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Experimental Investigation on Effect of FSW Parameters on Hardness and Microstructure of AA 6061 and AA 5083

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***Abstract*: The current investigation aims in assessment of the hardness and microstructural evolution of friction stir welded dissimilar metal alloy joints. The present work considers the aluminium alloys AA 6061 and AA 5083 in the form of sheets of 6mm thickness for the fabrication in the form of butt joint through friction stir welding using H13 tool steel FSW tool. Dissimilar friction stir welded joints were fabricated by varying the process parameters like rotational speed, traverse speed and axial force. The selected parameters are varied with three levels and three different specimens have been welded and the properties like hardness, microstructure is evaluated in this process. The selected factors have shown considerable effect over the hardness at the stir zone. The microstrutural examination has revealed that eutectic particles of Al-Mg-Si in matrix of AL solid solution present in all the three specimens.**

***Keywords*: AA 5083, AA 6061, Friction Stir Welding, Hardness, Micro Structure.**

1. Introduction

Aluminium and it's alloys has received a great attention in usage to act as a potential material for making products in many industries such as aerospace, automobile, construction, marine and so on. Aluminium is available in numerous series which can be treated further for making suitable for a particular application. The properties of the aluminium alloys can be varied by subjecting them to a suitable treatment before and after the manufacturing process Alloy systems are classified by a number system or by names indicating their main alloying constituents. Selecting the right alloy for a given application entails considerations of its tensile strength, density, ductility, formability, workability, weldability, and corrosion resistance, to name a few. Aluminium alloys are used extensively in aircraft due to their high strength-to-weight ratio. On the other hand, pure aluminium metal is much too soft for such uses, and it does not have the high tensile strength that is needed for airplanes and helicopters. With the growth of Aluminium within the welding fabrication industry, and its acceptance as an excellent alternative to steel for many applications, the welding of aluminium alloys by different processes and the effect of process parameters over the mechanical properties, metallurgical characteristics, temperature distribution, and residual stresses at the joint has become a field of interest in research [1]. The traditional joining process adopted to join similar and dissimilar aluminium alloys in the past has shown considerable defects at the joint and it has shown a direction to find an alternate solution for overcoming this problem. Many Researchers have suggested that Friction Stir Welding has evolved as a potential solution for producing welds on aluminum and magnesium alloys [2].

2. Literature Survey

J. Stephen Leon and V. Jayakumar [3] has investigated the mechanical properties of AA6061 alloy plates welded by FSW process and made a comparison with parent metal. The authors have selected a plate of dimension 300mm x150mm x 6mm for welding the plates by varying the parameters such as tool rotational speed and welding speed. The area of the weld nugget zone size slightly decreased as the welding speed increased. Comparing with other welding speeds, the lowest speed 16mm/min results better mechanical properties and increase in the area of the weld nugget. The authors have reported that the weld joint made by means of FSW have shown a superior tensile properties and impact strength than the parent metal due to higher hardness and fine microstructure. The most significant parameter which affects the mechanical properties is found to be the welding speed selected.

Ramaraju Ramgopal Varma, Abdullah Bin Ibrahim, Mohammed, Arifpin Bin Mansor [4] have reported about the effect of FSW input parameters such as rotational speed, traverse speed and axial load over the joint created by using dissimilar metal combinations. The authors have considered AL 5083 in the advancing side and AL 6061 in the retreating side. The authors have considered taguchi's L8 Orthogonal array for creating the experimental design matrix which consists a total of 8 experimental runs. The authors have evaluated the mechanical properties such as yield strength, elongation, tensile strength and micro hardness. The authors have concluded that increase in tensile behavior and hardness value may be obtained by increasing the tool rotational speed, axial force and keeping the weld speed as constant. Higher weld speeds have lead to lower metallurgical transformation at the joint and lower strengths have been observed. The optimized parameter combination of the input parameters are found to be rotational speed as 1000rpm, traverse speed 40mm/min and axial force of 3.5kN.

Indira Rani M., Marpu R. N. and A. C. S. Kumar [5] have studied the FSW process by welding AA 6061 Alloy plates of dimension 150mm x 75mm x 6.6mm by varying the rotational speed, welding speed and axial force is considered to be constant. The tool material used for welding the plate is H11 tool steel. The authors have evaluated the mechanical property tensile strength at room temperature. The authors have welded the plate in the form of butt joint and obtained the optimum parameter combinations for both annealed and tempered conditions. The tool rotation speed 800 rpm and welding speed 10 mm/min and 15 mm/min are the optimal parameters in annealed condition and The tool rotation speed 1000 rpm and welding speed 10 mm/min are the optimal parameters in 'T6' condition. The authors have concluded that both the tool rotational speed and weld speed has greater influence over the properties of welded joint.

N. Ravinder Reddy, G. Mohan Reddy [6]. The authors have reviewed the various research works carried in the field of FSW process and the benefits recommended by various authors to the environment, metallurgical formation and energy requirement for welding similar and dissimilar metal or alloys. The authors have made an extensive review about the process, its capabilities advantages, disadvantages, limitations, significant process parameters over mechanical properties, HAZ, TMAZ, nugget area, metallurgical formation at the weld, strength characteristics etc. the authors have stated that FSW welding is a novel process used to join metallic alloys. They have aloes described that Friction stir welding is in vogue in aerospace, automotive and other industrial establishments for connecting alloys like aluminum, magnesium and copper. Rotational speed, welding speed and the angle of attack are important in the process of FSW.

Ramona GABOR, Jorge F. dos Santos [7] have analyzed and found that FSW has been capable enough to produce welds of high quality with no defects, reduced cost and lower environmental impact when compared to traditional fusion welding. The authors have studied the process parameters influence on the connection formation between AA6082-T651 and AA5083-H111. The welded plates are tested for their tensile and hardness values at the connection area and it was observed by the authors the input parameters have significant effect over the mechanical properties considered for evaluation.

3. Friction Stir Welding

Friction Stir Welding (FSW) is a solid state welding process invented in the year 1991 developed and patented by, The Welding Institute (TWI) in Cambridge, United Kingdom. The development of this process was a significant change from the conventional rotary motion and linear reciprocating friction welding processes. It provided a great deal of flexibility within the friction welding process group. Friction stir welding (FSW) is a solid-state joining process that uses a non-consumable tool to join two facing work pieces without melting the workpiece material. Heat is generated by friction between the rotating tool and the workpiece material, which leads to a softened region near the FSW tool. While the tool is traversed along the joint line, it mechanically intermixes the two pieces of metal, and forges the hot and softened metal by the mechanical pressure, which is applied by the tool, much like joining clay, or dough. It is primarily used on wrought or extruded aluminium and particularly for structures which need very high weld strength.

Friction stir welding (FSW) is capable of fabricating either butt or lap joints, in a wide range of materials thickness and lengths. During FSW, heat is generated by rubbing a non-consumable tool on the substrate intended for joining and by the deformation produced by passing a tool through the material being joined. The rotating tool creates volumetric heating, so as the tool is progressed, a continuous joint is created. FSW, like other types of friction welds, is largely solid state in nature. As a result, friction stir welds are not susceptible to solidification related defects that may hinder other fusion welding processes. The parts intended for joining are usually arranged in a butt configuration. The rotating tool is then brought into contact with the work pieces. The tool has two basic components: the probe, which protrudes from the lower surface of the tool, and the shoulder, which is relatively large diameter. The length of the probe is typically designed to match closely the thickness of the work pieces. Welding is initiated by first plunging the rotating probe into the work pieces until the shoulder is in close contact with the component top surface. Friction heat is generated as the rotating shoulder rubs on the top surface under an applied force. Once sufficient heat is generated and conducted into the work piece, the rotating tool is propelled forward. Material is softened by the heating action of the shoulder, and transported by the probe across the bond line, facilitating the joint. The Fig. 1 shows the schematic diagram of Friction stir welding process [8].

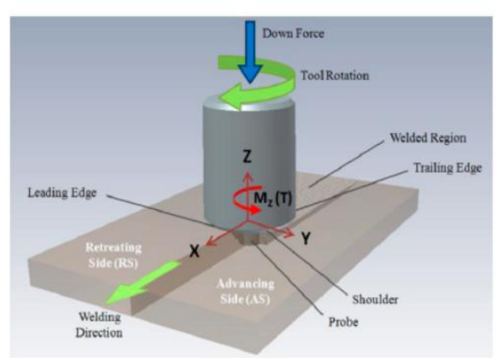

Fig. 1. Schematic diagram of friction stir welding

The primary and potential advantages of Friction Stir Welding over Conventional welding includes high mechanical properties, Improved safety due to the absence of toxic fumes or the spatter of molten material, Non consumables welding process, can be easily automated on simple milling machines with lower setup costs and less training.

4. Workpiece and Tool Materials

The present work considers two different aluminium alloys such as AA 5083 and AA 6061for creating a butt weld for analyzing the effect of FSW parameters over the hardness and microstructural evolution at the joint.

A. Aluminium AA5083

Aluminium 5083 is known for exceptional performance in extreme environments. Aluminium 5083 is highly resistant to attack by both seawater and industrial chemical environments. Aluminium 5083 also retains exceptional strength after welding. It has the highest strength of the non-heat treatable alloys but is not recommended for use in temperatures in excess of 65°C. The chemical composition of AA 5083 is listed in Table No 1 and Table 2 represents the physical, mechanical and thermal properties of AA 5083. AA 5083 has potential applications in Ship building, rail cars, vehicle bodies, tip truck bodies, mine skips and cages and pressure vessels.

Table 1
Chemical Composition of AA 5083

Element	% Present
Si	0.4
Fe	0.4
Cu	0.1
Mn	0.4-1.0
Mg	4.0-4.9
Zn	0.25
Ti	0.15
Cr	0.05-0.25
Al	Balance

Table 2
Physical, Mechanical and Thermal Properties of AA 5083

Property	Value
Density	2650 kg/m^3
Melting Point	570°C
Modulus of Elasticity	72 GPa
Electrical Resistivity	0.058x10-6 Ω.m
Thermal Conductivity	121 W/m.K
Thermal Expansion	25x10-6 /K

B. Aluminium Alloy AA6061

Aluminium alloy 6061 is one of the most extensively used of the 6000 series aluminium alloys. It is a versatile heat treatable extruded alloy with medium to high strength capabilities Aluminium alloy 6061 is a medium to high strength heat-treatable alloy with strength higher than 6005A. It has very good corrosion resistance and very good weldability although reduced strength in the weld zone. It has medium fatigue strength. It has good cold formability in the temper T4, but limited formability in T6 temper. Not suitable for very complex cross sections. The typical applications of AA 6061 alloy includes aircraft and aerospace components, marine fittings, transport, bicycle frames, camera lenses, driveshafts. The chemical composition of AA 6061 is listed in Table No 3 and Table 4 represents the physical and mechanical properties of AA 6061.

Table 3
Chemical Composition of AA 6061

Element	% Present
Aluminium (Al)	95.9 to 98.6 %
Magnesium (Mg)	0.8 to 1.2 %
Silicon (Si)	0.4 to 0.8 %
Iron (Fe)	0 to 0.7 %
Copper (Cu)	0.15 to 0.4 %
Chromium (Cr)	0.040 to 0.35 %
Zinc (Zn)	0 to 0.25 %
Manganese (Mn)	0 to 0.15 %
Residuals	0 to 0.15 %
Titanium (Ti)	0 to 0.15 %

Table 4
Physical and Mechanical Properties of AA 6061

Property	Value
Density	2.7 g/cm^3
Melting Point	580°C
Modulus of Elasticity	70-80 GPa
Poisson's Ratio	0.33

Welding tool design is critical in FSW. Optimizing tool geometry to produce more heat or achieve more efficient stirring offers two main benefits: improved breaking and mixing of the oxide layer (more efficient heat generation) yielding higher welding speed - and enhanced quality. Tool materials should feature high hardness at elevated temperature and should retain this hardness for an extended period. The combination of tool material and base material is therefore always crucial to the tool's operational lifetime. In recent times, many different tool designs and configurations have been developed; some of the basic FSW tools are shown in Fig. 2.

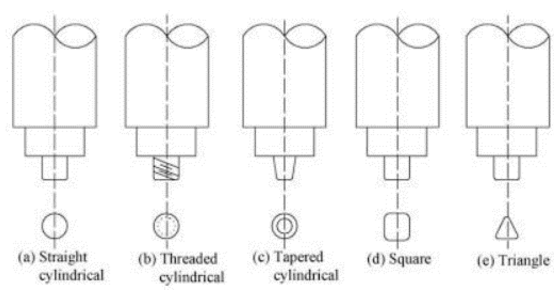

Fig. 2. FSW tools with varying pin profiles

Chromium hot-work tool steels are classified as group H steels by the AISI classification system. This series of steels start from H1 to H19. H13 chromium hot-work steel is widely used in hot and cold work tooling applications. Due to its excellent combination of high toughness and fatigue resistance H13 is used more than any other tool steel in tooling applications. The present work utilizes H13 tool steel FSW tool for joining dissimilar aluminium alloys with cylindrical pin diameter of 5mm and length 5.7mm. The Fig. 3 and 4 shows the image of FSW tool with cylindrical pin used in the current work and 2D view of the FSW tool with dimensions.

Fig. 3. FSW tool with cylindrical pin

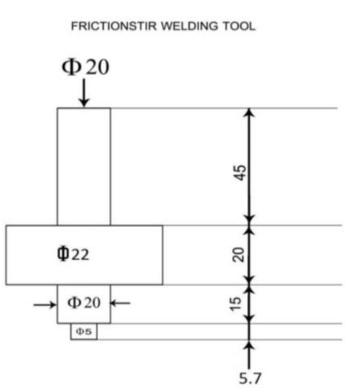

Fig. 4. 2D View of FSW tool with dimensions

The Table 4 and 5 represents the chemical composition and various properties of the H13 tool steel used in the current work.

Table 4
Tool Material Composition

Element	Content %
Chromium, Cr	4.75-5.50
Molybdenum, Mo	1.10-1.75
Silicon, Si	0.80-1.20
Vanadium, V	0.80-1.20
Carbon, C	0.32-0.45
Nickel, Ni	0.3
Copper, Cu	0.25
Manganese, Mn	0.20-0.50
Phosphorus, P	0.03
Sulfur, S	0.03

Table 5
Physical and Mechanical Properties of H13 Tool Steel

Property	Metric
Density	7.80 g/cm^3
Melting point	1427°C
Tensile strength, Ultimate	1200 - 1590 MPa
Tensile strength, Yield	1000 - 1380 MPa
Reduction of Area	50.00%
Modulus of elasticity	215 GPa

5. Experimental Setup and Procedure

The present work is conducted in an experimental setup which has a cylindrical, shouldered tool with a profiled probe which is rotates slowly and plunged into the weld joint between two pieces of sheet or plate material that are to be welded together. The parts that are to be welded must be clamped onto a backing bar in a manner that prevents the abutting joint faces from being forced apart or in any other way moved out of position. Frictional heat is generated between the wear-resistant welding tool and the material of the work pieces. This heat causes the work pieces to soften without reaching the melting point and allows the tool to traverse along the weld line. The resultant plasticized material is transferred from the leading edge of the tool to the trailing edge of the tool probe and is forged together by the intimate contact of the tool shoulder and the pin profile. This leaves a solid-phase bond between the two pieces. The process can be regarded as a solid-phase keyhole welding technique since a hole to accommodate the probe is generated, then moved along the weld during the welding sequence. The Fig. 5 shows the friction stir welding machine, here we can see vertical arm with the welding tool embedded in the holder. The work of this arm is to penetrate the pin into the horizontally clamped specimen. The present work has considered two aluminium plates (AA6061 and AA5083) with dimensions 100 mm ×50 mm × 6 mm plates, these plates are clamped using jigs on the moving bed. The required load and the RPM of the tool is set using control switches.

Fig. 5. Friction stir welding machine

The present work considers tool rotation speed, traverse speed and axial load as the varying input parameters for welding the dissimilar aluminum plates through Friction Stir Welding process. The tool rotational speed varies from 1000 RPM to 1400 RPM, Traverse speed varies between 20 mm/ min to 30 mm/min and the axial load applied varies from 5 KN to 7 KN In total three specimens have been welded by making combination of the varying FSW parameters and Specimen 1 is welded by considering the welding condition 1 (1400 RPM , 30 mm/min & 7 KN) , Specimen 2 is welded by considering the welding condition 2 (1200 RPM , 25 mm/min & 6 KN) , Specimen 3 is welded by considering the welding condition 1 (1000 RPM , 20 mm/min & 5 KN). The table 6 shows the input

Table 6
Friction Stir Welding Input Parameters

Parameters	Symbol	Unit	Level 1	Level 2	Level 3
Tool Rotational Speed	A	RPM	1400	1200	1000
Bed Moving Speed	B	mm/min	30	25	20
Axial Load	C	KN	7	6	5
Welding Condition			1	2	3

Table 7
Hardness values of different specimens

Specimen No	Welding Condition No	Trial 1	Trial 2	Trial 3	Average
1	1	85	86	84	85
2	2	78	76	76	77
3	3	87	87	86	87

parameters considered and their varying levels. The welded plates are further subjected for evaluation of hardness and microstructure at the welded area by adopting standard procedures and the research findings are tabulated.

6. Results and Discussion

The evaluation of hardness of the welding joint at stir zone has been carried out by using a micro hardness tester made from japan by adopting Vickers hardness test and according to the standard procedure described by ASTM E3-11. The hardness values of the three different specimens have been tested by taking three different values for a single specimen and the average value of the same has been considered. The microstructure evaluation at the stir zone has been conducted by using a metallurgical microscope by applying 1% HF solution as etchant. A magnification of 100X and 200X are considered and mircographs have been prepared. The metallurgical examination has revealed that the eutectic particles of Al-Mg-Si in matrix of AL solid solution is present. The hardness values of the different specimens and their average values are represented in Table 7.

The results indicate that the factors tool rotational speed, traverse speed and axial force applied have considerable effect over hardness. The hardness value increases by selecting the lowest levels.

7. Conclusion

The following conclusions may be arrived from the work carried out in FSW of dissimilar Aluminium alloys.

- Friction Stir Welding can be used to join AA6061 and AA5083 in dissimilar combinations.
- The traverse speed, load, rotational speed are found to affect the hardness of AA6061 - AA5083 joints obtained through FSW.
- The specimen welded by having 1200 RPM tool rotational speed with 25mm/min bed movement speed and subjected to vertical load of 6KN have shown low hardness value by comparing to the specimens welded by other parameters used.
- The microstructural examination has revealed eutectic particles of Al-Mg-Si in matrix of AL solid solution present in all the three specimens
- The hardness is comparatively less than the base metal.
- Through DOE concepts the study may be elaborated by preparing an experimental layout by Taguchi or Response surface methodology and more experimental work can be carried out.
- By including more output parameters multi response optimization of FSW input parameters can be done and the significant parameter affecting the output can be identified through ANOVA.

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