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A Review on Friction Stir Welding of Aluminium Alloys

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ABSTRACT: The latest trend in the automotive or aerospace industries, have focused on light-weight materials like aluminium. Aluminium is chosen over steel, mainly due to lower density of aluminium. The main challenges of aluminium to use for any application is the weld ability of the aluminium alloys. Aluminium is very reactive and due to its higher thermal conductivity, it is found to be difficult to weld using conventional welding process (GTAW & GMAW). Though, Friction stir welding (FSW) is the process that seems to be effective solid state joining process over conventional welding processes. This review article discuss about the process of friction stir welding and its impact on microstructure, hardness and strength of the joint.

KEYWORDS: Friction stir welding; Aluminium; microstructure; Grain refinement

I. INTRODUCTION

Friction stir Processing (FSP) is a new microstructural modifications technique; recently FSP has become an efficient tool for homogenizing and refining the grain structure of metal sheet. Friction stir processing is believed to have a great potential in the field of superplasticity. Results have been reported that FSP greatly enhances superplasticity in many Al alloy [1-2]. Friction stir processing is based on friction stir welding (FSW) which was invented by The Welding Institute (TWI) of United Kingdom in 1991 [3- 4].

Friction stir welding is one of the new entrants to the solid state joining techniques, which have made remarkable progress in welding technology. It is essentially a solid state joining process, widely used for the welding of light and difficult-to-weld metals and their alloys like aluminium, magnesium, copper etc [1]. Recently, its applications have been extended to the welding of high melting point materials such as various types of steels [5], Ti alloys [6], Ni-based super alloys [7], the welding of metal matrix composites and polythene [1].

Friction stir welding is being used in various engineering applications, which require the joining of dissimilar material combinations and which are not viable using conventional fusion welding techniques. With recent developments in technology of friction stir welding, it is now possible to carry out dissimilar welding of various types of steels with alloys of aluminium, magnesium, copper, titanium and also other alloy combinations [8]. Moreover, work pieces in the form of plates, sheets and hollow pipes can be welded by this method. Over a period of time developments in friction stir welding have led to different variants like friction stir processing, friction stir spot welding, friction stir channelling etc. [1]. Thus, it can be said that friction stir welding and its variants have brought a revolution in the field of solid state joining technology.

II. MOTIVATION

Forming and Formability of light weight alloys at room temperatures for aerospace and automotive applications present a major challenge. One way to improve the formability is to refine and homogenize the microstructure and form the sheet at high temperatures using advanced forming techniques such as superplastic forming. Recent observations have indicated that ultrafine grain sheet metals have superior formability at relatively moderate temperatures. However, the difficulty in producing ultrafine grain sheet metals hinders the widespread utilization of light weight alloys in the transportation industry. Conventional grain refinement techniques usually involve thermo-mechanical processing (e.g. hot rolling) which is costly, time consuming, and negatively affects the environment due to high energy consumption. Alternative effective grain refinement methods are very much needed.

As the concept of FSP being relatively new, there are many areas, which need thorough investigation to optimize the process and make it commercially viable. In order to obtain the desired finer grain size, certain process parameters like rotational and translation speeds, tool geometry etc., are to be controlled. Several investigations are being carried out in order to study the effects of these process parameters on the grain structure.

III. FRICTION STIR WELDING

Friction stir welding was invented by TWI, Cambridge in 1991 [3-4]. Friction stir welding involves the joining of metals without fusion or filler materials; it produces a plasticized region of material. A non-consumable rotating tool is pushed into the materials to be welded and then the central pin, followed by the shoulder, is brought into contact with the two parts to be joined as shown in Figure 1. The rotation of the tool heats up and plasticizes the materials it is in contact with and as the tool moves along the joint line, the material from the front of the tool is swept around this plasticized annulus to the rear, eliminating the interface. So the welds are created by the combined action of frictional heating and mechanical deformation due to a rotating tool. The maximum temperature reached is of the order of 0.8 of the melting temperature. The 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 pin penetrates the workpiece whereas the shoulder rubs with the top surface. The heat is generated primarily by friction between a rotating-translating tool and the workpiece, the shoulder of which rubs against the workpiece. There is a volumetric contribution to heat generation from the adiabatic heating due to deformation near the pin. The welding parameters have to be adjusted so that the ratio of frictional to volumetric deformation induced heating decreases as the workpiece becomes thicker. This is in order to ensure a sufficient heat input per unit length.

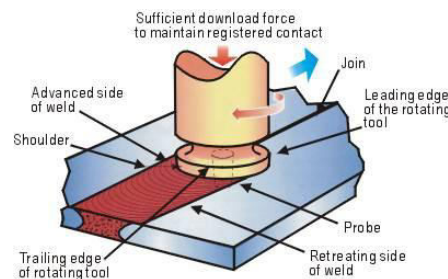


Figure 1: Schematic of Friction Stir Welding Process

Friction stir welding is used already in routine, as well as critical applications, because it produces strong and ductile joints. The process is most suitable for components which are flat and long (plates and sheets) but also it can be used for pipes, hollow sections, and positional welding.

Traditionally, friction welding is carried out by moving one component relative to the other along a common interface, while applying a compressive force across the joint. The friction heating generated at the interface softens both components, and when they become plasticized the interface material is extruded out of the edges of the joint so that clean material from each component is left along the original interface. The relative motion is then stopped, and a higher final compressive force may be applied before the joint is allowed to cool down. The key to friction welding is that no molten material is generated, the weld being formed in the solid state.

The friction heating is generated locally, so there is no widespread softening of the assembly. Friction welding has gained much interest among researchers and also in by industries because of the following advantages [9]:

- The weld is formed across the entire cross-sectional area of the interface in a single shot process.
- The technique is capable of joining dissimilar materials with different melting temperatures and physical properties.
- The process is completed in a few seconds with very high reproducibility – an essential requirement for a mass production industry.
- The process is environmentally friendly.
- This technique does not require consumables (filler wire, flux or gas) and produces no fumes.

Stages of Process:

For friction stir welding a specially designed cylindrical tool is used, the tool consists of a pin and a concentric larger diameter shoulder. While the tool is rotating the pin is plunged into the sheet and the shoulder comes in contact with the surface of the sheet. The friction between the tool and the sheet generates heat which softens the material without reaching the melting temperature of the material; that is why it is a solid state process. Then the tool is transverse in the desired direction while it is rotating. The rotation of the pin does the stirring action of the softened material which makes the material undergo intense plastic deformation yielding a dynamically recrystallized fine, equiaxed, and defect free grain structure. Stages of FSW is shown in Figure 2.

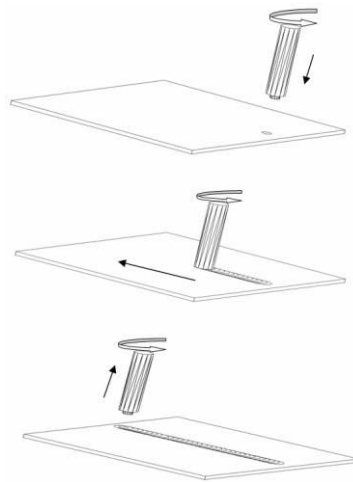


Figure 2: Schematic diagram showing stages of Friction Stir Welding Process.

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 rotation speed, tool traverse speed, tool tilt angle, insertion depth of the tool pin, etc [1]. The quality of friction stir welds depends upon the use of an optimum combination of these process parameters. For harder alloys or alloys with thicker sections, slower traverse speeds and lower rotational speeds are used. Increasing the rotational speed or decreasing traverse speeds increases heat input and welding temperatures. However, extremely high or low travel and rotational speeds can adversely affect properties. Any inappropriate combination of the process parameters may result in incomplete welds or the formation of defects or weld flaws. The most common defects observed during friction stir welding are : the groove and channel defects, lazy S defect, 'Kissing bond' defect, formation of voids, root flaws, joint line remnants, etc. [11].

Design of tools:

The design of the tool is a critical factor as a good tool can improve both the quality of the weld and the maximum possible welding speed. It is desirable that the tool material is sufficiently strong, tough and hard wearing, at the welding temperature. Further, it should have good oxidation resistance and low thermal conductivity, to minimize heat loss and thermal damage to the machinery further up the drive train [1]. Tool steels have been widely used for welding aluminium alloys within thickness ranges of 0.5 - 50 mm, but more advanced tool materials like Carbides, Polycrystalline Cubic Boron Nitride (PCBN) and tungsten rhenium (W-Re) alloys are necessary for more demanding applications such as highly abrasive metal matrix composites or higher melting point materials like steel or titanium. Different tool configurations & tool geometry is shown in the Figure 3 & 4 respectively.

Improvements in tool design have been shown to bring about substantial improvements in productivity and quality [12]. Modifications in the design of the pins (Threaded pins and fluted pins) ensured, that the plastically deformed material is fully delivered around the pin, and from the upper parts of the joint to the lower parts. This results in efficient mixing and enables the use of higher speeds and results in better quality, void free welds. Tools with scrolled

shoulders eliminated weld surface undercutting and the flash that extrudes under the tool shoulder. For performance of FSW both plates on which welding is done is required to be clamped properly.



Figure 3: Various tool design used for FSW Process

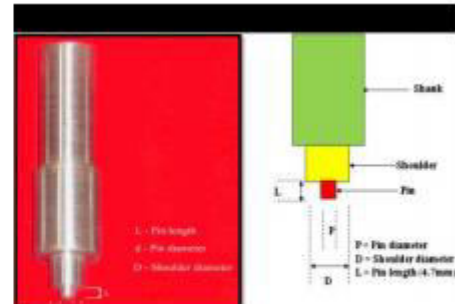


Figure 4: Tool Geometry of FSW Process

Heat affected zone during FSW Process:

During friction stir welding, a variety of interactions occur amongst the tool, work piece, backing plate and surrounding environment. These interactions affect the temperature distribution and material flow [13-14]. As a result of these 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. According to Threadgill [11] the four regions are (i) Parent Material, (ii) Nugget, (iii) Heat Affected Zone (HAZ) and (iv) Thermo-Mechanically Affected Zone (TMAZ). All these regions are identified in Figure 5, which shows the schematic of a typical cross section of a friction stir weld. 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 zone is 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 thermo-mechanically 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.

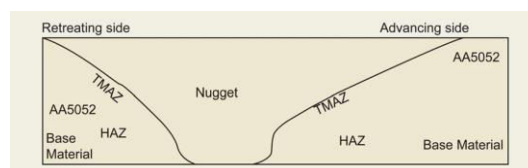


Figure 5: Schematic of the cross-section of the friction stir weld showing the various characteristic regions

Grain Structure:

The microstructural results using Orientation Imaging Microscopy (OIM) show the difference in grain size and homogeneity. As shown in Figure 6 the deformation zone consists of three zones: the nugget, the thermo mechanical zone (TMZ), and the heat affected zone (HAZ). The grain size distributions are shown, and it is obvious that grain size within the nugget region is smaller than the other regions. Also it is observed that heat affected zone is larger for the sample processed at 800 rpm than that processed at 600 rpm and this is because of the higher rotational speed which means more heat generated by friction.

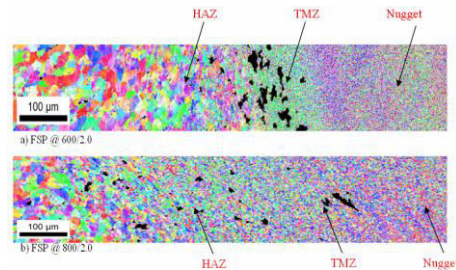


Figure 6: The grain structure at different locations of the FSW AA5052 sheet, at different conditions using OIM[9].

Hardness:

It can be seen that a hardness degradation region, i.e., softened region, has occurred in each joint, thus the tensile properties of the joint are lower than those of the base material.[15] It can be believed that FSW creates a softened region around the weld center in a number of precipitation hardened aluminium alloys. It was suggested that such a softening is caused by coarsening and dissolution of strengthening precipitates during the thermal cycle of the FSW [16].

Another observation of the micro hardness results is the hardness on one side of weld center differs from the other side (unsymmetrical weld). This difference can be explained as follows: In the leading side (advancing side) for the rotating tool where the rotational velocity vector and the forward motion vector are in the same direction and due to this there is higher heating on one side of the weld center and hence lower hardness.

Microhardness profiles below shown in Figure 7, there are two low-hardness zones on both sides of the weld center and they correspond to the two HAZs in the joint [17]. Considerable softening was observed in the weld zone. However, the hardness in the weld nugget and the thermal-mechanically affected zones is higher than that in the heat affected zone. This difference is attributable to the dynamic recrystallization that took place within the weld zone as a result of the friction heat and mechanical work. In the heat-affected zone, the hardness increases with increasing distance from the weld center and approaches that of the base metal at 12-15 mm from the weld center [18]. Another indication from microhardness results that increase with increasing welding speed for the same rotational speed for all welding parameter and it can be attribute to the low heat input when increasing welding speed during welding operation and that resulted in less material softening[19].

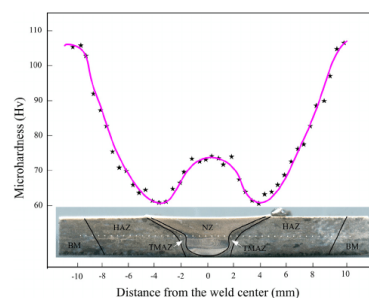


Figure 7. Micro hardness distributions of the FSW joint in Al alloy [20]

Comparison of FSW of Various Aluminium alloys:

Friction stir welding (FSW) has become an obvious choice for welding of “difficult to weld” aluminium alloys (5xxx series) or high-strength aluminium alloys (2xxx and 7xxx series). It has also facilitated welding of dissimilar aluminium alloys with same ease. The dissimilar welding of aluminium alloys has attracted more attention, since it offers an insight into many phenomena (e.g., material flow) which were not clear during the friction stir welding of similar Al alloys. General weld ability of Al alloys is shown in Figure 8.

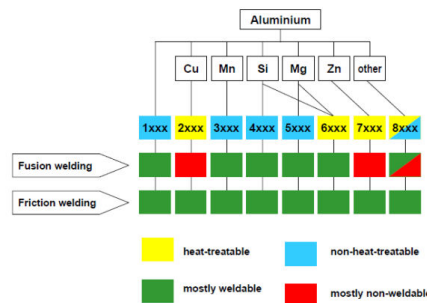


Figure 8. Weldability of Aluminum Alloys[21]

Lee et al. [22] studied the dissimilar lap joint FSW of AA 5052-H112 and AA 6061-T6 plates having thickness of 1mm and 2 mm, respectively, with various tool rotation speeds and tool traverse speeds according to the fixed location of each material on top or bottom sheet. They found that the interface morphologies were characterized by interface pull-up and pull-down in the advancing side and retreating side. The thickness of the thinner AA5052 sheet lessened due to the vertical movement of the materials. It was identified that the amount of vertical transport increased and consequently the thickness of AA5052 decreased when the heat input was increased either by increasing the tool rotation speeds or by decreasing the tool traverse speeds. Joint strengths mainly depended on the interface morphology and vertical movement of material.

Table 1: Composition of AA 5052 & AA 6061 alloys

Elements(wt%)	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
AA 5052	0.11	0.25	0.17	0.03	2.2	0.25	0.02	-
AA 6061	0.64	0.38	0.256	0.033	0.9	0.211	-	0.018

Park and Kim [24] investigated the effect of tool rotation speed and tool traverse speed on the stirring action and friction heat during FSW experiments on dissimilar Al alloys— AA5052-O and AA6061-T6. They used a range of process parameters to determine the mechanical strength of weld nugget of the dissimilar materials. They concluded that the optimum conditions were a travelling speed of 61 mm/min and rotation speed of 1600 rpm. Their observations of the weld surface finish and plastic flow behavior showed that the stirring effect increased and number of defects decreased when the traverse speed was decreased. Park et al [25] investigated the effect of material locations on the properties of dissimilar FSW joints of AA5052-H32 and AA6061-T6. They showed that the material mixing patterns in FSW joints vary depending on the location of base materials. For the given aluminium alloys, the materials were more properly mixed when AA5052-H32 was in the advancing side and AA6061-T6 was in the retreating side than the case of AA6061-T6 in the advancing side and AA5052-H32 aluminium alloy in the retreating side. It was found that for both combinations of material arrangement, AA5052-H32 showed the lowest value of microhardness in the heat-affected zone (HAZ), which clearly explained the reasons for the fracture of tensile test specimens at the 5052-H32 side.

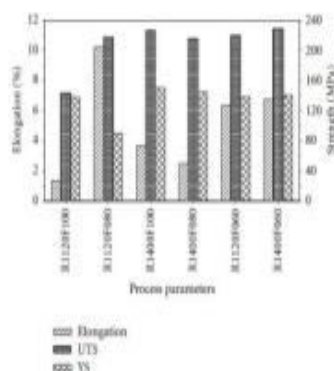


Figure 9: The % elongation, ultimate tensile strength (UTS), and yield strength (YS) for various combinations of process parameters for friction-stir-welded AA5052-AA6061 specimens.[27]

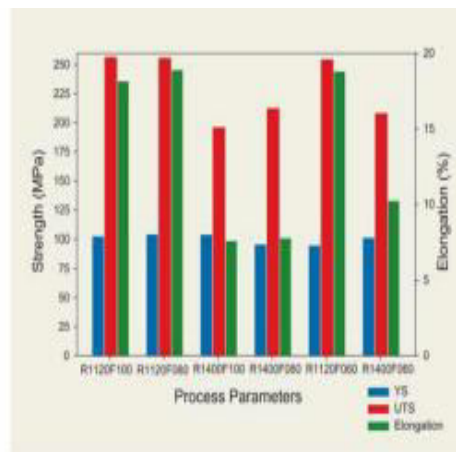


Figure 10: Comparison of the ultimate tensile strength, yield strength and ductility of the friction stir welds at various combinations of process parameters for AA5052[10]

Thus the inter diffusion of alloying elements and attaining of similar orientations in the nugget could have contributed to the good mechanical properties of the friction stir welded AA5052-AA6061 specimens. The tensile properties of the FSW AA5052- AA6061 specimens were better than the properties of the softest of the similar friction-stir-welded systems (i.e., FSW AA5052) from Figure 9 & 10.

IV. APPLICATION

- FSW is being used in all transport industries including shipbuilding, automotive, rail and aerospace industries [28].
- In shipbuilding industry, the FSW process is used for the production of large aluminium panels, which are made from aluminium extrusions.
- In aerospace industry, large tanks for satellite launch vehicles are fabricated by FSW from high-strength aluminium alloys.
- Several companies (The Boeing Company, Eclipse Aviation Corporation, Airbus etc.) manufacture lightweight aluminium airframe structures, fuselage and wing applications using FSW for commercial and military aircrafts.
- The railway industry uses FSW for the production of large prefabricated aluminium panels, which are made from aluminium extrusions.
- The automotive industry uses FSW in the production of components like light alloy wheels and fuel tanks.

V. SUMMARY

The present review has demonstrated the extensive research effort that continues to progress the understanding of FSW of aluminium alloys and its influence on their microstructure and properties. It identifies a number of areas that are worthwhile for further study. Friction stir welding is an effective microstructural modification process that produces very fine and homogenous grain structure. Generally, smaller grain sizes are obtained on weld nugget of all FSW joints. Microhardness drop was observed in the weld region of FSW joints and an increase in values of microhardness when increasing welding speed. In general, joint shows ductile mode of fracture.

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