DEVELOPMENTS IN THE FRICTION STIR WELDING OF METALS

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ABSTRACT Friction, which requires relative motion, pressure and time, is a powerful, efficient energy source for welding and reprocessing of materials. One variant, that of friction stir welding (FSW), is continuing to cause major excitement throughout the world for joining a range of alloys, particularly those based on aluminium. This presentation will trace the industrial development of the process since its invention in December 1991 to the present time. Attention will be given to tool evolution, welding properties, thermal management, innovations to enhance weld integrity, equipment evolution, and present and future applications through a range of industrial sectors.

Keywords: *Friction, tools, thermal management, applications, machines.*

1. INTRODUCTION

Some 100 years have now elapsed since Bevington filed the first patent on friction as a heat source for welding [1]. The primary conditions needed to utilise this very efficient heat source are relative motion (rotary, orbital, linear, etc), applied pressure and a given duration, all three now referred to as the friction triangle. If the world-wide use of friction welding is examined then it is evident that rotary motion is most widely used and understood for the joining of parts of which at least one is round. Equally, it is apparent that as many as 20 different methods of using frictional heating for either joining or reprocessing of materials where everything happens in the solid phase are now available [2]. One such method, that permits an even wider range of parts and geometries to be welded, and called friction stir welding (FSW), was invented by Wayne Thomas of TWI in England in December 1991 [3]. The author believes that the method represents a major step change in the joining of aluminium alloys and indeed other metals this century. Consequently, world-wide patents were filed from the invention date.

Friction stir welding, Fig. 1, is a relatively simple process whereby a specially shaped cylindrical tool with a profiled probe, made from a hard, wear resistant material relative to the material being welded, is rotated and plunged into the abutting edges of the parts to be joined. After entry of the profiled probe to almost the thickness of the material and to allow the tool shoulder to just penetrate into the plate, the rotating tool is translated along the joint line. The rotating tool develops frictional heating of the material, causing it to plasticise and flow from the front of the tool to the back, where it cools and consolidates to produce a high integrity weld, in the solid phase, i.e. no macroscopic melting.

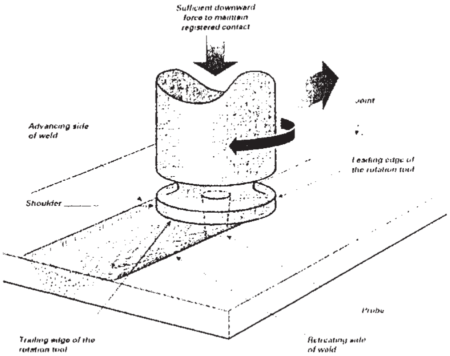


Fig. 1. Friction stir welding with a rotating tool - salient features

In the initial months after the patent filing, very simple tool designs involving smooth pin profiles clearly proved the feasibility of the process for welding 6,000 series aluminium alloys. However, a radical breakthrough occurred during a 3 year Group Sponsored Project which positively brought the technology forward for commercial exploitation. The primary improvement involved the threaded features of the pin [4], inclination of the tool, and a modification to the shoulder of the tool [5]. Such changes allowed high integrity joints to be produced with 6082 aluminium alloy in the thickness range 1.6mm to 12.7mm with acceptable reproducibility and good parametric tolerance limits, i.e. welding speed and tool rotation speed. Continuing development within that programme also confirmed that other alloys, such as 2219, 2014, 5083 and 7075, could equally be welded with success [6]. Perhaps of significant importance from this programme was that the welds were made in the solid phase with a fine grained microstructure, exhibiting acceptable tensile and bend properties. Also the welds showed remarkably good fatigue results when evaluated in the 'as-welded' condition. The equipment used for this development project were a simple milling machine and a converted routing facility. Consequently, when the welding conditions were evaluated by the individual sponsors on similar machines at their works, they were also almost immediately able to achieve success. Clearly therefore the process could be operated away from a Research Laboratory environment and now could no longer be regarded as a 'curiosity'.

The advantages that the process offers over the more conventional fusion welding processes are: low distortion, even in long welds; excellent mechanical properties as proven by fatigue, tensile and bend tests; no fume; no porosity; no spatter; low shrinkage; can operate in all positions; energy efficient; non-consumable tool; one tool can typically be used for up to 1000m of weld length in 6000 series aluminium alloys; no filler wire; no gas shielding for welding aluminium; no welder certification required; some tolerance to imperfect weld preparations - thin oxide layers can be accepted; no grinding, brushing or pickling required in mass production.

2. TOOLS AND SYSTEMS FOR FRICTION STIR WELDING

It is important to remember that the process is similar in some respects to both laser and electron beam welding since a keyhole is developed, albeit that FSW takes place in the solid phase. Therefore the design and materials required for the welding tool are critical to the successful filling of the keyhole and consequently weld integrity. For aluminium and its alloys in general, the use of hot worked tool steel of the AISI H13 type has proved to be satisfactory, certainly for a thickness range from 1.2mm to 16mm when welded in one pass. However, as thicknesses increase, especially for the high strength aluminium alloys, it may well be necessary to change to other materials for the tool in order to maintain a realistic weld size. The greatest changes are occurring with the tool designs to meet the following objectives: high productivity (faster welding speeds); welding force reduction (simplify fixturing and welding equipment); increase the weldable thickness range (i.e. 0.8mm to 50mm in one pass, double the thickness in two passes); closure of the keyhole on weld completion (extend applications range); increased life (cooling); application to other materials (copper, lead, steel, titanium, magnesium, etc); accommodate varying thicknesses (extend applications range); control of penetration by pressure feedback (weld quality); weld dressing (improve dynamic properties and aesthetic appearance).

The consequences of development in this important area have seen many patent applications being filed throughout the world. In the early years one such filing [5] identified weld improvements that were made by incorporating fins on the probe, while a patent application made by TWI [7] covered a wide selection of both shoulder and pin profiles that were considered appropriate to improve welding performance and joint integrity. Using selected combinations of the aforementioned profiles [8] has resulted in the process thickness range being extended to 50mm in one pass for 6000 series aluminium alloys, and welding speeds again for 6000 series 2-3mm thickness alloys being increased to 2-.3metres/min.

Effort to closing/fading out the keyhole when completing a weld, particularly those that are circumferential and annular, has been provided by NASA at Huntsville in the USA [9]. They have been developing a retractable probe tool, and evaluating its effect when welding aluminium lithium alloy (2195) [10]. Further developments with both movable probes and shoulders are also being appraised [11] to allow the FSW of aluminium alloys of varying thicknesses. A schematic of the tool is shown in Fig. 2. Another Boeing patent filing addresses the possible need to remove displaced material that will be left on the top face of the weld, by using radially located cutters on the welding tool [12].

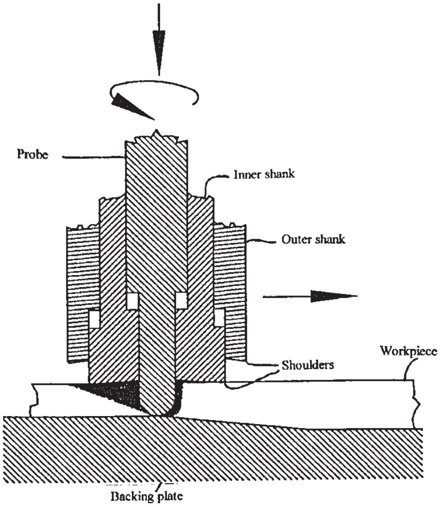
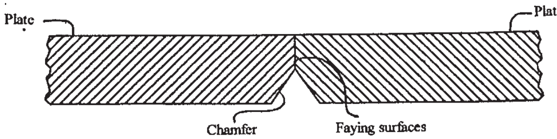
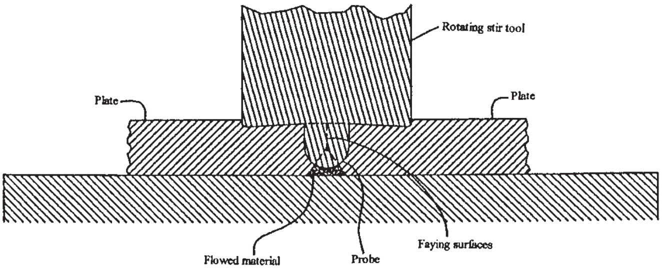


Fig. 2. Friction stir welding tool for welding variable thicknesses

For single pass full penetration welding using FSW it is imperative that the primary welding parameters of rotation speed, welding speed and tool plunge depth are maintained during the welding sequence. Of particular importance is the latter parameter in order to avoid the formation of a 'kissing bond' at the weld root. It is of interest to note that three different approaches are being considered. The first by Rosen [13] and Ding [14], as shown in Fig. 3, involves machining a back-surface relief in the weld root region in order that on completion of welding, deforming material will be forced through that location onto the backing support bar. Visual inspection of the weld back it is suggested will readily confirm that bond formation has taken place. The second approach suggested by Colligan [15] is to include in the backing bar (moving or stationary) a recessed groove to be located beneath the abutting parts. Now as a consequence of the developed perpendicular force acting on the plasticised stirred material, the latter will flow into the groove, thus ensuring full penetration. Clearly with this method, it may be necessary to undertake post weld machining to improve the static and dynamic performance of the weld. The third option under consideration relies upon sensing the pin depth and/or the perpendicular force during welding and then adopting a feedback system to control the plunge depth [16] by varying the probe length [17].



a. Before welding

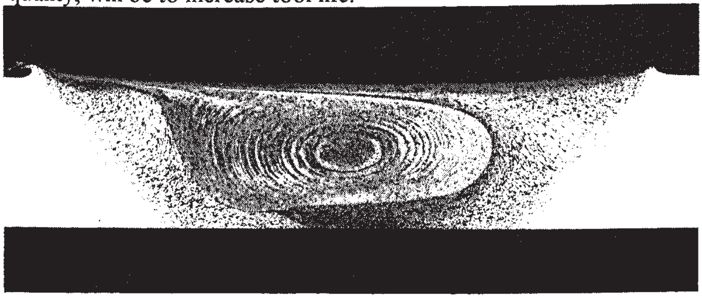


b. During welding
Fig. 3. Friction stir welding with back relief

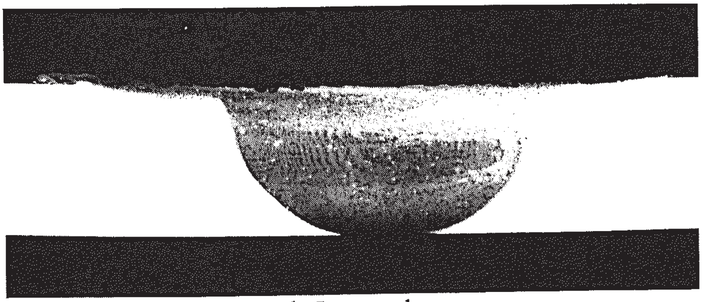
Finally, in order to increase the potential of the process to more diverse applications, the concept of a 'bobbin' tool, which was indeed considered back in 1993 [18], will be revisited. Such a tool could well remove the need for the present backing support bar in certain applications.

3. THERMAL MANAGEMENT

It is recognised that thermal energy is required to soften the material being welded in order to allow the tool to develop plastic material flow to fill the keyhole. Unfortunately, of course, when welding work hardened (5000 series) and heat treated aluminium alloys, there will inevitably be a thermally affected region of the weld where both proof stress and ultimate tensile strength will be adversely affected. This feature has prompted workers in the FSW field to seek solutions to minimise these effects. At TWI, for example, Threadgill, Howes and Thomas have and are continuing to evaluate the influence of heat extraction by using water cooled fixtures, backing bars with high thermal conductivity, and indeed using enforced cooling at the weld surface. Clearly, an extreme example of the latter is to actually make the weld when it is totally submerged in water - it does work! Preliminary results when welding a 7075 aluminium alloy nominally 6mm in thickness, showed that the proof stress and UTS were increased by 25% and 6% respectively when compared to previous welds produced with exactly the same welding parameters, but without enhanced thermal extraction, Fig. 4. Other researchers have also considered more careful control of the thermal energy, and one has filed a patent covering in-situ spraying of the weld region and externally and internally applying cooling to the welding tool [19]. One advantage of the latter approach, apart from improving weld quality, will be to increase tool life.



a. Conventional



b. Improved

Fig. 4. Friction stir welds in 6mm 7075-T7351 alloy

4. WELDING MACHINES

The primary requirements to operate FSW include the need to rotate the tool, traverse along the joint line, set and maintain the plunge depth, react the developed welding forces, and adequately clamp the parts. Many machinery systems such as millers and routers can easily satisfy most of the needs. During the early years of development most experimental trials were performed using relatively standard milling machines. However, as the technology continues to attract increasing interest from a wide range of industrial sectors there is a continual need for process development, fabrication of prototype assemblies and production equipment. The following machines represent a good cross-section that are now available to satisfy the above needs:

- TWI's Modular FW22 Machine - TWI's laboratory machine (Fig. 5) was built in October 1996 to accommodate large sheets and to weld prototype structures. The modular construction of FW22 enables it to be enlarged for specimens with even greater dimensions.

- Sheet thickness: 3mm-15mm Al alloy
- Max. welding speed: up to 1.2m/min
- Current max. sheet size: 3.4m length x 4m width
- Current max. working height: 1.15m

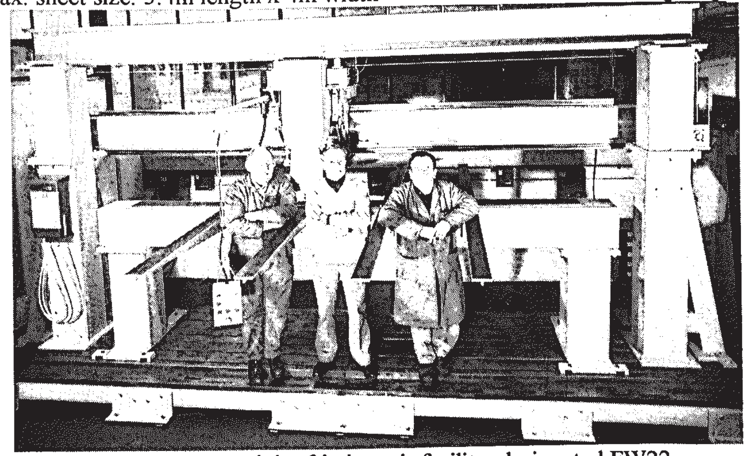


Fig. 5. TWI's modular friction stir facility, designated FW22

The machine has been primarily used to produce longitudinal welds using its traversing head, but when interfaced with appropriate manipulation devices and the welding head locked, circumferential welding can also be carried out. Under contract to the then McDonnell Douglas company, three prototype cylindrical tanks of nominal dimensions 1m diameter x 2m in length were fabricated with two longitudinal seam welds and two circumferential welds to attach the end caps, Fig. 6.

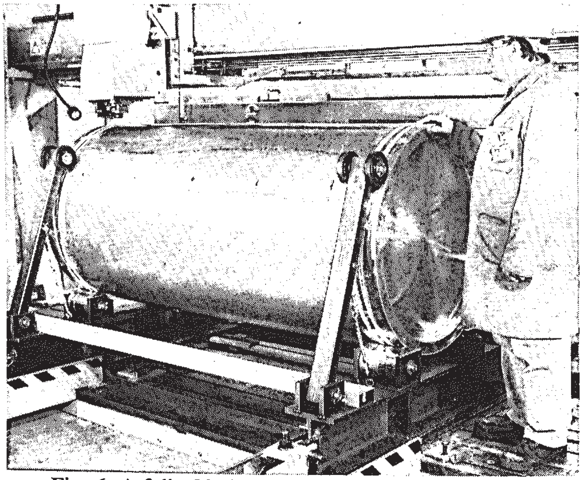


Fig. 6. A fully friction stir welded cylindrical tank.

- ESAB's Super Stir Production Machine - This company most probably can be accredited with building the first truly commercial FSW facility. The machine, which is installed at Marine Aluminium Aanensen [20], Norway, is capable of making 16m long welds. It is used for the mass production of panels which are made by joining extruded profiles. The machine [21] and the welding procedure have been approved by Det Norske Veritas and Germanischer Lloyd. ESAB also have demonstrated FSW using a special purpose R&D machine with a welding speed of 750mm/min in 5mm thick aluminium (6000 series) at the 14th International Welding Fair held in Essen in 1997.
- TWI's Demonstrator Machine - TWI's small transportable machine produces annular welds with hexagonal aluminium alloy discs. It has been exhibited at fairs in the USA, Sweden, Germany, and the United Kingdom in recent years. It is an eye catcher which enables visitors to produce their first friction stir weld themselves. It can be operated with 110V or 220V-240V single phase and has been used by TWI and its member companies to demonstrate the process.
- CRC's Portable Machine - TWI was involved in the commissioning of a prototype machine [22] which was designed and manufactured by their CRC partners at the Department for Mechanical Engineering of the University of Adelaide, Australia. This machine can be carried and aligned by two operators without the use of a crane or other lifting device. It has been used to weld curved sheets under site conditions in a shipyard.
- NASA's Improved Welding Facility - NASA at the Marshall Space Flight Center, Alabama, USA, are reported to have developed a complete system [23] for commercial implementation. They say the system can be used in a variety of welding and weld repair applications. It is capable of handling up to 6,000lbs (26.7kN) of axial load while operating within close tolerances. The system includes seven sub-components: a base foundation unit (BFU); an hydraulically controlled elevation platform (EP); the hydraulically adjustable pin tool (HAPT); backplate tooling, fixturing; a roller mechanism and the real-time adaptive computer numerical control (CNC); process control system (APCS). Together, these sub-components allow FSW to be used on the manufacturing floor as a complete welding system.

5. POTENTIAL APPLICATIONS

As the technology continues to mature as a viable joining process and becomes applicable to a wide range of materials, so the opportunities for exploitation expand to cover a wide range of industrial sectors, as follows:

5.1. Aerospace Industry

At present the aerospace industry is welding prototype parts by FSW. Opportunities exist to weld skins to spars, ribs, and stringers for use in military and civilian aircraft. This offers significant advantages compared to riveting and machining from solid, such as reduced manufacturing costs and weight savings. Longitudinal butt welds and circumferential lap welds of Al alloy fuel tanks for space vehicles have been friction stir welded and successfully tested. The process could also be used to increase the size of commercially available sheets by welding them before forming. The FSW process can therefore be considered for: wings; fuselages; empennages; cryogenic fuel tanks for space vehicles [24,25,26]; aviation fuel tanks; external throw away tanks for military aircraft; military and scientific rockets; repair of faulty MIG welds.

5.2. Land Transportation

The FSW process is currently being experimentally assessed by several automotive companies and suppliers to this industrial sector for its commercial application. A joint EWI/TWI Group Sponsored Project is investigating representative joint designs for automotive lightweight structures. Potential applications are: engine and chassis cradles [27]; wheel rims [28,29]; attachments to hydroformed tubes; tailored blanks [30], e.g. welding of different sheet thicknesses; space frames; welding extruded tubes to cast nodes; truck bodies; tail lifts for lorries; mobile cranes; armour plate vehicles; fuel tankers; caravans; busses and airfield transportation vehicles; motorcycle and bicycle frames; articulated lifts and personnel bridges; skips; repair of aluminium cars; magnesium and magnesium/aluminium joints.

5.3. Railway Industry

The commercial production of high speed trains made from aluminium extrusions which may be joined by FSW has been published. Applications include: high speed trains; rolling stock of railways, underground carriages, trams; railway tankers; goods wagons; container bodies

5.4. Shipbuilding and Marine Industries

The shipbuilding and marine industries are two of the first industry sectors which have adopted the process for commercial applications. The process is suitable for the following applications: panels for decks, sides, bulkheads and floors; aluminium extrusions; boat sections; hulls and superstructures; helicopter landing platforms [31]; offshore accommodation; marine structures; masts and booms, e.g. for sailing boats; refrigeration plant.

5.5. Electrical Industry

The electrical industry shows increasing interest in the application of FSW for: electric motor housings [32]; busbars; electrical connectors; encapsulation of electronics

5.6. Construction Industry

The use of portable FSW equipment is possible for: aluminium bridges [33]; facade panels made from aluminium, copper or titanium; window frames; aluminium pipelines [34]; aluminium reactors for power plants and the chemical industry; heat exchangers and air conditioners; pipe fabrication.

5.7. Other Industry sectors

Friction stir welding can also be considered for: refrigeration panels [35]; cooking equipment and kitchens; white goods; gas tanks and gas cylinders; connecting of aluminium or copper coils in rolling mills; furniture.

6. MATERIALS, THICKNESSES AND WELD PROPERTIES

In the learning years for FSW, emphasis was placed on the welding of aluminium and its alloys. Today there are very many organisations throughout the world carrying out experimental studies on metallurgical characterisation [36,37,38], corrosion [30,39], and evaluating the static [40,41,42] and dynamic [43,44,45] properties of welds in 2000, 5000, 6000 and 7000 series aluminium alloys. Also Mahoney et al have reported on the friction stir weldability of a metal matrix composite (MMC) 6092 aluminium alloy, reinforced with 17% SiC [51]. It is also to be expected that to complement these studies and in particular to be able to predict weld properties and microstructures, etc, many organisations are actively developing models for the process [46,47,48,49,50]

Tool development at TWI, particularly for aluminium alloy 6082, has extended the thickness range from 1.2mm to 50mm in one pass for simple butt welds. Also in the thinner alloy range improvements in tool design have enhanced the overall weld properties of lap welded joints. By employing specific geometric changes to the tool probe, particularly to include a 'whorl' profile, have brought success for thick section welding. Such an example is a two pass double-sided weld in the aforementioned alloy [52], Fig. 7 at 75mm thickness. Weld quality as determined by 180° bend and tensile testing was most encouraging. At this point it must be remembered that there was no pre-weld preparation (flat butt), no surface cleaning, no use of filler metal, and no gas shielding - even then each pass was welded at a speed of ~60mm/min.

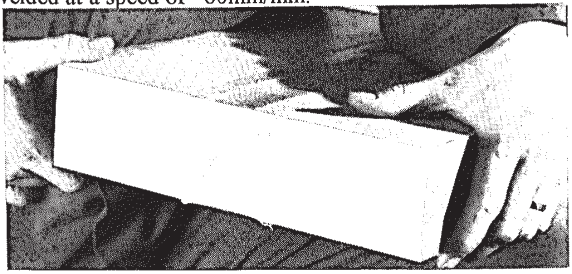


Fig. 7. 75mm thick 6082-T6 Al alloy friction stir welded with two passes

It is not unreasonable to consider the success of applying FSW to other non-ferrous, ductile, low melting point alloys. Indeed most promising results were achieved when welding 0.8mm thick Zinc roofing sheet, 3mm thick lead, 3mm-6mm thick copper, and 4.2mm thick cast magnesium alloy, Fig. 9. A macrosection taken from the magnesium alloy weld shows similar material flow features to aluminium alloy weldments; also a hardness trace transverse to the weld and at the sheet mid thickness revealed a slight increase in the weld nugget region to 68HV when compared to the parent hardness of 57HV. In most of the previous examples the alloys have been in the extruded, rolled or forged condition, but of course the magnesium alloy was in its 'cast' form. So the process will weld cast alloys, but will it weld cast to wrought? The answer is yes, even with dissimilar aluminium alloys and dissimilar material alloys where the former involved a cast Al-Si alloy to a 5000 series wrought alloy and the latter cast magnesium alloy to extruded 6000 series aluminium alloy. It is useful to remember that for both of these combinations, depending on the welding direction and tool rotation, one alloy will be stirred into the other and of course vice versa if the conditions are reversed.

More recent experimental investigations have demonstrated that low carbon steels of 3mm thickness can be friction stir welding and the resultant welds exhibit good bend ductility and full bending with no defects. Similar trials with Ti6/4 alloy show promise, but as with steel of significant importance is the choice of material for the welding tool. The primary requirements for a tool material to friction stir weld the higher melting point alloys are resistance to deformation, shear, wear, and alloying with the metals/alloys being welded.

7. CONCLUDING REMARKS

Within the several years since FSW was invented, five companies - three from Scandinavia, one from Japan and soon one from the USA, are/will use the process in commercial production. Also there are now more than 30 organisations from around the world that have licences to use the process. Also of significant importance is that two certifying authorities, Det Norske Veritas and Germanischer Lloyd, have accepted the technology for certain aluminium alloys and applications. It is also most likely that other authorities will be actively involved as the process enters production in other industrial sectors. Development and innovation do not stand still: even now work at TWI with new tool designs, materials and processes changes are reducing some of the problems with the method and permitting even higher welding speeds to be achieved. It may not be too long before robots and multi-axis CNC welding systems will friction stir weld more complex 3-D structures. Work at Universities and other Research Institutes throughout the world is progressing at a rapid pace which can only be of benefit to existing industries using the process, and others that are contemplating its use.

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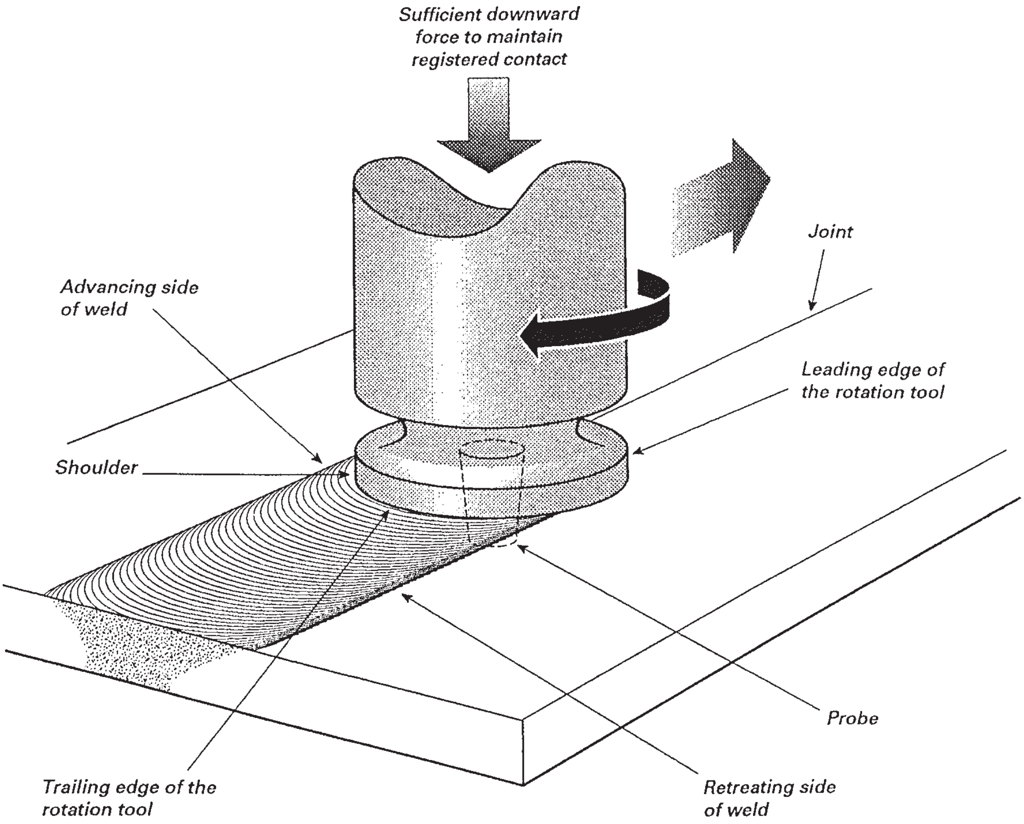
Sufficient downward force to maintain registered contact
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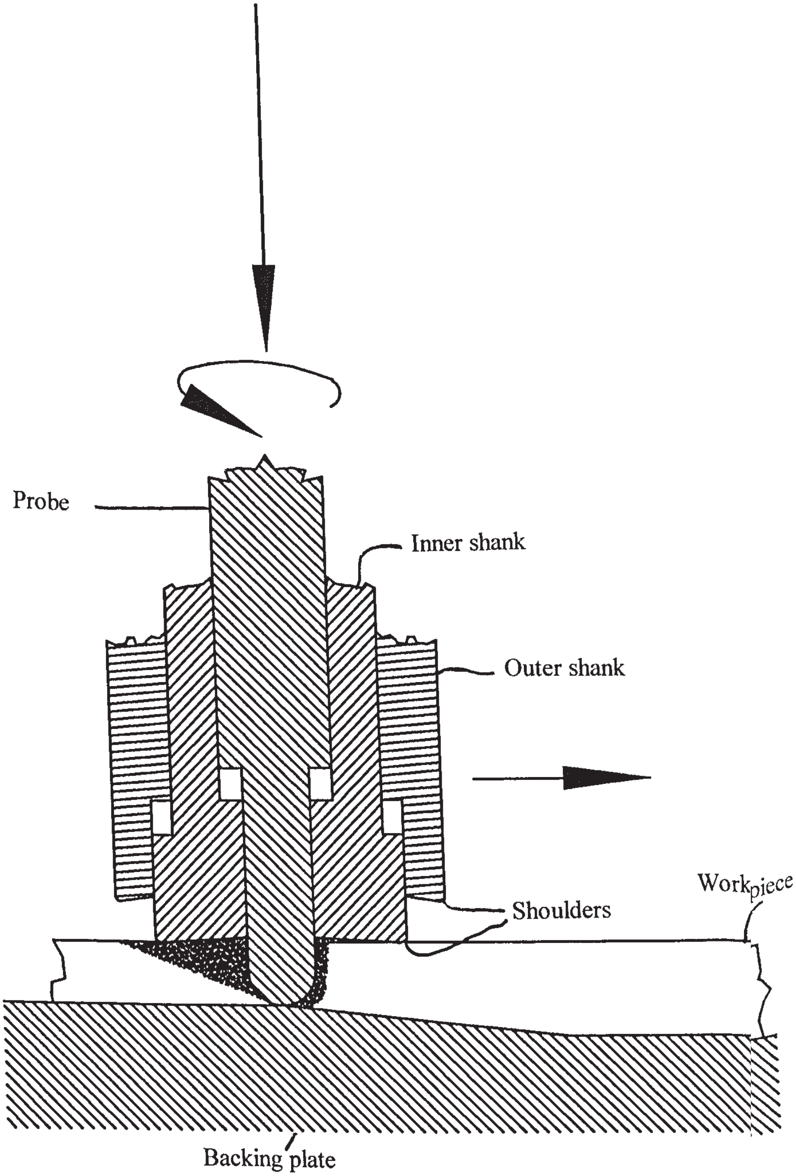
Advancing side of weld
Leading edge of the rotation tool
Shoulder
Probe
Trailing edge of the rotation tool
Retreating side of weld


Probe
Inner shank
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Shoulders
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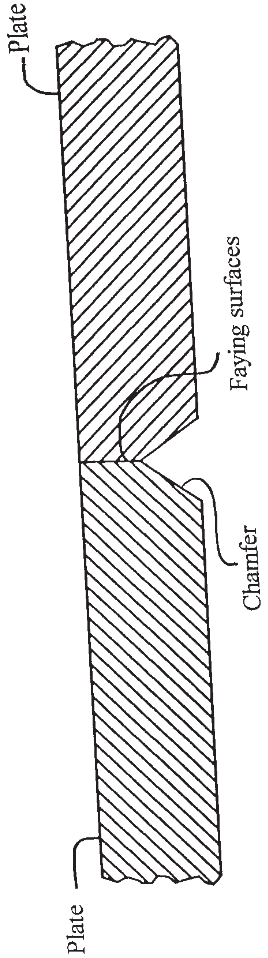
Backing plate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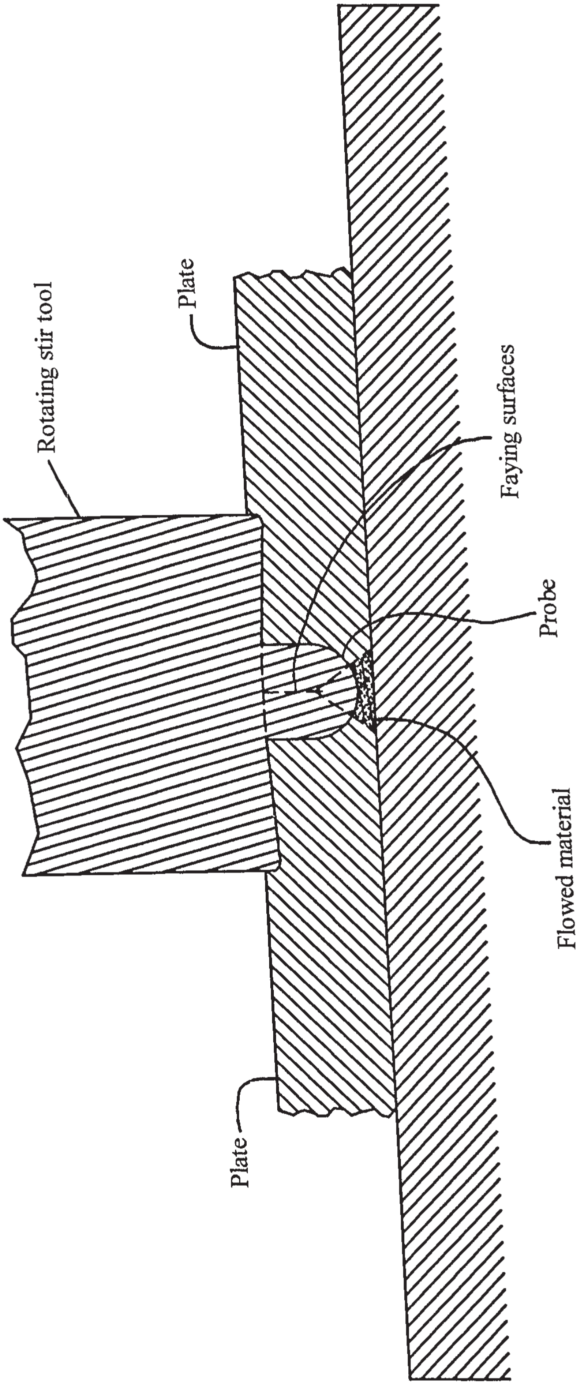
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