FRICTION STIR WELDING

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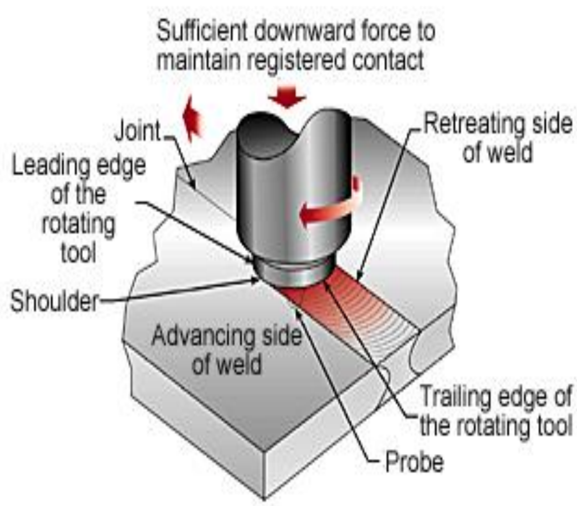
ABSTRACT: Friction Stir Welding (FSW) is a solid state joining process that involves joining of metals without fusion or filler materials. The frictional heat is produced from a rapidly rotating non-consumable high strength tool pin that extends from a cylindrical shoulder. The process is particularly applicable for aluminium alloys but can be extended to other products also. Plates, sheets and hollow pipes can be welded by this method. The process is also suitable for automation. The weld produced is of finer microstructure and superior in characteristics to that parent metal. FSW finds application in shipbuilding, aerospace, railway, electrical and automotive industry. The limitations of FSW are reduced by intensive research and development. Its cost effectiveness and ability to weld dissimilar metals makes it a commonly used welding process in recent times.

1. Introduction

In late 1991 a very novel and potentially world beating welding method was conceived at TWI. The process was duly named friction stir welding (FSW), and TWI filed for world-wide patent protection in December of that year. TWI (The Welding Institute) is a world famous institute in the UK that specializes in materials joining technology. Consistent with the more conventional methods of friction welding, which have been practiced since the early 1950s, the weld is made in the solid phase, that is, no melting is involved. Compared to conventional friction welding, FSW uses a rotating tool to generate the necessary heat for the process. Since its invention, the process has received world-wide attention and today two Scandinavian companies are using the technology in production, particularly for joining aluminium alloys. Also, FSW is a process that can be automated. It is also a cleaner and more efficient process compared to conventional techniques.

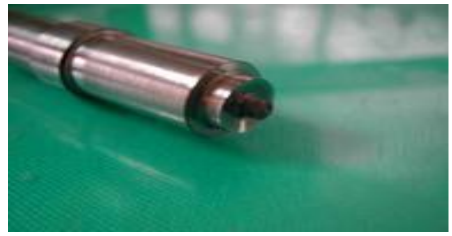
2. WORKING PRINCIPLE



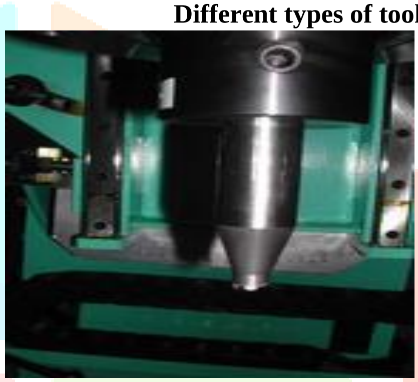
In friction stir welding (FSW) a cylindrical, shouldered tool with a profiled probe is rotated and slowly plunged into the joint line between two pieces butted together. The parts have to be clamped onto a backing bar in a manner that prevents the abutting joint faces from being forced apart. Frictional heat is generated between the wear resistant welding tool and the material of the work pieces. This heat causes the latter to soften without reaching the melting point and allows traversing of the tool along the weld line. The maximum temperature reached is of the order of 0.8 of the melting temperature of the material. The plasticized material is transferred from the leading edge of the tool to the trailing edge of the tool probe and is forged by the intimate contact of the tool shoulder and the pin profile. It leaves a solid phase bond between the two pieces. The process can be regarded as a solid phase keyhole welding technique since a hole to accommodate the probe is generated, then filled during the welding sequence

3 DESCRIPTION OF THE ROTATING TOOL PIN

The non-consumable tool has a circular section except at the end where there is a threaded probe or more complicated flute; the junction between the cylindrical portion and the probe is known as the shoulder. The probe penetrates the work piece whereas the shoulder rubs with the top surface. The tool has an end tap of 5 in 6 mm diameter and a height of 5 to 6 mm (may vary with the metal thickness). The tool is set in a positive angle of some degree in the welding direction. The design of the pin and shoulder assembly plays a major role on how the material moves during the process.



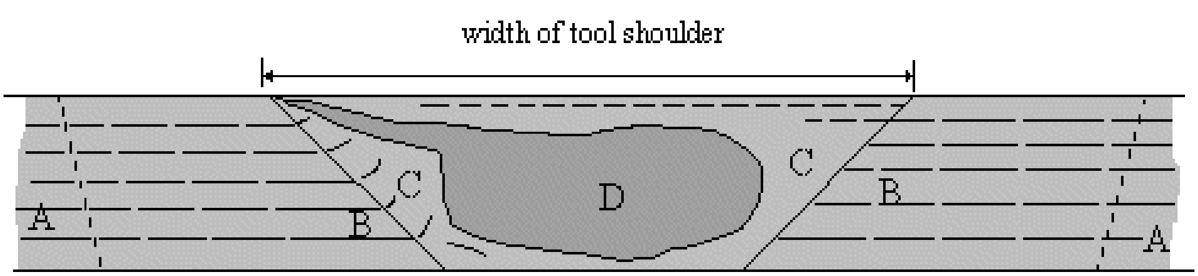
Different types of tools used



Tool mounted on the machine

4 MICROSTRUCTURE CLASSIFICATION

The first attempt at classifying microstructures was made by P L Threadgill (Bulletin, March 1997). This work was based solely on information available from aluminium alloys. However, it has become evident from work on other materials that the behavior of aluminium alloys is not typical of most metallic materials, and therefore the scheme cannot be broadened to encompass all materials. It is therefore proposed that the following revised scheme is used. This has been developed at TWI, but has been discussed with a number of appropriate people in industry and academia, and has also been provisionally accepted by the Friction Stir Welding Licensees Association. The system divides the weld zone into distinct regions as follows:



A. Unaffected material
B. Heat affected zone (HAZ)
C. Thermo-mechanically affected zone (TMAZ)
D. Weld nugget (Part of thermo-mechanically affected zone)

Unaffected material or parent metal: This is material remote from the weld, which has not been deformed, and which although it may have experienced a thermal cycle from the weld is not affected by the heat in terms of microstructure or mechanical properties.

Heat affected zone (HAZ): In this region, which clearly will lie closer to the weld centre, the material has experienced a thermal cycle, which has modified the microstructure and/or the mechanical properties. However, there is no plastic deformation occurring in this area. In the previous system, this was referred to as the "thermally affected zone". The term heat affected zone is now preferred, as this is a direct parallel with the heat affected zone in other thermal processes, and there is little justification for a separate name.

Thermo-mechanically affected zone (TMAZ): In this region, the material has been plastically deformed by the friction stir welding tool, and the heat from the process will also have exerted some influence on the material. In the case of aluminium, it is possible to get significant plastic strain without recrystallisation in this region, and there is generally a distinct boundary between the recrystallised zone and the deformed zones of the TMAZ. In the earlier classification, these two sub-zones were treated as distinct microstructural regions. However, subsequent work on other materials has shown that aluminium behaves in a different manner to most other materials, in that it can be extensively deformed at high temperature without recrystallisation. In other materials, the distinct recrystallised region (the nugget) is absent, and the whole of the TMAZ appears to be recrystallised.

Weld Nugget: The recrystallised area in the TMAZ in aluminium alloys has traditionally been called the nugget. Although this term is descriptive, it is not very scientific. However, its use has become widespread, and as there is no word which is equally simple with greater scientific merit, this term has been adopted. A schematic diagram is shown in the above Figure which clearly identifies the various regions. It has been suggested that the area immediately below the tool shoulder (which is clearly part of the TMAZ) should be given a separate category, as the grain structure is often different here. The microstructure here is determined by rubbing by the rear face of the shoulder, and the material may have cooled below its maximum. It is suggested that this area is treated as a separate sub-zone of the TMAZ.

5 FACTORS AFFECTING WELD QUALITY

- Type of metal
- Angle of tool
- Traversing speed of the tool
- Spinning speed of tool
- Pressure applied by the pin tool

Research is going on to combine the above factors in order to control the process in a better way.

6 MATERIAL SUITABILITY

TWI has concentrated most of its efforts to optimizing the process for the joining of aluminium and its alloys. Subsequent studies have shown that cast to cast and cast to extruded (wrought) combinations in similar and dissimilar aluminium alloys are equally possible. The following aluminium alloys could be successfully welded to yield reproducible high integrity welds within defined parametric tolerances:

- 2000 series aluminium (Al-Cu)
- 3000 series aluminium (Al-Mn)
- 4000 series aluminium (Al-Si)
- 5000 series aluminium (Al-Mg)
- 6000 series aluminium (Al-Mg-Si)
- 7000 series aluminium (Al-Zn)
- 8000 series aluminium (Al-Li)

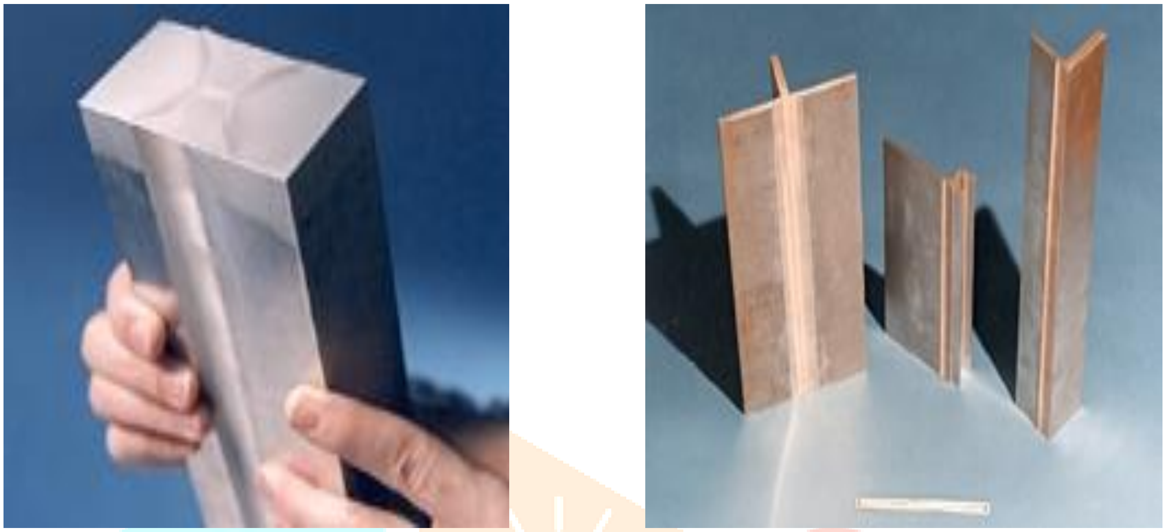
7 OTHER MATERIALS

The technology of friction stir welding has been extended to other materials also, on which researches are going on . Some of them are as follows-

- Copper and its alloys
- Lead
- Titanium and its alloys
- Magnesium and its alloys
- Zinc
- Plastics
- Mild steel

Companies practicing and developing FSW are spending a lot of money on improving its use for plastics. It has been demonstrated that FSW is a much more efficient and cleaner process than conventional adhesive bonding in plastics. But it is yet to be made cost and material effective. Ceramics is another field where FSW could be very useful in the future.

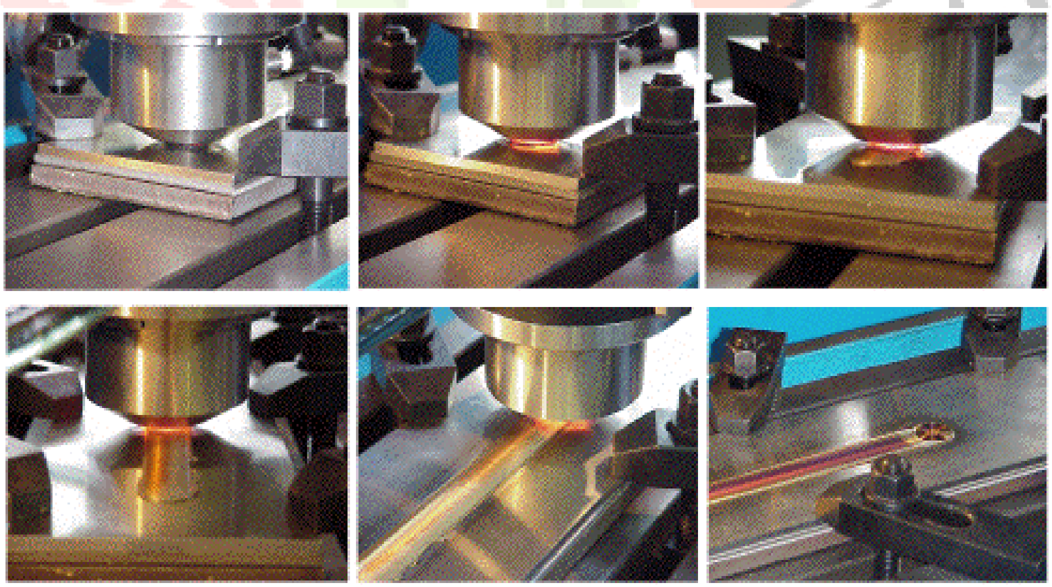
8 JOINT GEOMETRICS



The above figure shows friction stir welded parts

FSW is independent of gravity. Hence, it can be used to weld in any position- vertical, horizontal and even annular. For this reason FSW has been used to make circumferential annular welds in fuel tanks for spaceships. Besides these FSW can also be utilized for normal fillet and corner welds and also double v-butt joints etc.

9 FSW OF MILD STEEL



Created by Hitachi for University of Cambridge Use Only

Steel can be friction stir welded, but the essential problem is that tool materials wear rapidly. The sample becomes red hot during welding (as shown in the figure). Since the tool gets red hot it is necessary to protect it against the environment using a shielding gas. So generally FSW is avoided for mild steel. This is not such a great disadvantage since there are more efficient methods to weld mild steel. The weld shown is made by Hitachi of Japan.

10 FRICTION STIR WELDING MACHINES

10. 1 ESAB SuperStir TM machine FW28

The machine has a vacuum clamping table and can be used for non-linear joint lines.

- Sheet thickness: 1mm-25mm aluminium
- Work envelope: Approx 5 x 8 x 1m
- Maximum down force: Approx 60kN (6t)
- Maximum rotation speed: 5000rev/min :

10. 2 Modular machine FW22 to weld large size specimens

A laboratory machine was built in October 1996 to accommodate large sheets and to weld prototype structures. The modular construction of FW22 enables it to be easily enlarged for specimens with even larger dimensions.

- Sheet thickness: 3mm-15mm aluminium
- Maximum welding speed: up to 1.2m/min
- Current maximum sheet size: 3.4m length x 4m width
- Current maximum working height: 1.15m

10. 3 Moving gantry machine FW21

The purpose built friction stir welding machine FW21 was built in 1995. This machine uses a moving gantry, with which straight welds up to 2m long can be made. It was used to prove that welding conditions can be achieved which guarantee constant weld quality over the full length of long welds.

- Sheet thickness: 3mm-15mm aluminium
- Maximum welding speed: up to 1.0m/min
- Current maximum sheet size: 2m length x 1.2m width

10. 4 Heavy duty Friction Stir Welding machines FW18 and FW14

Two existing machines within TWI's Friction and Forge Welding Group have been modified exclusively to weld thick sections by FSW. The following thickness range has been experimentally investigated but the machines are not yet at their limits.

- Sheet thickness: 5mm-50mm aluminium from one side
  10mm-100mm aluminium from two sides
  5mm thick titanium from one side
- Power: up to 22kW
- Welding speed: up to 1m/min

10. 5 High rotation speed machine FW20

For welding thin aluminium sheets TWI equipped one of its existing machines with an air cooled high speed head which allows rotation speeds of up to 15,000rev/min.

- Sheet thickness: 1.2mm-12mm aluminium
- Maximum welding speed: up to 2.6m/min, infinitely variable

10. 6 Friction Stir Welding demonstrator FW16

TWI's small transportable machine produces annular welds with hexagonal aluminium alloy discs. It has been exhibited on fairs in 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 and has been used by TWI and its member companies to demonstrate the process.

11 ADVANTAGES OF FSW

- The process is environment friendly since no fumes or spatter is generated and no shielding gas is required.
- A non consumable tool is used
- Since the weld is obtained in solid phase, gravity does not play any part and hence the process can be done in all positions(vertical, horizontal, overhead or orbital)
- No grinding, brushing or pickling is required.
- Since the temperature involved in the process is quite low, shrinkage during solidification is less
- One tool can be typically used for up to 1000 metres of weld length (6000 series aluminium alloy)
- No fusion or filler materials is required
- No oxide removal necessary as in fusion welding.
- The weld obtained is of superior quality with excellent mechanical properties and fine micro structure.
- The process is cost effective since mechanical forming after welding can be avoided
- Dissimilar metals can be welded.
- Automation is possible

12 APPLICATIONS OF FSW

12. 1 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
- Hulls and superstructures
- Helicopter landing platforms
- Offshore accommodation
- Marine and transport structures
- Masts and booms, e.g. for sailing boats
- Refrigeration plant

12. 2 Aerospace industry

At present the aerospace industry is welding prototype parts by friction stir welding. 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 friction stir welding process can therefore be considered for:

- Wings, fuselages, empennages
- Cryogenic fuel tanks for space vehicles
- Aviation fuel tanks
- External throw away tanks for military aircraft
- Military and scientific rockets
- Repair of faulty MIG welds

12. 3 Railway industry

The commercial production of high speed trains made from aluminium extrusions which may be joined by friction stir welding has been published. Applications include:

- High speed trains
- Rolling stock of railways, underground carriages, trams
- Railway tankers and goods wagons
- Container bodies

12. 4 Land transportation

The friction stir welding process is currently being experimentally assessed by several automotive companies and suppliers to this industrial sector for its commercial application.. Potential applications are:

- Engine and chassis cradles
- Wheel rims
- Attachments to hydro formed tubes
- Tailored blanks, e.g. welding of different sheet thicknesses
- Space frames, e.g. welding extruded tubes to cast nodes
- Truck bodies
- Tail lifts for lorries
- Mobile cranes
- Armour plate vehicles
- Fuel tankers
- Caravans
- Buses and airfield transportation vehicles
- Motorcycle and bicycle frames
- Articulated lifts and personnel bridges
- Skips
- Repair of aluminium cars
- Magnesium and magnesium/aluminium joints

12. 5 Construction industry

The use of portable FSW equipment is possible for:

- Aluminium bridges
- Facade panels made from aluminium, copper or titanium
- Window frames
- Aluminium pipelines
- Aluminium reactors for power plants and the chemical industry
- Heat exchangers and air conditioners
- Pipe fabrication

12. 6 Electrical industry

The electrical industry shows increasing interest in the application of friction stir welding for:

- Electric motor housings
- Busbars

- Electrical connectors
- Encapsulation of electronics

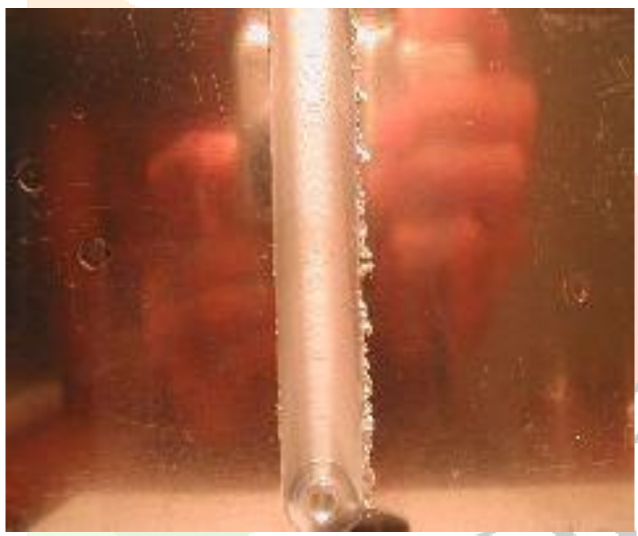
12.7 Other industry sectors

Friction stir welding can also be considered for:

- Refrigeration panels
- Cooking equipment and kitchens and furniture
- Gas tanks and gas cylinders, connecting of aluminium or copper coils in rolling mills

13 LIMITATIONS

- Welding speeds are moderately slower
- Work pieces must be rigidly clamped
- Backing bar required
- Keyhole at the end of each weld
- Requirement of different length pin tools when
- welding materials of varying thickness



Hole at the end of FSW

14 RETRACTABLE PIN TOOL

Two major drawbacks of FSW is the requirement for different length pin tools when welding materials of varying thickness and a keyhole at the end of the weld may be overcome with the help of a retractable pin tool developed by NASA. The automatic retractable pin tool uses a computer controlled motor to automatically retract the pin into the shoulder of the tool at the end of the weld preventing keyholes. This design allows the pin angle and length to be adjusted for changes in material thickness.

Retractable pin tool

15 FSW EQUIPMENT MANUFACTURERS

Some of the manufacturers of friction stir welding machines are:

- Friction stir welding link, U.S.A
- General tool company, U.S.A
- Hitachi limited, Japan
- Smart technology limited, U.K

16 AREAS OF ACTIVE DEVELOPMENT AND RESEARCH

- Development of new tool design
- Use of process at higher speeds
- Research in the use of other materials
- Investigation of fundamental characteristics of FSW created joints

17 CONCLUSION

Such has been the interest in FSW, which was patented not so long ago that considerable effort is being made in transferring the technological benefits from aluminium to other materials. Efforts are on to make the process more flexible. In the new millennium there is no doubt that the automotive sector will find an increasing number of uses for this process as its cost effectiveness and ability to weld dissimilar material combinations with minimal distortion is more widely appreciated. The process has been an excellent substitute for alloys that have inherent fusion welding problems.

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