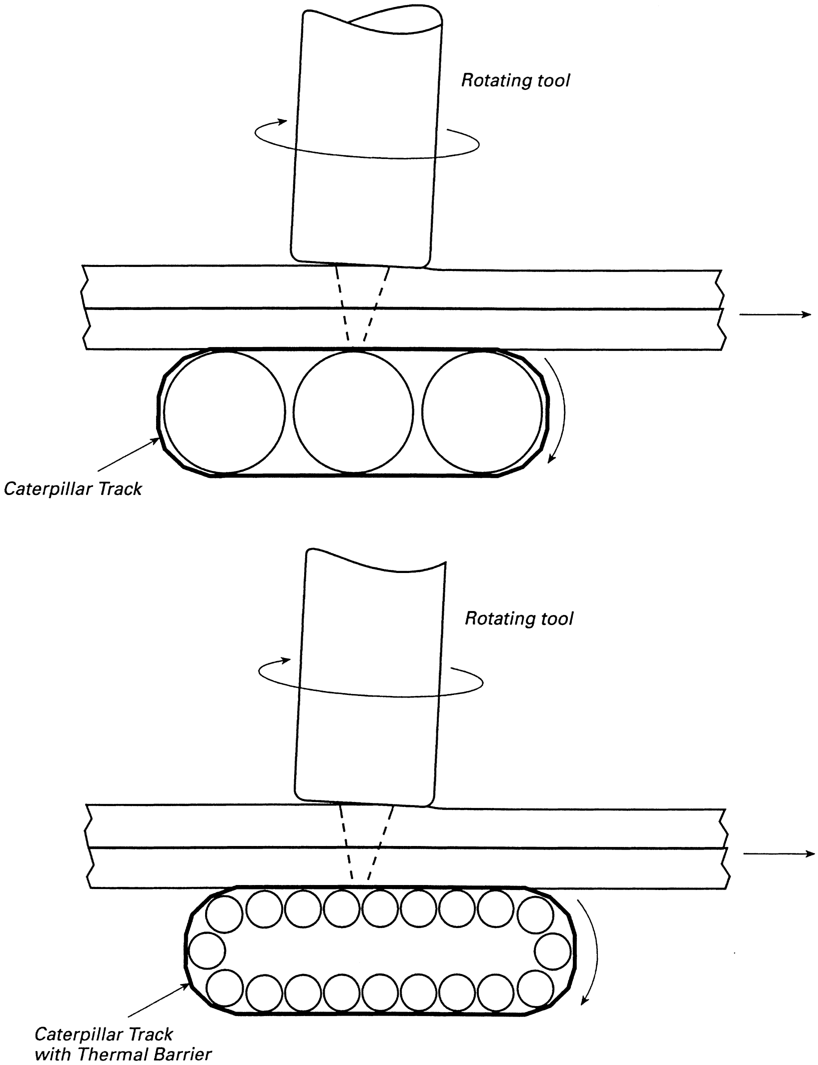

Figure 6 FSW seam welding of lapped sheet with roller\track support

The FSW technique will move ahead with thinner sheet and foam filled sections being produced at comparatively high traverse speeds. Developments that will enable the technique to be more flexible for thin sheet lap joining are being studied.

Moving reactive support-anvil

Figure 6 shows a miniature caterpillar track that could be developed to provide local support for the rotating tool, a ‘moving anvil’. Such a device would be able to fit into similar joint configurations as those accessible by traditional resistance welding techniques and tackle material thickness of about 1.5 mm or less. The moving anvil could be suitably interfaced with a robot for fully automatic seam and tack welding. The ‘moving anvil’ approach could also be considered as an alternative for a relatively large machine design. For example, instead of a rotating head traversing along a fixed reactive support, the material could be transported continuously over carrier rollers to a fixed work station, fitted with a ‘moving anvil’, much in the same way as a domestic sewing machine works. The ‘moving anvil’ concept may be worth considering for aerospace and automotive applications.

Concluding remarks

There is no doubt that the use of FSW will open up new markets and new opportunities as the technology gets wider recognition as a welding process that can produce superior welds, of improved reliability and of increased productivity. The FSW process is already in commercial use and has been found to be a robust process tolerant, technique that has much to offer.

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