Influence of Green Joining Technique (FSW) on Microstructural and Mechanical Properties of Similar and Dissimilar Materials – An Overview

Prashant S. H.[1],
[1]Assistant Professor,
Dept. ofMechanical Engg., Sir M VIT,
Bangalore – 562157

Dr. M S Ganesha Prasad[2]
[2]Professor& Head,
Dept. ofMechanical Engg.,
NHCE, Bangalore

PiyushM[3], Abhijit B[3], Ashlesh[3] and K H Amar[3]
[3]UG Scholars,
Dept. of Mechanical Engg.
Sir M VIT, Bangalore – 562157

Abstract - **Friction stir welding (FSW) is a relatively new solid-state joining process which offers various advantages like low distortion, absence of melt-related defects, high joint strength, etc. as compared to other conventional fusion welding techniques. This joining technique is energy efficient, environment friendly and versatile.Joining of similar and dissimilar materials is a very important aspect of industrial application. Especially joining of dissimilar materials is considered as a gateway for the implementation of lightweight materials in automobile and aerospace industries.In FSW, the technology diffusion has significantly outpaced the fundamental understanding of microstructural evolution and microstructure property relationships In this article, we are going to study about different heat zones developed during FSW process and its affect on microstructure and mechanical properties on similar and dissimilar materials.**

Keywords – Dissimilar material, Process parameters, Microstructure.

I. INTRODUCTION

Weldingis a process in which two metal pieces, similar or dissimilar may be joined by heating them to a temperature high enough to fuse the metal, with or without the application of pressure and with or without the aid of the filler materials.

Welding is generally classified into two broadly categories:

Fusion welding is achieved with a help of an intense heat source which leads to local melting and solidification removing the interface between the two base metals.
Solid-state welding is achieved without exceeding the solidus temperature of the base metal. Hence the base metal remains in solid state.

In solid state welding, the cohesive force between the metal atoms is utilized to join two metals. Solid state welding processes, like pressure welding, forge welding, ultrasonic welding, role bonding and diffusion welding are time consuming processes and require special surface preparation.

In late 1991, a very novel and potentially world beating welding method was conceived and the process was duly named friction stir welding (FSW). Friction Stir Welding is the only solid state welding processes which do not have drawbacks as other solid state welding processes and can be employed for butt welding and sheet welding of plates.The main advantage of FSW is that the original material characteristic remains unchanged.
FSW uses a rotating (non-consumable) cylindrical tool that consists of a shoulder and a probe (Fig). The shoulder is pressed against the surface of the materials being welded, while the probe is forced between the two components by a downward force. The rotation of the tool under this force generates a frictional heat that decreases the resistance to plastic deformation of the material. The softened material then easily moves behind the tool and forms a solid state weld as the stirred material is consolidated. FSW can be regarded as an autogenous keyhole joining technique

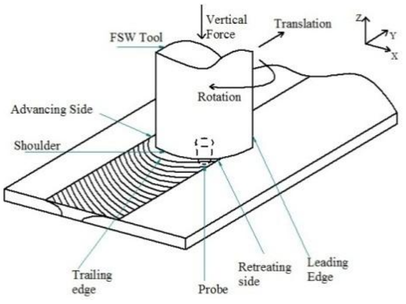

Fig. 1.Friction Stir Welding

The manufacturers are under increasing pressure to produce high strength and lighter products at the same time using less energy, less environmentally harmful materials, at lower cost in short time. FSW, being a solid-state, low-energy-input, repeatable mechanical process capable of producing very high-strength welds in a wide range of materials, offers a potentially lower-cost, environmentally safe solution to these challenges.

The weld-able materials using FSW are Aluminium (all alloys), Copper, Brass, Magnesium, Titanium, Steel Alloys, Stainless Steel, Tool Steel, Nickel, and Lead.

FSW is emerging as a very effective solid-state joining/processing technique. In a relatively short duration after invention, quite a few successful applications of FSW have been demonstrated below.

Shipbuilding and Marine Construction: The shipbuilding and marine industries are two of the first sectors that have adopted the process for commercial applications.

The process is suitable for the following applications:

- Panels for decks, sides, bulkheads and floors
- Hulls and superstructures
- Helicopter landing platforms
- Marine and transport structures
- Masts and booms, e.g. for sailing boats
- Refrigeration plant

Aerospace Industry: At present the aerospace industry is welding prototype and production 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 in Al alloy fuel tanks for space vehicles have been friction stir welded and successfully used. 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 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

Railway Industry: The commercial production of high speed trains made from aluminium extrusions, which may be joined by friction stir welding, has been established.

Applications include:

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

Container bodies

Road Transportation: The friction stir welding process is currently being used commercially and is also being assessed by several automotive companies and suppliers.

Existing and potential applications include:

- Engine and chassis cradles
- Wheel rims
- Attachments to hydro formed tubes
- 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

II. STEPS INVOLVED IN FSW PROCESS

The steps involved in process FSW are as follows:

- A rotating FSW tool plunges into the joint line of the base material and moves forward.
- When the rotating pin contacts the work surface, it rapidly friction heats the material at the point of contact, thus lowering the materials mechanical strength. Under an applied force the pin forges and extrudes the material in its path, until the shoulder of the pin is in intimate contact with the work surface.
- Frictional heat caused by the rotating pin creates a plasticised region around the pin.
- Pressure provided by the weld tool forces the plasticised material behind the pin, cooling and consolidating the weld.
- Stirring action takes place during a weld along the joint line of the plates.

At the junction the friction heating, produced by the rotating shoulder and pin, produce a substantial plasticised layer of metal beneath the tool shoulder and about the pin. When the work-piece is moved against the pin or vice-versa, the plasticised material is mashed by the leading face due to mechanical stirring and forging action imparted by the pin profile and its direction of rotation.

Consequently, as the stir welding tool proceeds down the joint line, it friction heats the abutting joint faces just ahead of the tool to a soft plastic state. It subsequently mashes the joint line, breaking up the oxide film and stirs and recombines the mashed material on the trailing side of the tool where the material cools to form a solid phase weld.

III. PROCESS PARAMETERS

In friction stir welding process, a number of process parameters have to be defined to get good, defect free joints. The important process parameters are:

- Tool geometry
- Tool axial force
- Spindle speed
- Tool transverse speed
- Tool tilt angle
- Feed rate
- Depth penetration

Tool geometryplays a very important role in obtaining good quality weld with sound mechanical properties. The tool comprises of shank, shoulder, and probe. The shoulder compresses the surface of the work piece and prevents the plasticize material from being expelled. The probe is to ensure sufficient working of material at the weld line and the control flow of the material around the tool to form weld of satisfactory quality as the weld progresses.

Tool axial force is the force or load which is applied along the tool axis and acts normal to the welding direction. Tool axial force is provided to initially plunge the probe and to plasticize the material under the tool shoulder in the weld region.

Spindle speed is the rotation frequency of the spindle of the machine measured in rpm. The best speed depends on the weld strength and quality of the weldment required, higher quality of weld and strength can be obtained at high speed operations. The rotational speed of the tool may vary from a few hundred rpm to several thousand rpm.

Tool transverse speed is defined as the rate at which the welding tool advances along the joint line and is given in mm/min. Tool transverse speed depends on the dimensions and alloys which are being used. Increasing the transverse speed lies in trying to minimise the tool shoulder diameter, to increase tool rotation speed and to develop tool shoulder and puin profiles as to increase the effective forward movement of tool per rotation.

InTool tilt angle the tool can be tilted from its vertical position to increase the backward forging action. It provides the ‘wedging’ action for the material being transferred from the advancing side to retreating side of the weld on the trailing side of the tool.

Feed rate is the velocity at which the tool is fed, that is advanced against the work-piece. It is expressed in units of distance per revolution. It affects the heat control and the appearance of the weld.

Depth of penetration is the insertion depth of pin is associated with the pin height. When the insertion depth is too shallow, the shoulder of the tool does not contact the work piece surface and if the insertion depth is too deep shoulder of the tool plunges into the work-piece and a significant concave weld is produced.

IV. HEAT ZONES

In Friction Stir Welding, a variety of interactionsoccur amongst the tool, work piece, backing plate and surrounding environment. These interactions affect the temperature distribution and material flow. Due tothese complex interactions, the microstructure in and around the weld region is affected. This has resulted in the classification of friction stir welds, into four micro structurally distinct regions. The four regions are (A) Parent Material, (B) Heat Affected Zone (HAZ) and (C) Thermo Mechanically Affected Zone (TMAZ),(D) Nugget (marked by circle). All these regions are identified in the figure, which shows the schematic of a typical cross-section of a friction stir weld.

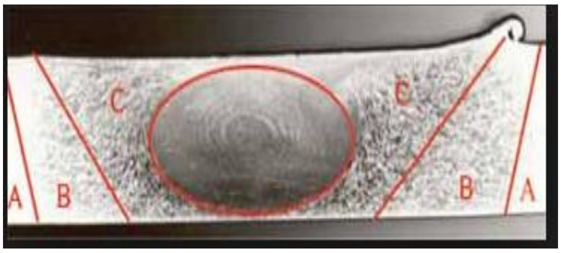

Fig.2. Different Zones formation during FSW

The parent material(or base material) is the region which does not undergo deformation and the microstructure in this region is not affected by the heat produced during the process. No detectable changes are seen in the microstructure of this region.

The nugget region is formed by the intense plastic deformation induced mainly by the tool pin and consists of fine recrystallized grains. Hence this zone is also referred to as ‘dynamically recrystallized zone’.

The heat affected zoneis the region which is affected only by heat and there is no plastic deformation. In this region, the microstructure and/or properties are modified by the thermal heat.

The thermomechanically affected zone surrounds the nugget and it experiences lower temperatures and less deformation, as compared to those in the nugget. In this region, the material is plastically deformed by the tool and is affected by the heat produced (both due to deformation and friction) during the process.

Unlike FS Welds of similar alloys that exhibit four distinctregions, namely Parent Material, Heat Affected Zone (HAZ), Thermo-Mechanically Affected Zone (TMAZ), and Stirred Zone (also called Nugget), the dissimilar welds exhibit eight distinct regions as shown in Fig. 3: (a) Parent Material, (b) HAZ, (c) TMAZ and (d) Stirred Zone for the retreating side alloy and (e) Stirred Zone, (f) TMAZ, (g) HAZ and (h) Parent Material for the advancing side alloy.

V. ADVANTAGES

The process advantages result from the fact that the FSW process takes place in the solid phase below the melting point of the materials to be joined. The benefits include the ability to join materials that are difficult to fusion weld, for example, 2XXX and 7XXX aluminium alloys, magnesium and copper. Friction stir welding can use purpose-designed equipment or modified existing machine tool technology. The process is also suitable for automation and is adaptable for robot use.

Other advantages are as follows:

- Low distortion and shrinkage, even in long welds
- Excellent mechanical properties in fatigue, tensile and bend tests
- No arc or fumes
- No porosity
- No spatter
- Can operate in all positions
- Energy efficient

- One tool can typically be used for up to 1000m of weld length in 6XXX series aluminium alloys
- No filler wire required
- No gas shielding for welding aluminium
- Some tolerance to imperfect weld preparations - thin oxide layers can be accepted
- No grinding, brushing or pickling required in mass production
- Can weld aluminium and copper of >75mm thickness in one pass.

VI. LIMITATIONS

- Exit hole left when tool is withdrawn.
- Large down forces required with heavy-duty clamping necessary to hold the plates together.
- Less flexible than manual and arc processes (difficulties with thickness variations and non-linear welds).
- Often slower traverse rate than some fusion welding techniques, although this may be offset if fewer welding passes are required.

VII. PROBLEM FORMULATION

Materials like aluminium, bronze, and copper have low melting point due to which it cannot be welded using fusion welding and also it alters the original metal characteristics. Fusion welding is not as productive as continuous wire process and also costs more.It is limited to flat and horizontal welding. Material wastage is very high which results in frequent start and stop of process to change the electrode. There is limitation to automate fusion welding process. A conventional welding technique produces fumes which are harmful to the environment.

For this reason Friction Stir Welding is recommended which has many advantages, including improved mechanical properties, improved process robustness, lack of consumables, less health and environmental issues and operating cost advantages. FSW has gained significant interest in automotive and aerospace and industries. FSW is the also the only solid state process which is not time consuming and does not require surface prepare preparation. If parameters are well defined FSW can be automated. It is also the best choice for joining dissimilar metals.

VIII. LITERATURE REVIEW ON FSW OF DISSIMILAR MATERIALS

Friction Stir Welding can be used to join high strength aerospace aluminium alloy and other metallic alloys that are hard to weld by conventional fusion welding. FSW is considered to be the most significant development in the metal joining in a decade. Below are some recent work done by researchers on similar and dissimilar metals:

James Florian Quinn et. al. (1), performed a process for adjoining materials by friction stir welding. Two adjacent material segments are heated by localized heating to raise the temperature of each segment along the intersection to a discrete predefined level below the melting point of the particular segment of material being heated. In conjunction with this discrete localized heating, friction stir welding is carried out along the intersection to form the solid state bond.

Jawdat A (2)investigated the butt welding of aluminium with copper by friction stir welding. The rotation direction of the tool and the probe offset with respect to centre of butt line are the main welding parameters affecting the welding quality founded in this study. A sound welding has been obtained when aluminium arranged on advancing side, with sufficient probe offset to aluminium side. Also, defect free Al-Cu welded joint produced when the copper arranged on advancing side with probe offset to aluminium side. So, probe offset play as important factor rather than direction of rotation in welding Al-Cu by friction stir welding.Welding tools with flat shoulder of 18mm diameter, and 20 mm height, made of high carbon steel, were used.

H Uzun et al. (3), carried out the joining of Al 6013-T4 alloy and X5CrNi18-10 stainless steel was carried out using friction stir welding (FSR) technique. The microstructure, hardness and fatigue properties of fiction stir welded 6013 aluminium alloy to stainless steel have been investigated. Optical microscopy was used to characterise the microstructures of the weld nugget, the heat affected zone (HAZ), thermo-mechanical affected zone (TMAZ) and the base materials. The results show that FSR can be used the joining of dissimilar Al 6013 alloy and X5CrNi18-10 stainless steel. Seven different zones of the microstructure in the welding are reported as follows: (1) parent stainless steel, (2) HAZ in the stainless steel at advancing side of weld, (3) TMAZ in the stainless steel at advancing side of weld, (4) weld nugget, (5) TMAZ in the Al alloy at retreating side of weld, (6) HAZ in the Al alloy at retreating side of weld and (7) parent Al alloy. A good correlation between the hardness distribution and the welding zones are observed. Fatigue properties of Al 6013-T4/X5CrNi18-10 stainless steel joints were found to be approximately 30% lower than that of the Al 6013-T6 alloy base metal.

Y C Chen et al. (4), tried to lap join Al–Si alloy and pure titanium using friction stir welding technology. Microstructure and tensile properties of joints were examined. The maximum failure load of joints reached 62% of Al–Si alloy base metal with the joints fractured at the interface. X-ray diffraction results showed that new phase of $TiAl_3$ formed at the interface. The microstructure evolution and the joining mechanism of aluminium–titanium joints were systematically discussed.

Satish V Kailas et al. (5), attempted to understand the mechanism of friction stir weld formation and the role of friction stir welding tool in it. This has been done by understanding the material flow pattern in the weld produced in a special experiment, where the interaction of the friction stir welding tool with the base material is continuously increased. The results show that there are two different modes of material flow regimes involved in the friction stir weld formation; namely “pin-driven flow” and “shoulder-driven flow”. These material flow regimes merge together to form a defect-free weld. The etching contrast in these regimes gives rise to onion ring pattern in friction stir welds. In addition to that based on the material flow characteristics a mechanism of weld formation is proposed.

Yen-Lung Chen (6) stats that when a friction stir weld tool penetrates the interface of two workpieces of dissimilar metal alloy materials, the resultant weld of the different alloy materials may produce a weak weld joint. Such weak joints are often experienced, for example, when attempting to form spot welds or other friction stir welds between a magnesium alloy sheet or strip and an aluminium alloy sheet or strip. It is discovered that suitable coating compositions placed at the interface of assembled workpieces can alter the composition of the friction stir weld material and strengthen the resulting bond. In the example of friction stir welds between magnesium alloy and aluminium alloy workpieces, it is found that combinations of copper, tin, and zinc, and other powders can strengthen the magnesium-containing and aluminium-containing friction stir weld material.

YJ Kwon et al. (7), carried out the friction stir welding between dissimilar materials like magnesium and aluminium alloy plates with thicknesses of 2 mm was performed. The tool for welding was rotated at speeds ranging from 800 to 1600 rpm under a constant traverse speed of 300 mm/min. For tool rotation speeds of 1000, 1200, and 1400 rpm, defect-free welds were successfully obtained and the surface morphology of the welds became smoother as the tool rotation speed was increased. The relatively simple bonded interface was clearly evident and had a zigzag pattern. A mixed microstructure of magnesium and aluminium alloys was formed near the bonded interface. The maximum tensile strength of about 132 MPa was obtained at the tool rotation speed of 1000 rpm. However, there were not noteworthy changes in the tensile strength as a function of the tool rotation speed. The elongation was 2% or less, regardless of the tool rotation speed.

Takehiko Watanabe et al. (8), tried to butt-weld an aluminium alloy plate to a mild steel plate by friction stir welding and investigated the effects of a pin rotation speed, the position for the pin axis to be inserted on the tensile strength and the microstructure of the joint. The behaviour of the oxide film on the faying surface of the steel during welding also was examined.The main results obtained are as follows. Butt-welding of an aluminium alloy plate to a steel plate was easily and successfully achieved by friction stir welding. The maximum tensile strength of the joint was about 86% of that of the aluminium alloy base metal. A small amount of intermetallic compounds was formed at the upper part of the steel/aluminium interface, while no intermetallic compounds were observed in the middle and bottom parts of the interface. The regions where the intermetallic compounds formed seemed to be fracture paths in the joint. Many fragments of the steel were scattered in the aluminium alloy matrix and the oxide film removed from the faying surface of the steel by the rubbing motion of a rotating pin was observed at the interface between the steel fragments and the aluminium alloy matrix.

Maria Claudia Theodoro et al. (9), carried out the verification of the viability of dissimilar UNS S31603 austenitic and UNS S32750 super duplex stainless steels joined by friction stir welding, 6mm thick plates were welded using a PCBNWRe tool. The welded joints were performed in position control mode at rotational speeds of 100 to 300 rpm and a feed rate of 100 mm/min. The joints performed with 150 and 200 rpm showed good appearance and no defects. The metallographic analysis of both joints showed no internal defects and that the material flow pattern is visible only in the stirred zone (SZ) of the super duplex steel. On the SZ top, these patterns are made of regions of different phases (ferrite and austenite), and on the bottom and central part of the SZ, these patterns are formed by alternated regions of different grain sizes. The ferrite grains in the super duplex steel are larger than those in the austenitic ones along the SZ and thermo mechanically affected zone, explained by the difference between austenite and ferrite recrystallization kinetics. The amount of ferrite islands present on the austenitic steel base metal decreased near the SZ interface, caused by the dissolving of the ferrite in austenitic matrix. No other phases were found in both joints. The best weld parameters were found to be 200 rpm rotation speed, 100 mm/min feed rate, and tool position control.

K. Kimapong et al. (10), tried to butt joint weld of an aluminum alloy plate to a mild steel plate using friction stir welding. This study investigated the effects of pin rotation speed, position of the pin axis, and pin diameter on the tensile strength and microstructure of the joint. The main results obtained are as follows:

Butt-joint welding of an aluminum alloy plate to a steel plate was easily and successfully achieved. The maximum tensile strength of the joint was about 86% of that of the aluminum alloy base metal.Many fragments of the steel were scattered in the aluminum alloy matrix, and fracture tended to occur along the interface between the fragment and the aluminum matrix. A small amount of intermetallic compounds was formed at the upper part of the steel/aluminum interface, while no intermetallic compounds were observed in the middle and bottom regions of the interface. A small amount of intermetallic compound was also often formed at the interface between the steel fragments and the aluminum matrix. The regions where the intermetallic compounds formed seem to be fracture paths in a joint.

T. DebRoy et al. (11), noted that friction stir welding does not involve bulk melting of the components that are joined. This has inspired attempts to exploit it for joining materials which differ in properties, chemical composition or structure, and where fusion can lead to detrimental reactions. The purpose of this special issue of Science and Technology of Welding and Joining was to assess the status of friction stir welding of dissimilar alloys and to identify the opportunities and challenges for the future.

A.A.Mclean et al. (12), carried out preliminary investigation into the application of friction stir welding for joining a magnesium alloy to an aluminium alloy. The work has shown that liquation during the welding process can lead to the formation of a brittle intermetallic at the joint interface. This intermetallic has a microstructure composed of a divorced lamellar eutectic containing Al12Mg17 and magnesium. The formation of this microstructure and its influence on mechanical properties are discussed in terms of solidification theory.

Sahidi et al. (13) thought that the joining of steels to aluminium alloys can be used for producing steel/aluminium bimetallic parts in a wide range of industrial areas. Friction Stir Welding is a solid – state thermo – mechanical joining process (a combination of extruding and forging). The overall aim of this study is to get the optimum parameters for the materials under considerations, to investigate the Heated Affected Zone (HAZ), Thermo – Mechanical Affected Zone (TMAZ) and Weld Nugget (WN) besides to study the defects occurring during welding process by applying different parameters chosen. The welding process was done by using conventional milling machine. Three experiments being used are the Tensile Testing, Optical Microscopy (OM) and Electron Scanning Microscopy (SEM) to get the strength of the joint and the metallographic studies. The findings also found out that suitable parameters being choose give less defect and intermetallic compounds (IMCs). Therefore, at higher speed and lower tool plunge length, the joint strength decreased due to lack of bonding between aluminium and steel.

Ivan Galvao et al. (18) obtained in his present research, relative to friction stir welding of 1 mm thick plates of aluminium, copper, copper-zinc and zinc alloys, prove that the application of the process in the joining of very thin plates is feasible and desirable. In fact, independently of the base material, the welds produced presented very good morphological characteristics and significant grain refinement in the nugget. Tensile and hardness tests provedthat all the welds were at least in even-match relative to the base material properties. Based on the AA 5182 aluminium alloy results it was also possible to conclude that augmenting the welding speed, which improvesprocess productivity, increases grain refinement in the nugget, improving the mechanical properties of the welds.

N.T. Kumbhar et al. (19) carried out Friction Stir Welding (FSW) of aluminium,magnesium, copper and titanium alloys by using HSS tool. Being a solid state joining process, friction stir welding offers various advantages like low distortion, absence of melt-related defects, high joint strength,etc. as compared to other conventional fusion welding techniques. A brief overview of the friction stir welding process and recent developments are presented in this paper. In addition, a composite picture of the work done at BARC, relating to the microstructural developments in a friction stir welded Al 5052 alloy is presented.

IX. SCOPE

The environment friendly friction stir welding process is a potential and proven method for welding high strength alloys. This solid state localized thermo-mechanical joining process is a predominantly used for butt and large joints with no consumables. Apart from this it also does not alter the characteristics of the parent metal. If we are able to determine the parameter that influences the weld most than we will be able to automate the complete welding process and thereby increase the productivity.

X.CONCLUSION

Friction stir welding is a recent form of welding technique that has not yet been widely used in industries. Still lot of research is needed in the area of dissimilar metal joining using FSW. Nowadays due to demands of strength with lightweight in structural components which cannot be obtained in a single material, one needs to use various combinations of materials. Hence research has to be carried out in joining dissimilar materials using FSW as it does not alter the characteristics of the parent material and also no smoke is formed during welding, hence environment friendly.

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