Microstructural And Mechanical Characterization of Friction Stir Weld on A Aerospace Aluminium Alloy

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Abstract- *FSW is a solid state welding process and joining similar or dissimilar metals in which the relative motion between the tool and the work piece produces heat which makes the material of two edges being joined by plastic atomic diffusion.FSW widely used for the welding of light and difficult to weld metals and their alloys like aluminium, magnesium, copper etc. For FSW process tool is a critical component to the success of the process. FSW process used for the aerospace, railway, land transportation, ship building/marine, and the construction industries. For the experimentation of FSW high carbon high chromium (HCHCr) tool steel with tapered cylindrical pin shape having 50-55 HRC is used. It is having extremely high wear resistance properties, good softening resistance at elevated temperature, fine carbide size and grain size with high toughness and can withstands the impact load. All experiments are performed using AL 2014 aluminium alloy as a work piece. In this experimental work tool rotational speed (rpm), welding speed (mm/min) and axial tool tilt angle (degree) are used as process parameters. The main response variables were weld quality and weld strength.*

Keywords- Friction stir welding, tool rotational speed, welding speed, tool tilt angle, weld quality, weld strength

I. INTRODUCTION

In FSW, a non-consumable rotating shouldered-pin-tool is dove into the interface between two plates being welded, until the point when the moment that the shoulder touches the surface of the base material, and afterward tool is transverse along the weld line. In FSW, frictional heat is produced by rubbing of tool shoulder and base material surface. During traversing, softened material from the leading edge moves to the trailing edge due to the tool rotation and the transverse movement of the tool, and this transferred material is consolidated in the trailing edge of the tool by the application of an axial force. FSW parameters are tool geometry, axial force, rotational speed, transverse speed and tool tilt angle. Friction Stir Welding (FSW) is a basic procedure in which a turning tube shaped tool with a shoulder and a profiled pin is dove into the connecting plates to be joined and navigated along the line of the joint. The plates are solidly clipped on to the bed of the FSW equipment to prevent them from coming apart during welding. A cylindrical tool rotating at high speed is slowly plunged into the plate material, until the shoulder of the tool touches the upper surface of the material. A downward force is applied to maintain the contact. Frictional heat is created between the tool and the material which causes the plasticized material to get heated and softened, without reaching the melting point. The tool is then traversed along the joint line, until it reaches the end of the weld.

As the tool is moved toward welding, the main edge of the tool forces the plasticized material on either side of the butt line to the back of the tool. In effect, the transferred material is forged by the intimate contact of the shoulder and the pin profile. Keeping in mind the end goal to accomplish finish through-thickness welding, the length of the pin ought to be somewhat not as much as the plate thickness, since only limited amount of deformation occurs below the pin. The tool is generally tilted by 2-4°, to encourage better union of the material in the weld.

In FSW, the ordinarily comprises of a round and hollow shoulder with a profiled test, additionally called the pin. The material or materials being welded can be known as the work piece, part, test, or plate. The joint where the samples are adjoined will be referred to as the weld line. The part used to support and clamp the sample is called the backing plate, backing bar, or anvil. The tool rotates at an angular velocity given in revolutions per minute (RPM), which will be referred to as rotational speed (RS). The translational speed at which the device goes along the weld line is known as feed rate or travel speed (TS), and will be given in millimeter per second (mm/s) or inches per minute (ipm).

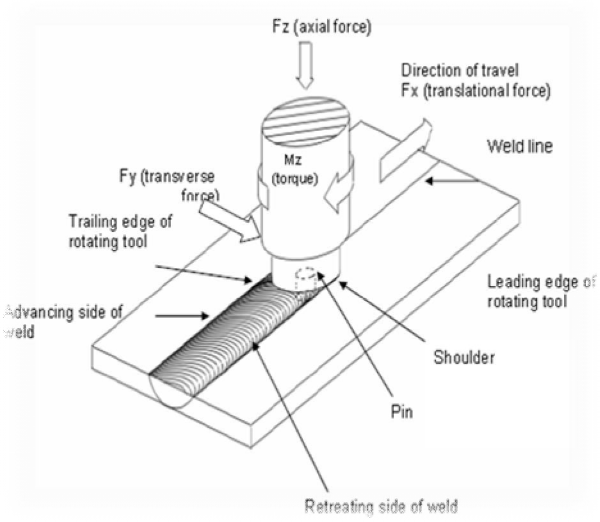

Fig 1. Schematic of the Friction Stir Welding Process[2]

II. LITERATURE SURVEY

S Rajakumar et.al studied that the influence of process and tool parameters on tensile strength properties of AA7075-T6 joints produced by friction stir welding and conclude that the joint fabricated using the FSW process parameters of 1400 rpm (tool rotational speed), 60 mm/min (welding speed), 8 KN (axial force), with the tool parameters of 15 mm (shoulder diameter), 5 mm (pin diameter), 45 HRC (apparatus hardness) yielded higher quality properties contrasted with different joints and the greatest quality properties of 315 MPa yield quality, 373 MPa of rigidity, 397 MPa of score elasticity, 203 HV of hardness and 77% of joint productivity separately was achieved for the joint created utilizing over the procedure and instrument parameters. Defect free fine grained microstructure of weld nugget is important factors for the higher tensile strength of the joint.

Hussain and quadri have made an attempt to determine and evaluate the influence of the process parameters of FSW on the weldments. The Vickers hardness, elasticity and radiography are considered for examination by shifting instrument speed, device nourish and keeping up steady profundity of entrance of weld. Trials were directed on AA6351 Aluminium amalgam in a CNC vertical machining focus. The yield variables are measured in UTM, Vickers hardness analyzer and radiography hardware. Comes about show solid connection and strong correlation between the weldment quality and process parameters. Rigidity is found to increment with increment in rotational speed. Most extreme Tensile quality of 172 Mpa was seen at 1350 rpm (for 115 mm/min sustain). Fig. 2.1 shows the effect of tensile strength on tool rotation speed and feed.

Chand and Bunyan found the optimum tool material for joining of butt joint aluminium alloy AA6061 by considering the three major factors at three levels namely tool material, rotational speed and axial force. Conclusions were made from their investigation that two plates of aluminium alloy AA6061 welded in butt joint. A maximum equivalent stress of (208.77 Mpa) exhibited by tool with optimal process parameters (tool rotational speed, 1200 rpm; axial force, 1000N) as obtained from taguchi method and the axial force is the dominant parameter for equivalent stress developed on the tool followed by rotational speed.

Barcellon et.al studied experimental activity on friction stir welding (FSW) of aluminium alloys. Butt joints of two different materials, namely AA2024-T4 and AA7075-T6, were investigated from a metallurgical point of view. He conclude the percentage of insoluble particles locally decreases due to the tool pin action; the recrystallisation phenomena occurring in the nugget zone contrast the material softening due to precipitates density decrease; an inhomogeneous decrease of the material mechanical characteristics is observed and in particular a reduction of the material micro-hardness values is obtained, with minimum values reached in correspondence of the thermally altered zones of the material.

Hwang et al. studied and experimentally explore the thermal histories, temperature distributions in a work piece during a friction stir welding (FSW) process involving the butt joining of aluminium 6061-T6. They said that the appropriate temperatures for a successful FSW process are between 365 and 390^0c, temperatures on the advancing side are slightly higher than those on the retreating side and the elasticity, the hardness at the thermo-mechanically influenced zone (TMAZ) are around one-portion of the base metals.

Elangovan et.al concentrated the impact of hardware stick profile and device bear measurement on FSP zone arrangement in AA6061 aluminium compound. Five diverse device stick profiles (straight barrel shaped, decreased round and hollow, strung tube shaped, triangular and square) with three distinctive shoulder measurements have been utilized by them to manufacture the joints. They examined the arrangement of FSP zone visibly, and elastic properties of the joints have been assessed and associated with the FSP zone development. From the examination they found that the square stick profiled apparatus with 18 mm bear distance across created mechanically solid and metallurgically imperfection free welds contrasted with other device stick profiles.

Rodrigues et.al concentrated the weldability of AA 5083-H111 (non-warm treatable) and AA 6082-T6 (warm treatable)aluminium alloys was compared by analyzing the welds obtained from both materials under a large range of welding conditions. They said that in FSW of both base materials, the high transverse speed can be achieved by carefully choosing process and tool parameters, these in turn are strongly dependent on the base material characteristics and plate thickness.

III. OBJECTIVE

The aim of present study is to examine the mechanical and microstructural properties of aerospace aluminium alloy AL 2014 and its welded joint produced by friction stir welding (FSW). The research objectives of this thesis can be summarized into following major parts:

1. To demonstrate feasibility of FSW of aluminium alloy to defect free.
2. Analysis of mechanical properties like tensile strength, Microhardness of friction stir welding joints.
3. Finding engineering stress strain curves at different strain rate.
4. To observe microstructure analysis for friction stir welding (FSW) joints to compare base metal (Grain size refinement and microstructure of friction stir welding joints).
5. To optimize process parameter for friction stir welding (FSW) joints.

IV. METHODOLOGY

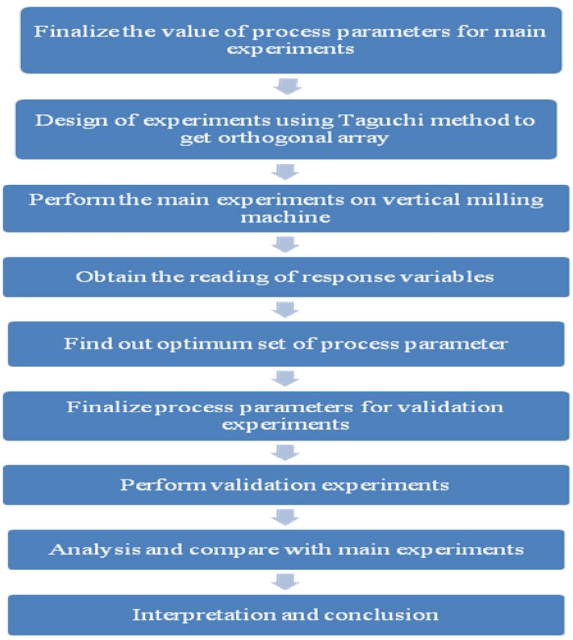

Fig 2. Methodology description.

V. EXPERIMENTAL WORK

A. Material Selection For FSW

a. Work piece Material

Aluminum alloy 2014 is an aluminum based alloy often used in the aerospace industry. It is easily machined in certain tempers, and among the strongest available aluminum alloys, as well as having high hardness. The 2014 is the second most popular of the 2000 series aluminum alloys, after 2014 aluminum alloy. It is commonly extruded and forged. Aluminum alloy 2014 is a medium strength alloy with excellent corrosion resistance. It has the highest strength of the 2000 series alloys. Alloy 2014 is known as an aerospace alloy. Typical composition limits are shown in Table I. In plate form, 2014 is the alloy most commonly used for machining. As a relatively new alloy, the higher strength of 2014 has seen it is many applications. The addition of a large amount of manganese controls the grain structure which in turn results in a stronger alloy. It is difficult to produce thin walled, complicated extrusion shapes in alloy 2014. The extruded surface finish is not as smooth as other similar strength alloys in the 2000 series.

TABLE I. MECHANICAL PROPERTIES OF BASE METAL AL 2014

Material	Hardness(HV)	Ultimate Strength (MPa)	Elongation %
Al 2014 T6	155	474	03

Plate of size 60×50×3 mm is required for testing of tensile strength on universal testing machine. The aim for machining both sides of the plates is to make them parallel for the FSW machine clamping system. The parallel plates enabled the uniformity in welding the gaps between the plates.

b. Material Selection of Tool for FSW

Friction stirring is a thermo mechanical deformation process where the tool temperature approaches the solidus temperature of base metal. Production of a quality friction stir weld requires proper tool material selection for the desired application. Actually, there are imperative impacts to the apparatus amid welding: rough wear, high temperature and dynamic impacts. Table II shows summary of tool materials.
The following characteristics have to be considered for material choice,

i. Ambient and elevated temperature strength,

ii. Elevated temperature stability,
iii. Wear resistance,
iv. Coefficient of thermal expansion.

TABLE II. SUMMARY OF TOOL MATERIALS

Alloys to be welded	Thickness (mm)	Tool Material
Aluminium alloys	3 – 50	Tool steels, Co-WC composite
Magnesium alloys	3 – 10	Tool steel, WC composite
Copper alloys	3 – 50	Ni-alloys, W-alloys, PCBN, Tool steels
Titanium alloys	3 – 10	W-alloys
Stainless steels	3 – 10	PCBN, W-alloys
Low-alloy steels	3 – 10	WC composite, PCBN
Nickel alloys	3 – 10	PCBN

For these experimentation tungsten carbide tool is used for friction stir welding (FSW). Tungsten carbide is a chemical compound containing equal parts of tungsten and carbon atoms. In its most basic form, tungsten carbide is a fine gray powder, but it can be pressed and formed into shapes for use in industrial machinery, cutting tools. Tungsten carbide is approximately twice as strong as steel, with a young's modulus of approximately 530-700 GPa and is double the density of steel**.** The Fig. 3 shows FSW tool of Tungsten carbide material.

Fig.3. FSW Tool

B. Welding Procedure

Following welding procedure were adopted for performing the welding. The stepwise procedure is given below:-

i. With the help of trial tests four parameters like tool rotational speed, welding speed, axial force and tool geometry were considered for friction stir welding of aluminium alloy.
ii. Range of the parameter is selected.
iii. Experimentations are performed as per the design of experiments.
iv. Single pass procedure is followed to fabricate the joints.
v. Weld joint is made by joining two plates having dimensions (60 x 50 x 3) mm using single side welds.
vi. The plates to be welded are safely clasped in the installation so that the plates remain set up and don't take off because of the welding strengths.
vii. The rotational motion of the spindle was started and the tool is then kept in contact with the surface of the plates and the pin is penetrated to a predetermined depth in the surfaces of the plates to be welded.
viii. The tool is given some time as it rotates in contact with the surfaces to soften the material because of the frictional heat is created and a short time later the tool is given forward movement which formed the weld. The tool is pulled back after the weld is finished. The process leaves a hole at the end of joint.

C. Taguchi Method

It is an engineering method for product or process design that focuses on minimizing variation or sensitivity to noise. When used properly, Taguchi Design provide a powerful and efficient method for designing products that operate consistently and optimally over a variety of conditions. In robust parameter design, the essential objective is to discover factor settings that minimize response variation, while adjusting (or keeping) the process on target. After you determine which factors affect variation, you can try to find settings for controllable factors that will either reduce the variation, make the product insensitive to changes in uncontrollable (noise) factors, or both.

TABLE III. PROCESS PARAMETERS AND THEIR LEVEL FOR FINAL EXPERIMENTATION

Levels	Tool rotational Speed (rpm)	Welding speed (mm/min)	Tilt angle (^{0} C)
Level 1	970	69	0
Level 2	1200	86	1.5
Level 3	1500	110	2

Design of experiments is a method of designing experiments, in which only selected number of experiments are to be performed. For example if there are three parameters with three levels of each parameter, then the total number of experiments to be performed is $3^3 = 27$ experiments. But using design of experiments method, only 9 experiments are required to be performed. On the basis of these 9 experiments, the significance and optimal levels of each parameter is obtained.

TABLE IV. L_9 (3^3) ORTHOGONAL ARRAY FOR FINAL EXPERIMENTATIONS

Tool rotational Speed (rpm)	Welding speed (mm/min)	Tilt angle (^{0} C)
970	69	0
970	86	1.5
970	110	2
1200	69	1.5
1200	86	2
1200	110	0
1500	69	2
1500	86	0
1500	110	1.5

VI. TESTING AND ANALYSIS

A. Tensile Test

Transverse tensile test samples are prepared from welds joints according to the ASTM specifications, E8/E8M – 09 [ASTM-2009] by horizontal milling machine using specimen of two inch gauge length as shown in Fig 4. Nine tensile test pieces are prepared from the each weld joints to ensure accuracy. The experiments are carried out on universal testing machine.

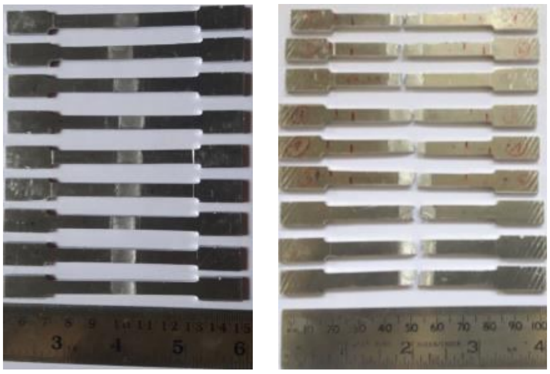

Fig 4. Tensile Testing Specimen (a and b) before and after weld joints

B. Microhardness Test

To have clear identification of microstructure and to prevent worn out of SiC particles, wet polishing technique is used. To polish the weld specimens, Silicon carbide waterproof abrasive polish papers of grades 220, 400, 600, 800, 1000 and 1200 respectively are used. The benefit of using these polish papers is that we can polish the specimen by continuously injecting a jet of water between the work piece and polish paper. It prevents the worn out of SiC particles and also prevent the heating of the work piece which may cause change in microstructure properties after that mirror polish are done using velvet paper and diamond paste.

Fig 5. Microhardness Weld Specimen & Vickers Hardness Tester

VII. RESULT AND DISSCUSION

A. Analysis of tensile strength

Analysis of tensile strength using universal tensile testing machine with a constant cross head speed of 4 mm/min at room temperature. The stress-strain curve for base metal as well as all FSW joints sample as shown in fig.6.

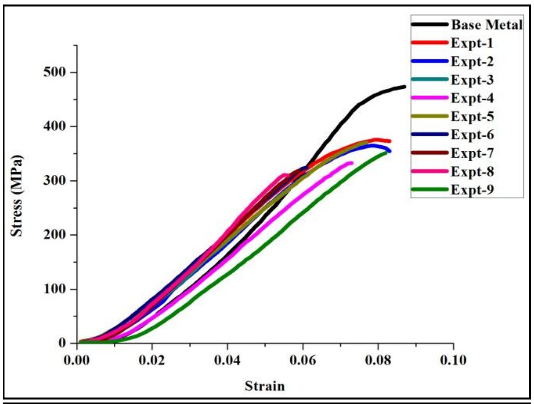

Fig 6. Stress-Strain Curve for Weld Joints Expt-1 to 9 (Combined)

The effect of various input parameters on output responses will be analyzed using taguchi method. The table V indicates that tool rotational speed is most significant parameter influencing tensile strength.

TABLE V. RESPONSE TABLE FOR SIGNAL TO NOISE RATIOS LARGER IS BETTER (FINAL EXPERIMENTS)

Level	Tool Rotational Speed (rpm)	Welding Speed (mm/min)	Tilt Angle (⁰ C)
1	49.64	50.65	50.42
2	50.68	50.74	50.40
3	51.11	50.03	50.60
Delta	1.47	0.71	0.20
Rank	1	2	3

Main effect plot for tensile strength is as shown in Fig. 7

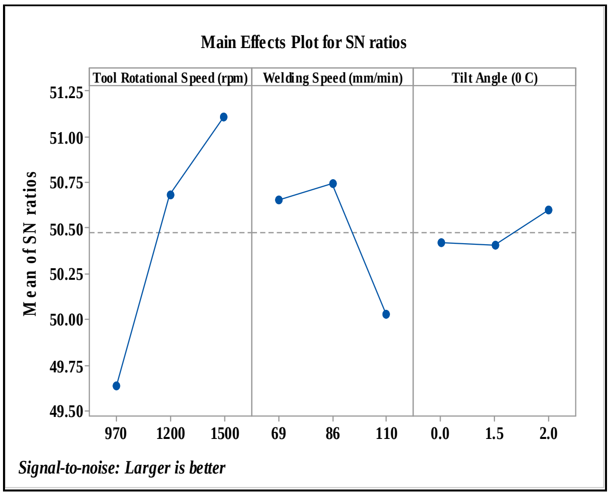

Fig 7. Main Effects Plot of SN Ratios for Tensile Strength (N/mm^2) (Final Experiments)

B. Analysis of Microhardness

To evaluate the mechanical properties of FSW joints at different welding parameters, the Vickers micro hardness on the transverse cross section was performed by micro hardness tester. The hardness profiles were measured at 1 mm deep from the joints surface with regular intervals of 0.5 mm using a load of 0.05 gm for dwell time 10 sec. The micro hardness distribution for FSW zone as shown in fig.8.

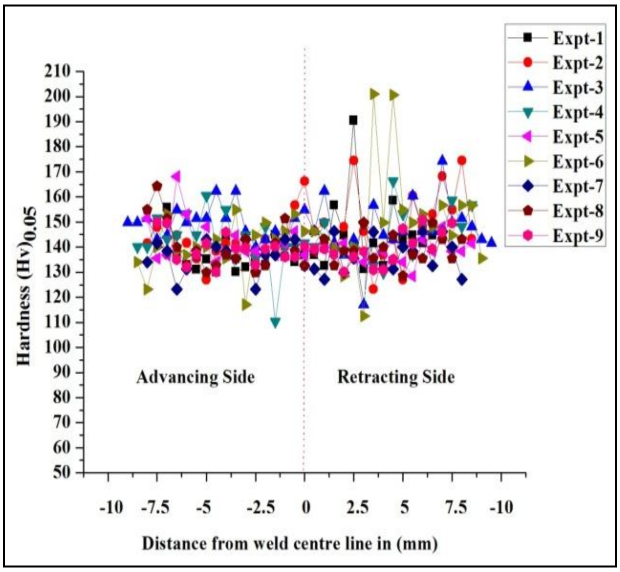

Fig.8 Micro hardness distribution of weld joints Expt-1 to 9 (Combined)

The effect of various input parameters on output responses will be analyzed using taguchi method. The table VI indicates that tool rotational speed is most significant parameter influencing micro hardness.

TABLE VI. RESPONSE TABLE FOR MICRO HARDNESS [FINAL EXPERIMENTS]

Level	Tool Rotational Speed (rpm)	Welding Speed (mm/min)	Tilt Angle (⁰ C)
1	42.82	42.94	43.04
2	43.23	43.00	43.06
3	43.13	43.22	43.06
Delta	0.41	0.28	0.02
Rank	1	2	3

Main effect plot for tensile strength is as shown in Fig. 9

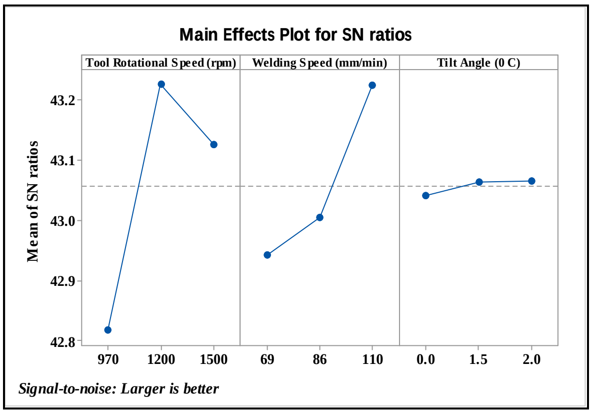

Fig 9. Main Effects Plot for Micro hardness [Final Experiments]

C. Analysis of Microstructure

The cross sections of the welds produced by conical tool profiles were subjected to metallographic examination to observe the microstructure. Usually, friction stir welded joints are free from solidification related defects since, there is no melting takes place during welding and the metals are joined in solid state itself due to the heat generated by the friction and flow of metal by the stirring action. However, FSW joints are prone to other defects like pin hole, tunnel defect, piping defect, kissing bond etc., due to improper flow of metal and insufficient consolidation of metal in the FSP (weld nugget) region. Microstructures are taken on the face of the base material specimens at 400X using optical microscope, one at center of welding surface and base metal side which is shown in fig 10.

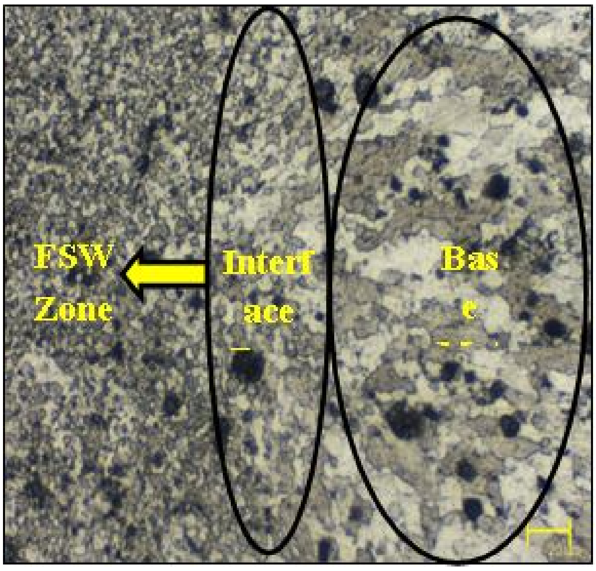

Fig 10. Optical Micrograph a) Base Metal, b) FSW Zone and c) Interface Zone

VIII. CONCLUSION

1. Micro hardness of FSW is found to increase with increase in rotational speed. Maximum micro hardness of 149 Hv is observed at 1200 rpm (tool rotation speed), 110 mm/min (welding speed), 0^0 (tilt angle).
2. Tensile strength of FSW is found to increase with increase in rotational speed. Maximum tensile strength of 376 MPa is observed at 1500 rpm (tool rotation speed), 69 mm/min (welding speed), 2^0 (tilt angle).
3. As the tool rotation speed and welding speed is reduced the ultimate tensile strength of FSW decreases and defect occur.
4. The ultimate tensile strength of butt weld reaches to 80 % of the base metal ultimate tensile strength.
5. As received base material grains are elongated and grain size for base material as 16 µm and after welding grain refinement observed as grain size 8 µm.

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REFERENCES

[1] S. Rajakumar, C.Muralidharan, V.Balasubramanian, “Influence of friction stir welding process and tool parameters on strength properties of AA7075-T6 aluminium alloy joints”, Department of Manufacturing Engineering, Annamalai University,(August 2010).

[2] A.K.Hussain and S.A.P.Quadri, “Evaluation of Parameters of Friction Stir Welding For Aluminium AA 6351 Alloy”, International Journal of Engineering Science and Technology, Vol. 2, (2010).

[3] Mr.A.G.Chand and J.Bunyan, “Application of Taguchi Technique For Friction Stir Welding of Aluminium Alloy AA6061**”,** International Journal of Engineering Research & Technology, Vol. 2, (June - 2013).

[4] A.Barcellona, G.Buffa, L.Fratini and D.Palmeri, “On microstructural phenomena occurring in friction stir welding of aluminiumalloys”,Journal of materials processing technology (2006).

[5] Y.M.Hwang, Z.W.Kang, Y.C.Chiou and H.H.Hsu, “Experimental study on temperature distributions within the work piece during friction stir welding of aluminium alloys”, International Journal of Machine Tools & Manufacture, (Dec 2007).

[6] K. Elangovan and V. Balasubramanian,“Influences of tool pin profile and tool shoulder diameter on the formation of friction stir processing zone in AA6061 aluminiumalloy”,Department of Manufacturing Engineering, Annamalai University,(2007).

[7] D.M.Rodrigues, C.Leita, R.Louro, H.Gouveia and A.Loureiro, "High speed friction stir welding of aluminium alloys", Science and Technology of Welding and Joining, (2010).

[8] P.Rohilla and N.Kumar, "Experimental investigation of Tool Geometry on Mechanical Properties of Friction Stir Welding of AA6061", International Journal of Engineering Research & Technology Vol-3, (August 2013)