Effect of Process Parameters on Mechanical Properties of Friction Stir.Welded Joint of Two Dissimilar Al-Alloys

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***Abstract*—This Friction Stir Welding (FSW) has a potential for wide-spread applications. Aluminum alloys generally have low weldability with traditional fusion-welding process. However, the development of Friction Stir Welding (FSW) has provided an alternative, improved way of producing aluminum joints, in a faster and more reliable manner. The FSW process has several advantages, in particular the possibility to weld dissimilar aluminum alloys. However it is necessary to overcome some challenges for its wide-spread uses. Tool design and the selection of process parameters are critical issues in the usage of this process. This study focuses on the process parameters that is required for producing effective friction stir welding of two dissimilar alloys AL6101-T6 alloy to AL6351-T6 alloy. Proper tool design has been employed to analyze the influence of rotational speed and welding speed over the micro structural and tensile properties. Effect of process parameters on microstructure, hardness distribution and tensile properties of the weld joints were investigated. By varying process parameters, defect free weld joints were produced. The hardness in AL6351T6 was more than hardness of AL6101-T6. The good mixing of both the materials joined was obtained at lower welding and higher rotational speed. The tensile testing evolutions of welded specimen shows lower strength compared to both parent material.**

Keywords*— FSW, mechanical properties, tensile strength, hardness, microstructure

I. INTRODUCTION

This Friction stir welding (FSW) is a solid-state process, which means that the objects are joined without melting of base metals. It is a dynamically developing version of pressure welding process. In FSW, a cylindrical shouldered tool with a profiled pin is rotated and plunged in to the joint area between two pieces of sheet or plate material [1]. The schematic representation of FSW process is shown in Fig-1 In FSW process,[2] a non consumable tool is used for joining the plates. The parts which are to be joined should be properly clamped to prevent separation. The frictional heat between the wear resistant welding tool and the work pieces causes latter to soften without reaching melting point, allowing the tool to traverse along the weld line. The plasticized material transformed to the trailing edge of the tool pin, is forged through intimate contact with the tool shoulder and pin profile. On cooling a solid phase bond is created between the work pieces The production of components of aluminum alloys is not very complex; but joining of these materials can sometimes cause serious problems. Lack of structural transformations in solid state and excellent thermal and electrical conductivity causes problems in fusion and resistance welding of aluminum alloys. That led to the development of friction stir welding a solid state joining technique in which the joined materials is plasticized by heat generated by friction between the surface of the plates and the contact surface of a special tool, composed of two main parts: shoulder and pin. Shoulder is responsible for the generation of heat and for containing the plasticized material in the weld zone, while pin mixes the material of the components to be welded, thus creating a joint. This allows for producing defect free welds characterized by good mechanical properties[3].

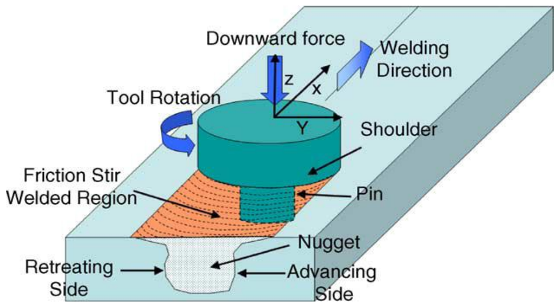

Fig. 1 Friction stir welding process [2]

. K. Elangovan et al. (2008) studied the influence of tool pin profile and welding speed on the formation of friction stir processing (FSP) zone in AA2219 Aluminum alloy. Here five different tool pin profiles (straight cylindrical, frustum cylindrical, threaded cylindrical, conical and square) with three different shoulder diameters have been used to fabricate the joints at three different welding speeds. The formation of FSP zone has been analyzed microscopically. Tensile properties of joints have been evaluated and correlated with the FSP zone formation. It is found that the square pin profiled tool produces mechanically sound and metallurgic ally defect free welds compared to other tool pin profiles [4]. H. S Patil et al. (2010) had done the experimental study on the effect of welding speed and tool pin profiles on AA6082-0 Aluminum friction stir welded butt joints. They conclude that the appearance of weld is well and no defect was found. Variation of stress is function of strain. The effect of different welding speed and tool pin profile is on ultimate tensile stress and elongation. The joint fabricated using taper screw thread pin exhibits superior tensile properties [5]. Adamowski J ,and Szkodo M, (2007) studied the friction stir welds of Aluminum alloy AW6082T6. They conclude that the hardness of both the heat affected zone and the weld nugget is lower than that of the base metal. Tensile strength of FSW weld is directly proportional to welding speed. Hardness drop observed in weld region [6]. Cabibbo M., et al. (2007) studied the microstructure and mechanical properties ofAA6056 friction stir welded plate. They investigated their work by using polarized optical and transmission electron microscopy techniques. Tensile test showed yield and ultimate strength slightly lower across the weld compared to parent material. This difference causes reduction in ductility of the weld region [7]. Wang D. & Liu S. (2004) done study of friction stir welding of Aluminum .They found that the microstructure of the FSW weld consists of very fine and equiaxed grains instead of the coarse and band-like structure of the half cold-hardening Aluminum plate and the heat-affected zone is very small. Tensile strength of the weld is about 20% lower than that of the hardening Aluminum plate, but about 10% higher microhardness is demonstrated by the welds in comparison with that of the Aluminum plate in annealing condition. Both of the microhardness and tensile strength of the FSW weld are affected by travel rate of the welding head pin. Good welds can be produced when pin and shoulder diameters of the welding head are in the proportion of 1:3 and the best visual quality [8] . Sakthivel T, et al (2008) studied the effect of welding speed on micro-structure and mechanical properties of friction–stir welded Aluminum. They concluded that the microstructure of weld nugget consists of fine equiaxed grains. These grains are more homogeneous at lower welding speed than at higher welding speed. Size of the weld zone becomes wider when decreasing the traverse speed as result of a large amount of frictional heat and easy material flow. Weld zone hardness is decreasing as compared to the parent metal but the hardness slightly increases with the increase of welding speed. The ultimate tensile strength increases when traverse speed decreases. Best mechanical properties obtained at low traverse speed due to homogeneous grains and higher heat input [9]. Tensile elongation decreases with increase in tool rotational speed. Similar studies have been performed by few researchers on dissimilar aluminum alloys and the study on dissimilar aluminum alloys can be further extended. particularly on dissimilar FSW between AL6101T6 & AL6351T6. Many studies have been conducted to characterize the resulting

microstructure in welds especially in dissimilar aluminum alloys. Many researchers studied and reported the base materials microstructure and its properties. However, there are not enough literatures on microstructure characterization of dissimilar materials especially on aluminum alloys between 6000&7000 series. The aim of this paper is to present the effects of welding parameters on mechanical properties with SEM analysis for dissimilar welds of aluminum alloys between Al6101T6 & AL6351T6 produced at different rotational speed.

2. EXPERIMENTAL PROCEDURE

2.1 SELECTION OF TOOL

The AISI D2 steel rod has been used for fabricating FSW tool in this study. The chemical composition of FSW tool is shown in Table1. It has excellent abrasive resistance and fatigue strength. A duplex microstructure with coarse complex carbide provides the steel with high wear resistance and good toughness. The fabricated friction stir welding tool has two main parts: shoulder and round bottom cylindrical pin as shown in Fig.3. The fabricated steel FSW tool has been heat treated.

Table1: chemical composition of FSW tool

Constituents	C	Si	Mn	P	S	Cr	Fe
Wt %	1.82	0.479	0.61	0.028	0.036	11.939	Bal.

Table 2: FSW tool material mechanical properties

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Properties	Values
Density	7700 kg/m^3
Modulus of Elasticity	210 Gpa
Hardness, Brinell	255
Ultimate tensile strength	1736 Mpa
0.2% offset yield strength	1532 Mpa
Poisson's ratio	0.27-0.3

Table 3: Tool Design and specification

Tool	shoulder	Pin		
	Diameter (mm)	Base diameter (mm)	Top diameter (mm)	Length (mm)
1	25	7	5	11.5

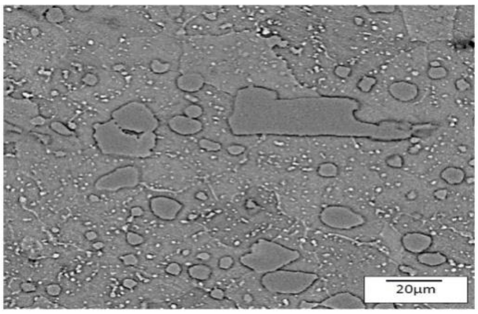

Fig. 2 Microstructures of AISI D2 tool steel

Fig. 3 FSW tool with threaded tip

2.2 Selection of working material

The selected materials for this study were Al 6101 T6 and Al 6351 T6. The chemical compositions and mechanical properties have been given in Table 4 and 5.

Table 4: Chemical compositions of the working materials

Al Alloy	Cu	Mg	Si	Fe	Mn	Al
6101 T6	0.05	0.65	0.5	0.5	0.03	rest
6351 T6	0.10	0.80	0.95	0.60	0.70	rest

Table 5: Mechanical properties of working materials

Al Alloy	UTS (Mpa)	YS (Mpa)	Elongation (%)	Hardness (VHN)
6101T6	220	195	15	71
6351T6	310	285	14	95

The dimension of the work piece has been kept 160 mm × 50 mm ×12 mm for each of the Al-alloy for making FSW butt joint as shown in Fig. 4.

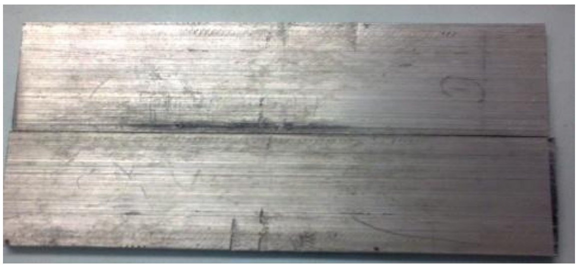

Fig. 4 working AL-plates to be welded

2.3.Experimental set up

Friction stir welding set up has been made on copy a milling machine having capacity 1.5 HP made in U.S.A. In this process FSW tool was attached to the tool post and rotated tool has been plunged into the joint line between two pieces of working plate material (AL6101 T6and AL6351 T6), which were butted together as shown in Fig. 5 .The working plates have been clamped rigidly clamped onto a backing plate in a manner that prevents the abutting joint faces from being forced apart. The length of tool pin was slightly less than the weld depth required and the tool shoulder had been in intimate contact with the work piece surface during welding process. Frictional heat is generated between the wear resistant welding tool shoulder and pin, and the material of the work-pieces. This heat, along with the heat generated by the mechanical mixing process and the adiabatic heat within the material, cause the stirred materials to soften without reaching the melting point (hence cited a solid-state process). As the pin is moved in the direction of welding the leading face of the pin assisted by a special pin profile, forces plasticized material to the back of the pin while applying substantial pressure force to consolidate the weld metal [10]. The process parameters such as tool shoulder diameter, tool rotational speed & feed rate were considered by keeping the axial force constant. Welded plates were cut from transverse direction using power saw to prepare samples for micro structural and mechanical examination. For microstructural examination samples were polished using standard metallographic procedures and then polished samples were etched with the Keller's reagent. Etched samples were then examined using optical microscope and scanning electron microscope (Hitachi S-3000N) made in Japan. For tensile studies, the samples were prepared according to the ASTM E8 standards by Universal Milling machine and tests were carried out at a cross head speed of 0.5 mm/min. Micro Hardness were carried out using Leica microscope at a load of 0.2 kg with dwell time of 15 second across the various weld zone.

Fig. 5 FSW experimental Set-up

3. RESULTS & DISCUSSION

Defect free FSW samples were made by considering the process parameters such as tool shoulder diameter, tool rotational speed and welding speed. On the basis of literature reviewed, following process parameters have been selected for study, their ranges and nomenclature used for specimens are mentioned on the Table 6 and 7

Table 6: Selected process parameters for FSW

Sl. no.	Parent material (P1)	Parent material (P2)	Tool dia. (mm)	Tool rotational Speed (rpm)	Welding speed (mm/min)
1	Al 6101T6	Al 6351T6	25	800	13
2	Al 6101T6	Al 6351T6	25	1200	12

3.1 Tensile test

- AMERICAN SOCIETY OF TESTING MATERIALS guide lines were followed for preparing the test specimens. Table 7 shows the results of the tensile specimens.

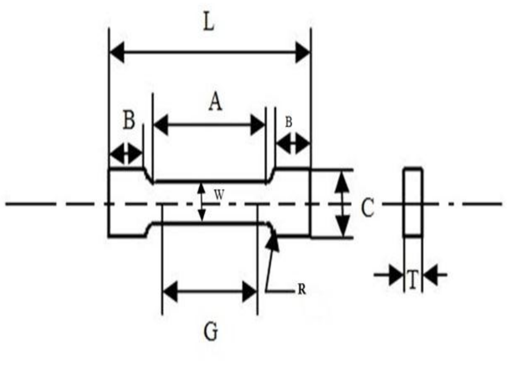

Fig. 6 Tensile test specimen diagram

G - Gauge length = 25mm

W – Width = 6 mm

T – Thickness = thickness of material = 12 mm

R – Radius of fillet = 6mm

L – Overall length = 100mm

A – Length of reduced section = 32mm

B – Length of grip section = 30mm

C – Width of grip section = 10mm

Two tensile specimens for every welded sample and the parent material were fabricated. Total twelve specimens for tensile test, coding 1a, 1b ,2a, 2b, P1 and P2 were fabricated. Tensile specimens are shown in Fig. 7 The fracture occurred at the centre of marked gauge length. The tested tensile test samples have been shown in Fig 8

Fig. 7 Tensile test samples

Fig. 8 Tested tensile test samples

3.2 Tensile test results

Table 7 Tension test results

Specimen no.	UTS (Mpa)	Elongation (mm)	Percentage elongation (%)
1a	96.83	29	16
1b	99.2	29	16
2a	102.79	28.5	14
2b	111.24	28	12
P1	201.44	31.5	24.4
P2	302.94	30	20

3.2.1 Effect of process parameter on Ultimate tensile strength:-

Figure 9 depicts that increase in tool rotation affect the ultimate tensile strength in dissimilar weld. The strength of both welds joint is less than strength of parent materials. Ultimate tensile strength of the weld joint increases with rotational speed of tool.

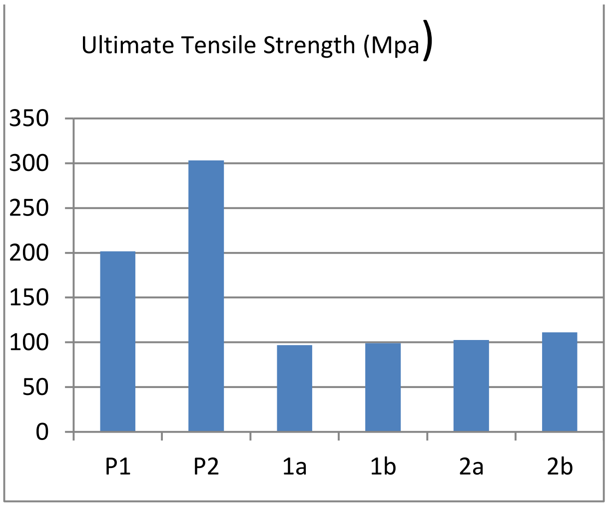

Fig. 9 Ultimate Tensile strength of parent materials and welds

.3.2.2. Effect of process parameter on Elongation:-

From Fig.10 it has been observed that as the tool rotation increases percent elongation also decreases in dissimilar weld. It has also been observed that percentage elongation of both the welds joint less than that of parent materials.

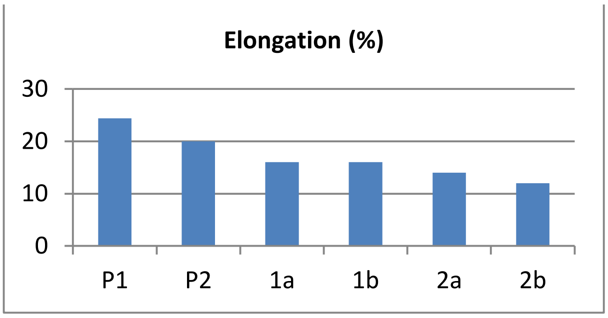

Fig 10: % Elongation of base metal and welds

4. BRINELL HARDNESS TEST:-

- Hardness number for the welding cross section evaluated by Brinell's hardness test. Figure 11 shows specimens for hardness test. The Brinell hardness number (BHN) can be calculated by dividing the load applied to the surface area of the indentation. This indentation was measured and the result was calculated as;

$$BHN = \frac{2P}{\pi D\left[D - \sqrt{D^2 - d^2}\right]}$$

- Where, P= Load on the indentation tool Kg.

  D= diameter of steel ball in mm

Fig. 11 Brinell hardness tested samples specimen

Table no. 8 Result of hardness test

Specimen no.	points	Indentation dia.(d) (mm)	Brinell Hardness (BHN)
1	a	3.9	51
	b	3.7	58
	c	3	95
2	a	4.1	44
	b	3.7	58
	c	3.1	88

4.1 Brinell Hardness Analysis:-

Variation of hardness on specimen 1 and 2 across various zones of welded joints is shown in Fig. 12. It has been observed that hardness of the parent material (P1) less than that of the hardness of parent material (P2). As rotational speed increases hardness decreases in both parent materials (P1and P2). The hardness in weld zone remains constant in both rotational speeds.

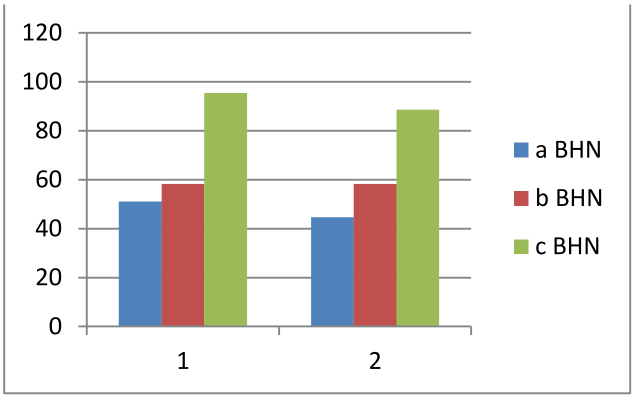

Fig. 12 Variation of Hardness across various weld zone

5. MICROSTRUCTURE:-

Due to severe plastic deformation and high temperature in the stirred zone during FSW recrystallization and microstructure evolution occurs in stirred zone and precipitate dissolution and coarsening within and around the stirred zone. On the basis of microstructural characterization of grains and the precipitates, Different zones namely (a) weld nugget (WN), (b) thermo-mechanically affected zone (TMAZ), (c) heat-affected zone (HAZ) and (d) Base material (BM) have been identified. The microstructural variations in different zones have considerable effect on post weld mechanical properties.

5.1 Microstructure for parent aluminum alloys

Figure 13 (a) shows the microstructure of AL 6101 T6 in which particles of Mg_2Si are evenly precipitated in aluminum solid solution. Some inter metallics which are undissolved also present 13(b) Figure shows the microstructure of AL 6351 T6 which is typical precipitation hardened matrix with the fine precipitation of $Cu\text{-}Al_2$. The high hardness measured shows the precipitation of the strengthening agents are complete.

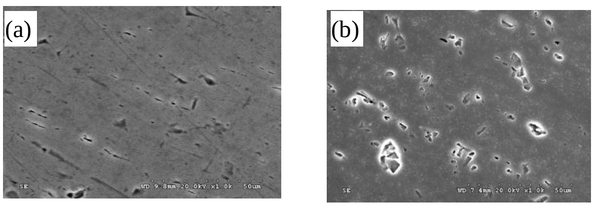

Fig. 13 Microstructure of parent material (a) Al6101T6 and (b) Al6351T6

5.2 Microstructure studies for dissimilar welds

The microstructure of the different weld regions of sample no. 2 has been shown in Fig.14. The weld undergoes considerable amount of thermal cycle, there is grain refinement occurs in FSW process. Irrespective of the tool design, the material that flows around the tool undergoes extreme levels of plastic deformation, which leads to a recrystallized fine equiaxed grain structure under high temperature and plastic deformation in the weld region due to stirring process. In the parent material, equiaxed grains are oriented along the rolling direction. In the transition region between the weld zone and parent metal, the grain dimension increases compared to the nugget zone and the grain orientation possesses a less equiaxed character. The region adjacent to the nugget zone i.e. TMAZ is characterized by a highly deformed structure. The parent material elongated grains were deformed in an upward flowing pattern around the nugget zone. Althougth the TMAZ underwent plastic deformation complete recrystallization did not occur in this zone due to insufficient deformation strain [2,11].The nugget zone exhibited a recrystallized fine grain structure with grain sizes increases from the weld region to the parent material [12]. Figure 14 shows the microstructure in various zones of the joint interface of weld cross section.

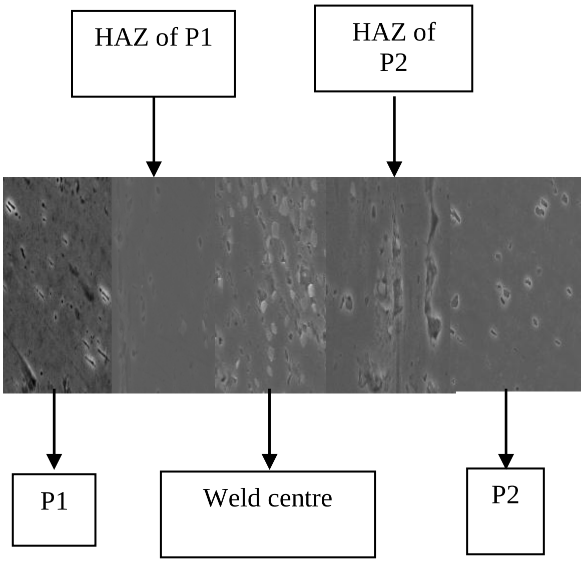

Fig.14 The microstructure of the different regions. (a) P1 (AL6101 T6), (b) HAZ of parent P 1 (c) nugget zone(weld centre), (d). HAZ of parent P 2 T6 (e) P 2 (AL6351 T6)

6 . MICRO-HARDNESS

Micro-hardness has been measured on dissimilar welded sample no. 2 on the cross section perpendicular to the welding direction.

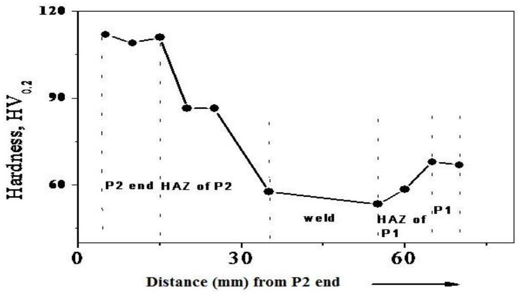

Fig.15 Micro hardness profile of dissimilar weld sample

The micro hardness of the weld zone and the heat affected zones were measured for sample and the obtained micro hardness profile has been shown in Fig. 15. It can be observed from the graph that the hardness value of the weld zone is lower than the parent material P2. It indicates the improved ductility of weld. Hardness of parent material 2 (AL6351T6) is more than parent material 1 (AL6101T6). There is some difference in the hardness values of weld zone and heat affected zone (HAZ)

7. CONCLUSIONS:-

The major conclusions derived from the results of this study are:

- Friction stir welding of dissimilar materials Al 6101 T6 & Al 6351 T6 was successfully performed. It was observed that at higher rotation speed & low weld speed weld quality is good.
- Process parameters and tool profile has an effect on quality of weld.
- The Ultimate Tensile strength of welded joints are lower than the parent materials strength.
- It is found that the hardness values of AL6101T6 was lower than AL6351T6 . The hardness value of weld zone can be comparable to hardness of heat affected zone.
- From the micro-structural study it has been observed that the weld zone is stirred and having more grain refinement as compared to the HAZ zone. Softening of the material in the weld nugget and heat affected zone was observed i.e. micro-hardness of both heat affected zone and weld nugget is lower than that of parent material. The inter diffusion of alloying elements and development of similar orientation in the nugget could have contributed to the better tensile properties of the friction stir welded Al6101T6 &Al6351T6 joints
- Results of this study have demonstrated the feasibility of friction stir welding of two dissimilar aluminium alloys and its mechanical properties can be comparable to the base material. Furthermore, the improvement of current weld quality and properties using the FSW process needs to be looked into.

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