A Review on Friction Stir Welding for Aluminium Alloy to Steel

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Abstract- Friction stir welding is a relatively new solid state joining process which locale a major role in different industry including the aerospace, automotive and manufacturing industry field to join aluminium alloy and steel that are hard to weld by fusion welding process. FSW has inspired researchers to join dissimilar materials such as Al Alloy to Steel which different in properties and sound weld with intermetallic compounds layer has been produced. The purpose of the development of this technique was to reduce the common issues associated with other joining mechanism such as fusion welding, brazing and soldering etc. In Friction stir welding, the energy input and distortion are significantly lower than in fusion welding technique, thus improve the welding properties and the resulting joints offers less distortion, less residual stresses, fewer weld defects. This paper reviews the work done in the above mentioned area and concludes by suggesting further scope for research in Friction stir welding.

Keywords- Friction stir welding, Tool Design, Microstructure and Mechanical properties

1. INTRODUCTION

The need of joining dissimilar materials often arises in industrial application due to demand for reduced weight and improved performance from engineering structure. Friction stir welding can be performed on a variety of joint configuration including butt joint, lap joint and T joint (1). Friction stir welding is a solid-state joining process invented in 1991 at The Welding Institute, U K (2). Friction stir welding is a promising candidate for joining dissimilar materials and a non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and traversed along the line of joint (3). Honda Motor Corporation has implemented FSW to join dissimilar aluminum alloy and steel in an automobile front structural component in production vehicle Honda Accord. The front sub frame which carries the engine and some suspension components is made of die cast aluminum and press formed steel halves. FSW was applied to weld the aluminum to the steel in a lap configuration at various locations as indicated by short stitches and Honda claimed that the total body weight is reduced by 25% compared to the conventional steel sub frame with reduced electricity consumption by approximately 50% (4). Mazda Motor Corporation has developed direct friction stir spot joining technology to weld aluminum alloy and steel and applied it to join the trunk lid of the Mazda MX-5. Friction stir welding is an innovative low temperature welding process due to rotation and pressure of a tool, frictional heat is produced and the parts soften plastically in the area of the rotating tool without reaching the melting point there by joining the parts. FSW has many advantages over the fusion welding technique because, process temperatures remains below the melting point of the weld material, there is no need for filler material. Friction stir welding is also an energy efficient process that produces no fumes; spatter and arc flash (5). Friction stir welding can produce high quality welds in materials like aluminium, nickel, magnesium, titanium and steel. Friction stir welding process includes three phenomena; heating, plastic deformation and forging (6). During FSW process, the material undergoes intense plastic deformation at elevated temperature, resulting in generation of fine and equiaxed recrystallized grains and the fine microstructure in FSW produces good mechanical properties. In Friction stir welding there are two sides one is advancing side and other is retreating side and give the idea of advancing side and retreating side in the transverse direction of welding. Material on advanced side mixed more vigorously than material on retreating side. The Retreating side is the side where the velocity vector of tool rotation and traverse direction are opposite and in the advancing side the velocity vector of tool rotation and traverse direction are similar. In butt joint configuration, the higher melting temperature plate is often placed on the advancing side and lower one is on retreating side and welding tool is offset from the butt interface towards the lower melting temperature materials to prevent over heating of low melting temperature material and tool wear.

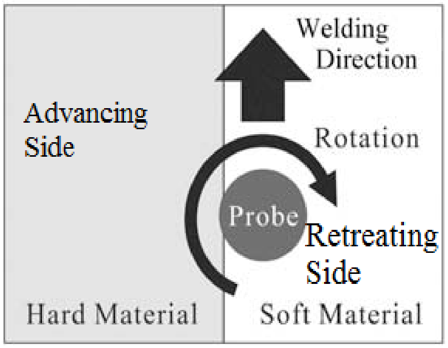

Fig. 1 Side of FSW (12)

The multi-pass joint is formed of at least 2 FSW joints in parallel configuration. The first and second pass joints define transversely opposite advancing and retreating side. The second pass joint is disposed to at least partially overlap the retreating side of the first pass joint. Thus the material at the retreating side of the first pass joint that may be insufficiently mixed during formation of the first pass joint is remixed. The weld nugget zone and TMAZ are the weakest part of the joint. Stir zone marks the area of greatest material deformation region and as such indicates the pin position through the weld process. This region is also representative of the area of greatest heat thus undergoes the highest degree of recrystallization and the structure of stir zone like an onion ring structure. TMAZ located immediately either side of the stir zone and the temperature in this region is lower and resulting in a lower degree of recrystallization. In HAZ a very little grain recovery occurs compared to the central region. The benefits over the fusion welding for HAZ are that since FSW is solid-state, cracking is neglected for these common reasons.

2. Tool Geometry and Materials

For a given joint design in FSW the weld quality, cost and tool wear are important consideration in the selection of the tool material and tool geometry. Tool design is the most powerful aspect of FSW process for development joint without any defects such as voids incomplete root penetration etc. In the welding tool, the tool shoulders are designed to produce heat through friction and material deformation to the surface of work-piece. The diameter of shoulders is generally depends on the pin size adopted (7). Generally the concave, convex scroll, flat shoulders should be used for joining for dissimilar materials (8). The designs of tool pin are much more complex compared to the shoulders. Tool pin is designed to disrupt the faying surface of the work-piece. Generally the threads, steps, flats pin have been widely used for control the material flow for better mechanical mixing (9). The welding tool has mainly 3 functions; heating the work-piece, movement of material to produce the joint and containment of the hot metal beneath the tool shoulders. Weld quality and tool wear are two important factors in the selection of tool material. Due to the severe heating of the tool during FSW significantly wear may result if the tool material has low yield strength at high temperature. Stresses experienced by the tool are dependent on the yield strength of the work-piece at high temperature. Temperature in the work-piece depends on the material properties of tool such as the thermal conductivity and co-efficient of thermal expansion which also effect the thermal stresses in the tool.

Tool steel is commonly used a tooling material for joining of the dissimilar materials in both lap and butt configuration. When welding is performed between low and high melting temperature materials such as Al or Mg alloy to steel and Al or Mg alloy to titanium alloy, tool steel and alloy steel have been used in both lap and butt joint configuration (14). Tungsten based tools such as tungsten carbide and tungsten rhenium are also used for joining low to high melting temperature materials (12). In the lap configuration tool steel use as a tool materials and placing of softer plate on the top for joining the dissimilar materials for avoiding tool wear. When welding is performed for high melting temperature materials such as steel to steel and steel to nickel alloy, tungsten carbide cobalt or polycrystalline cubic boron nitride (PCBN) used as a tool materials (10).

3. Literature Review

Welding between the Aluminium Alloy to steel is difficult by conventional welding process because the dissimilar base metal and dissimilar melting point temperature so Friction stir welding is suitable for joining of Al Alloy to Steel. For joining of Al Alloy to Steel the FSW tool can not be plunged symmetrically in to the joint line because excessive heating of steel which will cause melting of Al Alloy and produced the defective weld. Hence for this purpose the offset method is used during FSW. In the offset method, the centre of the tool is plunged towards the low melting temperature materials (11).

R. S. Coelho (12) studied the microstructure and mechanical properties of FSW of dissimilar AA6181-T4 and two grades of high strength steel (HSS) Of DP600 and HC260LA with the use of Tungsten-Rhenium WRe25 FSW tool of 13 mm shoulder diameter with concave shape and 5 mm cylindrical non threaded pin and minimum wear is occurs when the pin is plunged in to the softer AA6181-T4 and does not contact with the HSS. In both the joints, a small amount of detached particle of HSS transported in to the Al Alloy and the softer HSS interface deformed strongly, larger detached particle compare to the harder HSS. Intermetallic phase formation and interlocking occurs due to the high shear strain rate and friction heating during the process. The microstructure at the interface is non-smooth and complex due to α-Fe (ferrite) grains and a very thin layer of intermetallic Fe_xAl_y compounds formed by chemical reaction and diffusion between the Al and Steel as shown in fig. 2.

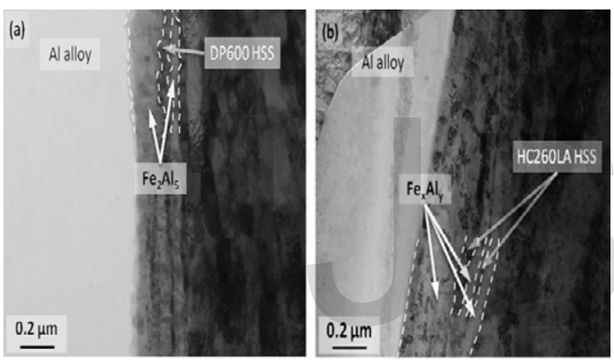

Fig. 2 Weld interface of Al- steel (12)

The highest Hardness values in both the cases were observed in the weld interface between the Al and steel. The tensile property in both the cases observe in the table given table.

Joints	Yield strength (Mpa)	Tensile strength (Mpa)	Elongation (%)
Al-HC260LA	112±2	200±8	8±1
Al-Dp600	119±2	211±2	7±1

Fractography analysis showed that failure occurs far away from the joint interface on the retreating side crossing the interface of Al Alloy Base metal, HAZ, TMAZ and Nugget zone because this region reveals the presence highly deformed grains and evidence of sub-grain development.

T. Tanaka (13) studied the joint strength of dissimilar FSW of mild steel to AA7075-T6 Al Alloys of 3 mm plate thickness with varies the tool rotation speed 400-1200 rpm and fixe welding speed 100 mm/min. FSW tool having a probe diameter of 4 mm, shoulder diameter of 12 mm, and a probe length of 2.9 mm and the probe was thrust towards the steel surface by a distance .3-.4 mm. For FSW of 400 rpm failure occurs during milling and FSW of high rotation speed of 1000-1200 rpm failure by stress due to thermal contraction after welding. The value of high tensile strength 333 Mpa obtain at 500 rpm and intermetallic thickness ≤ .1 μm and the failure location at weld interface.

Thaiping Chen (14) studied the effect of process parameters on FSW joints of dissimilar AA6061-T651 to Steel SS400 and FSW tool is made of AISI 4140 with shoulder diameter 20 mm and cylindrical pin diameter varies 6, 7, 8 mm. tool rotational speed 550-800 rpm, welding speed .9, 1.2, 1.5 mm/sec and tool tilt angle 1, 2, 3 degree. The lower welding speed and rotation speed, which are the significant FSW process parameters, yield a higher C-notch Charpy impact value. The welding speed of 0.9 mm/s, combined with a rotation speed of 550 rpm yields the best quality of impact values, and an acceptable quality of tensile strength. The various sizes of the steel fragments resemble to the onion shapes in the metallography, The TMAZ and HAZ in the SS400 side are difficult to observe.

M. Dehghani (15) studied the microstructure and mechanical properties of dissimilar AA3003-H18 to mild steel of 3 mm thickness with varies the tool shoulder diameters 24, 18 mm and cylindrical non threaded pin of diameter 6 mm and different tool rotation speed and welding speed. The results showed that at constant welding speed, increasing the tool rotation speed increased the heat input of the weld zone and tunnel and cavity were formed, which resulted in reduction in ultimate tensile strength of the joints and similarly at constant rotation speed, increasing welding speed increased the ultimate tensile strength by decreasing the heat input factor. By increasing the heat input, the tensile fracture occurred at the aluminium TMAZ and by decreasing the heat input, fracture occurred at the Al-Steel interface due to thick layer of Al_5Fe_2 was found. The thickness of intermetallic layer increased from 0.8 μm to 7.8 μm by increasing the heat input factor. A continuous layer of intermetallic compound at aluminum/steel faying surface was found to be Al_5Fe_2 and Al_6 (Fe, Mn) intermetallic compound was found in the weld nugget as scattered particles as shown in fig.3.

ISSN 2229-5518

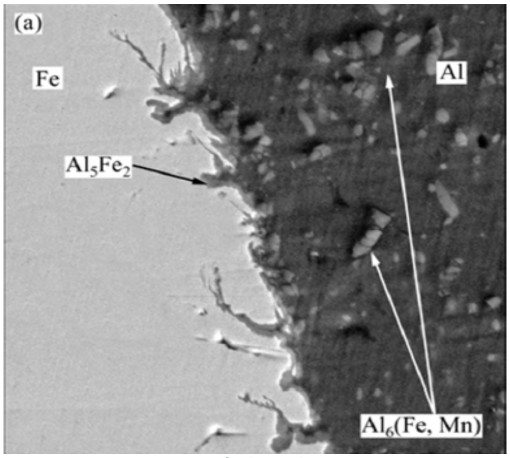

Fig. 3 FSW of Al-Steel (15)

Seung-Boo Jung (16) studied Interfacial reaction of friction stir welding of dissimilar AA6056-T4 to 304 austenitic stainless steel with tool rotation and welding speed were 800 rpm and 80 mm/min, tool pin center was shifted towards the Al Alloy to avoid pin erosion and overheating of Al Alloy plate. A complex interface structure, which consists of a swirl or vortex like intercalated structure and a thin intermetallic layer produced. The formation of an intercalated structure was mainly related to the severe plastic deformation induced by the tool's stirring action and intermetallic layer was found to be mainly composed of Al, and Fe elements along with some Cr, Ni and Si.

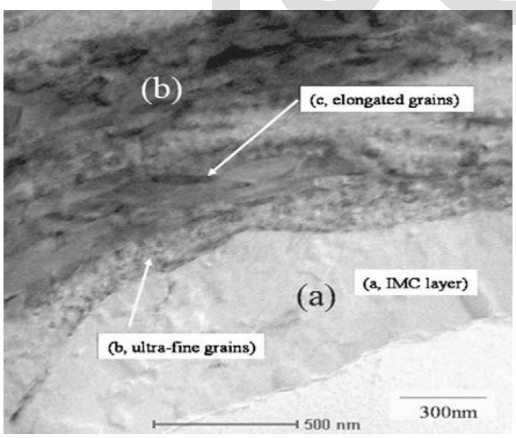

Fig. 4 show mixed layer and intermetallic compound layer (16)

The thickness of the intermetallic compound layer was approximately 250 nm and was identified as the Al_4Fe phase with a hexagonal close-packed structure and adjacent to this layer, an ultra fine grain structure and elongated grains were observed as shown in fig. 4 and the elongated grains appeared consist of ferrite phase. The ultra-fine grains may be formed by the severe plastic deformation and the diffusion of Fe, Cr and Ni.

Huseyin Uzun (17) studied the FSW of dissimilar AA6013-T4 to X5CrNi18-10 stainless steel with tool rotation and welding speed were 800 rpm and 80 mm/min and the tool pin was shifted towards the Al Alloy plate. The hardness of the weld nugget shows variable values due to the presence of the fine or coarse dispersed stainless steel particles in the weld nugget. The hardness value at the retreating side decreased towards the weld nugget from the level of the TMAZ in the stainless steel at advancing side of weld and the minimum hardness indicated to the HAZ in the Al 6013-T4 alloy is located around 6 to 11 mm from the weld centre at the retreating side. Fatigue properties of Al Alloy to stainless steel joints were found to be approximately 30% lower than that of the Al 6013-T6 alloy base metal.

N. Sasi Karthik Sai (18) studied the optimize parameters of friction stir welding of dissimilar AA5086 to stainless steel 410 with the welding parameter like tool rotation speed, welding speed and tool offset were varied according to L9 orthogonal array designed using MINITAB 17 statistical software.

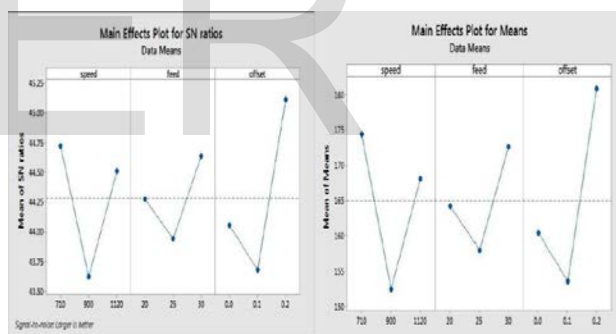

Fig. 5 S-N Curve (18)

The tensile strength is estimated to be the maximum at 710 rpm rotation speed, offset 0.2 and 30 mm/min travel feed; which is optimal from the plots obtained as shown in fig. 5.

W. H. Jiang (19) Feasibility study of friction stir welding of dissimilar AA6061-T6 to AISI 1018 steel with the tool made of H13 tool steel of shoulder and pin diameter is 25 mm, 5.5 mm respectively and the rotational speed of the tool was 914 r/min and its traverse speed was 140mm/min. During FSW, the Al alloy in the nugget melted locally and reacted strongly with steel pieces, resulting in the formation of the Al–steel intermetallic compounds, $Al_{13}Fe_4$ and Al_5Fe_2. The tensile failure occurred at the boundary between the nugget and the TMAZ of the base Al alloy, indicating that the weld has a high joining strength and the hardness that fluctuates strongly within the nugget, the average hardness of the nugget is much higher than that of the base Al alloy.

N. Karimi (20) studied the friction stir welding of dissimilar AA1100-H14 to AISI 1045 carbon steel with the tool consists of a shoulder diameter of 20 mm and a conical probe with the diameters of 4mm and the tool material is tungsten carbide. The welding experiments were also made with different tool offset between -1 mm to 1.5 mm and rotation speed 710, 1000 rpm, welding speed 20, 28, 40 mm/min respectively. The maximum tensile strength of a joint was obtained at the pin offset of 1.5 mm toward Al Alloy as shown in fig. 6. Tensile strength properties of Al1100-1045 carbon steel joints were found to be approximately 20% lower than that of the Al 1100-H14 alloy base metal.

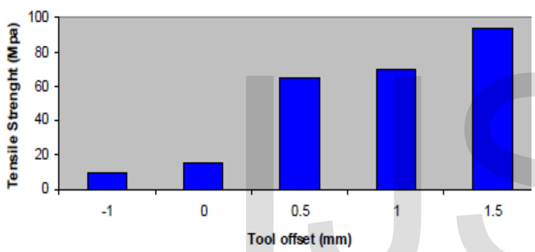

Fig.6 Tensile strength of FSW Al-Steel (20)

At a low offset, steel particles were scattered in Al Alloy matrix and these particles became larger in size and some voids were formed, resulting in decrease in the joint tensile strength.

Jun Ni (21) studied the effect of process parameters on friction stir welding of dissimilar AA6061-T6 to advanced high strength steel with the welding parameters like tool rotation speed, welding speed and tool offset. A thin IMC layer of thickness less than 1 µm was formed at the interface due to diffusion and reaction the composition of FeAl or Fe_3Al can contribute to joint strength and higher welding speed can shorten high temperature period and thus reduce the interlayer thickness. The highest ultimate tensile strength of FSW joints obtained in this study was 240 MPa, which is about 85% of the base Al alloy at the tool rotational speed of 1800 rpm, welding speed of 90 mm/min and the tool offset of 1.63 mm.

T. Yasui (22) studied the weldability between AA6063-T5 to carbon steel S45C with the FSW tool made of SKD61 steel of tool shoulder diameter 20 mm, pin diameter 4 mm and pin length 4.5 mm respectively. A thin intermediate layer is formed in the weld interface of effective welded joints and as increase in shoulder diameter enables a maximum welding speed of 1000 mm/min to be attained produced welded joints have fracture strength of 160 MPa that is joint efficiency of 75%. Loss of hardness occurring in stir zone and HAZ on the 6063 side after welding and maximum softening occurs near the boundary between the stir zone and HAZ. The tensile test results show fracture to occur at that position.

S. Kundu (23) studied FSW of dissimilar interstitial free steel to commercial pure aluminium using tool rotation speed 600, 900, 1200 rpm and welding speed 100 mm/min with the high speed steel tool having 25 mm shoulder diameter and a conical pin of 5 mm diameter and 2.7 mm in length. The Al_3Fe intermetallic compounds were formed at the interface of the FSW joints and the thicknesses of intermetallic compounds increase with the increase in the tool rotating speed due to the higher heat generated by the high rotating tool shoulder. The grain sizes at the stir region of the friction stir welded joints are finer at higher rotational speed and the micro-hardness in the joint interface is greater than the base materials. Maximum tensile strength of 123 MPa obtained at tool rotational speed 600 rpm and increase in the tool rotational speed, the weld strength decreases gradually due to the increase in the thickness of intermetallic compounds.

4. Conclusion

The present review has been undertaken, with an objective of FSW of Al alloy to Steel and to study the effect of mechanical properties, microstructure and FSW parameters. Compared to the conventional fusion welding process, FSW is found to be a very useful and economical technique for joining Al alloy to steel because of the considerable improvement in ductility, strength, micro-hardness, fatigue and fracture toughness and also 80 to 85 % of yield stress of the base material has been achieved. Various studies have highlighted the effect of intermetallic on the formation of the joint and its strength was found to reduce on formation of thick inter metallic like Al13Fe4 and Al5Fe2. FSW exhibits a higher fatigue life as compare to laser welding and MIG welding but lower than that of the base materials. Tool designs is very important factors for producing the sound and defect free weld and mostly cylindrical threaded pin and concave shoulder are widely used welding tool features. In the present review FSW process parameters such as tool rotational speed, welding speed, spindle tilt angle and tool type should be conduct for improving the ultimate tensile strength, micro-hardness and percentage elongation of FSW joint by choosing optimum weld parameters. Heat and material flow during FSW are important issues of concern so a wide research should be conducted on these two phenomena.

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