EFFECT OF PROCESS PARAMETERS ON FRICTION STIR WELDED AA 6061 ALUMINUM ALLOY BUTT JOINTS.

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ABSTRACT

Friction stir welding is a solid state welding process for joining metallic alloys has emerged as an alternative technology used for high strength alloys that are difficult to join with conventional techniques. The applications of FSW Process are found in several industries such as aerospace, automotive and marine industries for joining Aluminum, magnesium and copper alloys. The FSW Process parameters such as rotational speed, welding speed, tool pin profile, tilt angle, plunge speed, axial force play vital role in the analysis of weld quality deciding joint strength. AA6061 aluminum alloy (A1mg-si) has widely used in fabrication of light weight structures. An attempt has been made to investigate the effect of different welding parameters on the weld quality of AA6061 aluminum alloy. Cylindrical pin profile is used for tool pin profile in this research. The quality of the weld is well and no defect is found using this tool. Consequently, the obtained results explained the variation of stress as a function of strain and the effect of different welding parameters on yield strength, ultimate tensile strength & elongation.

Keywords: Friction Stir Welding, AA6061 Aluminum Alloy, Tool Rotational Speed, Welding Speed, Mechanical Properties.

I. INTRODUCTION

Friction stir welding (FSW) is a solid state joining Process developed and patented by the welding institute (TWI), UK in 1991[1]. FSW is a continuous, hot shear, auto genius Process involving a Non-consumable rotating tool of the harder material then the base Material. FSW has emerged as welding Technique used in high strength alloys (2xxx, 6xxx, 7xxx and 8xxx series) for Aerospace, automotive and marine applications [2] that were difficult to join with conventional Techniques. Defect free welds with good mechanical Prosperities have been made with FSW in a variety of aluminum alloys. This solid state process leads to minimal micro structural changes and better mechanical prosperities then conventional welding. In this investigation, an attempt has been made to understand the effect of parameters on the weld quality of AA6061 alloys using FSW process. Cylindrical pin is used as tool pin profile in this research. The pin traveled longitudinally at different welding speeds (mm/min) and the tool rotation speed was held between 800Rpm to 1500Rpm in all of the experiments. Consequently the appearance of the weld for different welding parameters has been examined by using x-ray Radiography technique and the Impact of the stress as a function of strain and the effect of different welding parameters on ultimate tensile strength yield strength and elongation are analyzed.

II. FRICTION STIR WELDING PROCESS

FSW is produced by rotating and plunging a specially designed cylindrical, shouldered tool with a small diameter pin into the joint line between two butted plates [3]. Frictional heat causes the metal to soften and allows the tool to traverse along the joint line. In this process, the two plates are clamped on a rigid back plate. The fixturing prevents the plates from spreading apart or lifting during welding. The welding tool, consists of a shank, Shoulder and pin, is then rotated to a prescribed speed. The tool is slowly plunged in to the work piece material at the butt line, until the shoulder of the tool forcibly contacts the upper surface of material and pin is a short distance from the back plate. A downward force is applied to maintain the contact and a short dwell time (10sec) is observed to allow for the development of the thermal fields for preheating and softening the material along the joint. Upon reaching end of the weld, the tool is withdrawn while it is still being rotated. As the pin is withdrawn, it leaves a keyhole at the end of the weld. The FSW process of butt joint is as shown in fig 1, the key hole at the end of the weld as shown in fig 2.

Fig 1. Principle of the FSW process for butt joints.

Fig2.Key holes at the end of the welds.

III. SELECTION OF MATERIAL

Aluminum Alloy AA 6061:- Aluminum alloy AA 6061 is a high strength alloy with excellent corrosion Resistance. This alloy is known as structural alloys. In plate form, AA 6061 is the alloy most commonly used for machining. The addition of large amount of manganese controls the grain structure which in turn results in a stronger alloy.

Table1:- Chemical Composition of Aluminum alloy AA 6061 (wt%)

Si	Fe	Cu	Mn	Mg	Ti	Cr	Others	Aluminum
0.598	0.343	0.265	0.07	1.095	0.016	0.204	0.048	Balance

Table2:- Mechanical Properties of Aluminum alloy AA 6061.

Base material	AA 6061
Density (X 1000 kg/m^3)	2.7
Elastic Modulus (Gpa)	70

Ultimate Tensile Strength (Mpa)	240.921
Yield Strength (MPa)	176.247
Hardness (VHN)5kg	105
Percentage Elongation	16.78

IV. TOOL DESIGN

Tool design influences heat generation, plastic flow, the power required and the uniformity of the Welded Joint [4]. The shoulder generates most of the heat and prevents the plasticized material from escaping from the work piece while, both the shoulder and the tool pin affect the material flow. Friction Stir Welded Tool in this study as shown in fig3.

Fig 3: Schematic Diagram of Tool pin Profile.

V. SELECTION OF PROCESS PARAMETERS

The important parameters affecting tensile strength are tool rotational speed, welding speed, plunge speed, tool tilt angle, axial load, tool penetration depth. Out of these parameters such as tool tilt angle and axial load can be varied only on machines dedicated to FSW. The other factors which primarily affect the strength of the joint yet can be varied easily on any vertical machine centre are tool rotation speed (N), tool traverse speed (V) and tool plunge speed (P). Therefore these three parameters are chosen in the present study.

VI. TOOL MANUFACTURING

The FSW Tool is designed for this Research is tool pin profile of cylinder of D/d ratio 3. Out of various Tool materials like tool steel, High speed steel (HSS), high carbon chromium steel, carbon and carbon boron nitride, among which HSS steel is chosen as Tool material because of it's high strength, high hot hardness, easy to process, easily available and low cost. The FSW tool is manufactured using CNC Turning centre and wire cut EDM (WEDM) machine. The tools are oil hardened to obtain a hardness of 60-62 HRC.

The tool material properties as given in table (3). The hardening temperature of HSS-M_2 is 1240-1290^{0}C, the quenching medium is oil/air, the tempering temperature is 550-580^{0}C and Brinel Rockwell hardness is 64-66.

Table3: Chemical Composition of Tool Material

C	Si	MN	Cr	Ni	W	Co	V	Mo
0.75-0.9	0.10-0.35	0.20-0.40	3.57-4.50	-	5.50-6.50	-	1.75-2.00	5.50-6.50

VII. WELDING PARAMETERS

The initial Joint Configuration was obtained by securing the plates in position using mechanical clamps. The direction of welding as normal to the rolling direction. Single pass welding procedure was used to fabricate the joint. The welding parameters used to fabricate the joints are presented in Table (4). Welding parameters influence the friction stir welded joints. If the tool rotational speed increases, it shows that there is a increase in elongation [5].

Table 4:- Welding Parameters

Welding Parameters/Range	Minimum(-)	Maximum(+)
Tool Rotational Speed (Rpm)	800	1500
Welding Speed (mm/min)	30	80
Plunge Speed (mm/min)	10	20

VIII. EXPERIMENTAL WORK

The Friction stir welds have been carried out by using a properly design clamping fixture that allows the user to fix the two sheets (75mm * 150mm) with the rolled plate of 5mm thickness to be butt welded on a CNC Vertical milling machine. Fig4 shows the experimental set up describing clamping and welding of FSW process.

Fig4. Experimental Set up Describing Clamping and Welding of FSW Process

In this investigation the base material AA 6061 which is widely used in aircraft and auto motive applications due to its high strength. FSW plates were examined using X- ray Radiography. There were no apparent defects in welded plates.

IX. DESIGN OF EXPERIMENTS

Table 5: Design of Experiments (DOE)

EXP No	Speed (N)Rpm	Welding speed(f) (mm/min)	Plunge Speed (mm/min)	Fu (N/mm2)	Fy N/mm2	% elongation
1	1500	80	20	115.749	114.597	2.48
2	1500	80	10	118.07	114.578	3.76
3	1500	30	20	114.56	113.38	3.3
4	1500	30	10	96.653	96.653	4.7
5	800	80	20	117.025	117.025	2.6
6	800	80	10	117.025	117.025	2.66
7	800	30	20	134.6	134.6	2.1
8	800	30	10	119.89	109.9	3.7

X. MECHANICAL TESTS

Friction stir welded samples were tested for tensile, impact, microstructure and micro hardness properties. The testing procedures, geometry of the samples including dimensions as per ASTM standards.

10.1 Tensile Test

Plain tensile strength and notch tensile strength are carried on UTM (10,000Kgf). The ASTM standard test samples are shown in fig 5 & fig6.

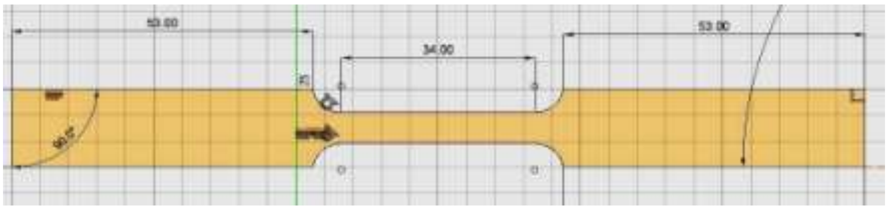


Fig5: Tensile Test Sample

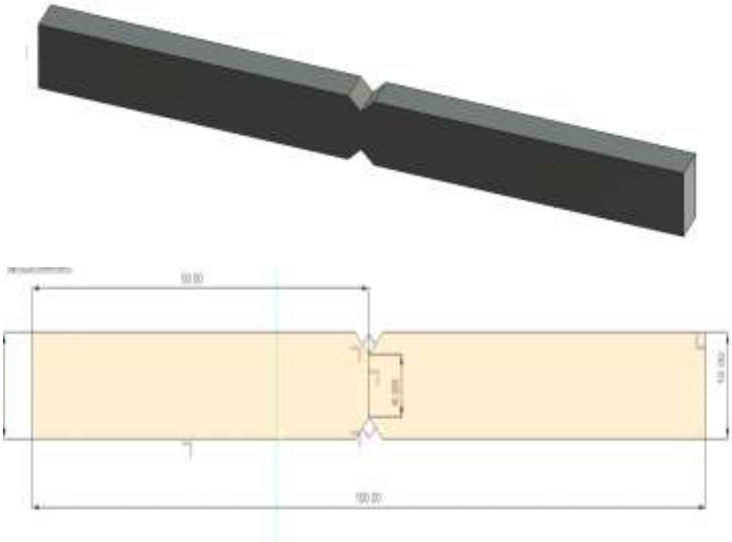


Fig6: Notch Tensile Sample

10.2 Impact Test

Impact test samples are prepared from the welded joint. The charpy V- notch impact toughness test carried on FIT-300(EN) machine. ASTM standard test sample as shown in fig (7).

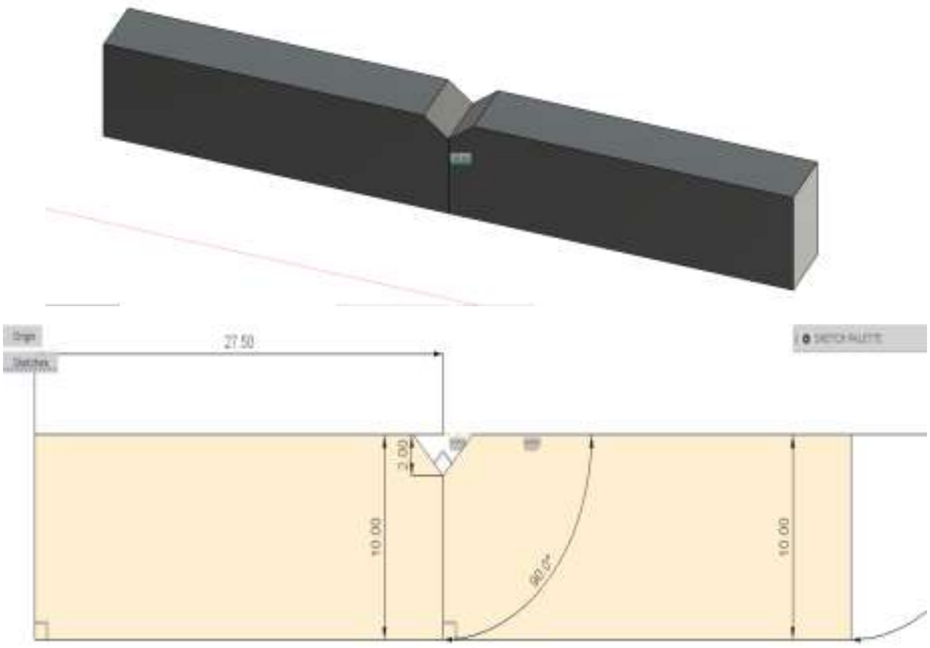


Fig 7: Impact Toughness Test Sample

10.3 Hardness Test

The samples are cut from welded joints by wire cut EDM and polished and etched. Micro hardness tests were conducted using digital micro hardness tester. A 100 gram load is applied for all the samples for a period of 15secs while measuring the hardness. The micro hardness was measured at equal intervals across weld ments.

10.4 Bend Test

Bend tests were carried out using UTM (10000 Kgf) tester. 90˚ bend tests were conducted. The ASTM standard bend test specimen as shown in fig8.

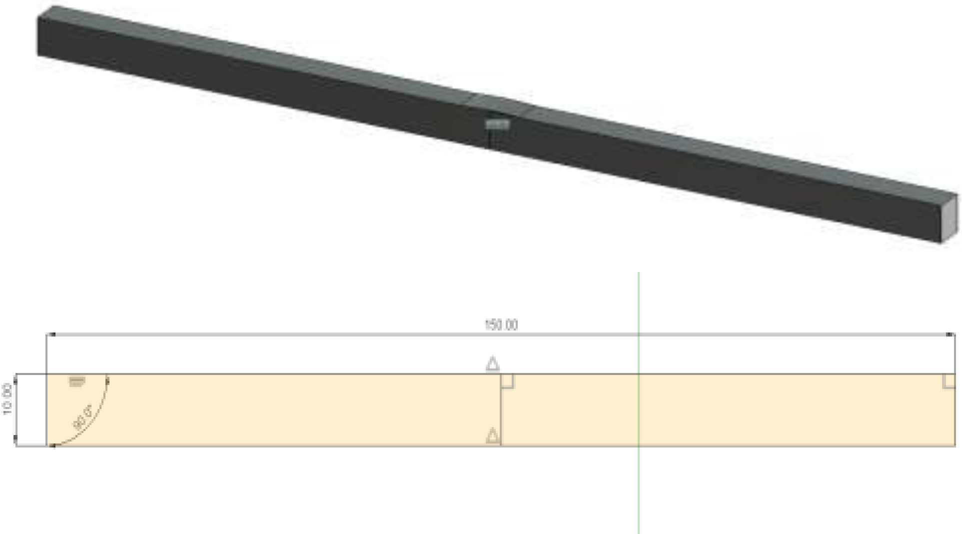


Fig8: Bend Test Specimen

10.5 Metallography

A low magnification Metscope -1 make was employed for observing the beed shape. The friction stir welded samples were sectioned by using wire cut EDM. Silver mirror image is obtained after following the standard procedural steps of Metallography. Etching is done carefully using Keller's regent (3ml Hcl, 5ml HNO_3, 2ml HF and 190ml distilled water). Micro scope was used for determination of microstructures at various locations.

XI. RESULTS & DISCUSSIONS

11.1 Visual Inspection

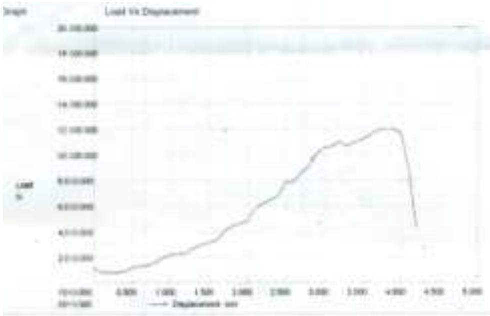
Visual inspection of the welds revealed that the welds are of high quality and defect free. However pin holes are formed at being and termination of the tool along centre line of weld. Surface roughness and semi circular striations are found in weld made at low welding speeds. Welds are smooth at high welding speed.

11.2 Tensile Strength Test

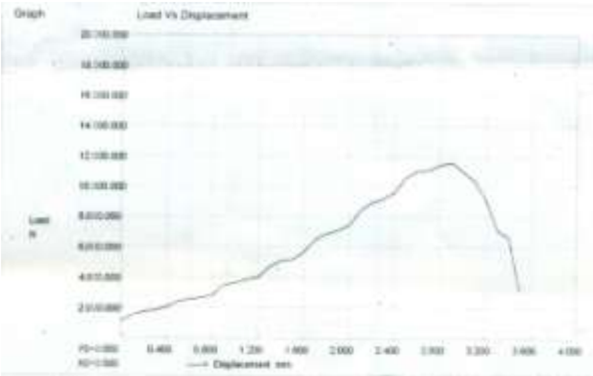
It is observed that the increase in rotational speed has resulted in increases of Tensile strength. The reason is that higher the speed, the higher will be the deformation and heat generation in the weld. This will result in finer grain structures, because of which tensile strength is increases. The result by tensile test which was observed during the experiments were shown in Graphs 1 to 8. The fractured specimens as shown in fig (9).

Fig 9. Fractured Specimens after Tensile Test

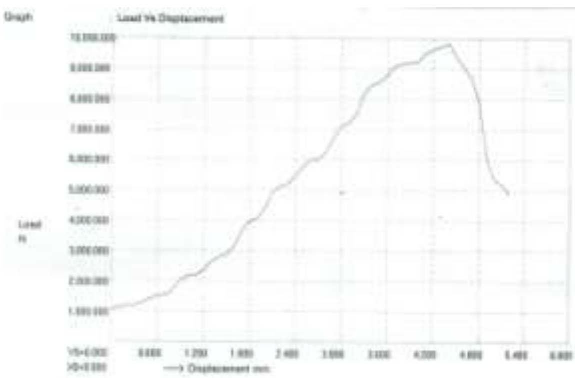
Graph 1.Stress-Strain Diagram for Specimen 1



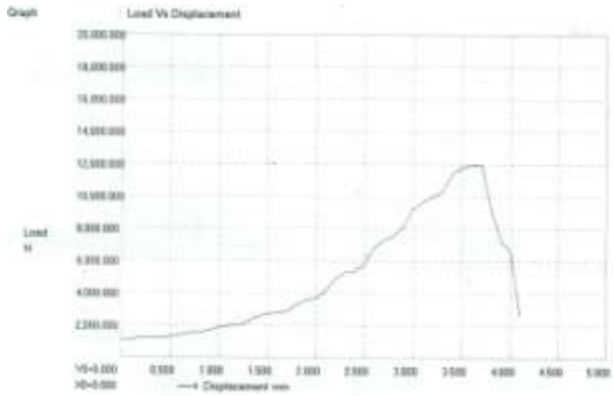
Graph2.Stress-Strain Diagram for Specimen 2



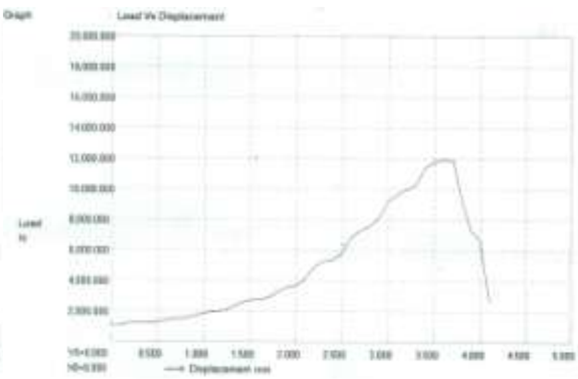
Graph 3.Stress-Strain Diagram for Specimen 3



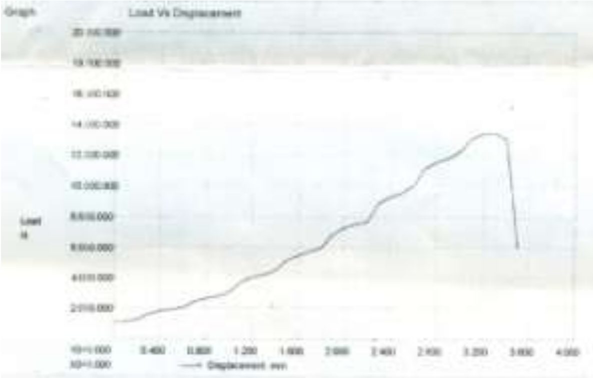
Graph4.Stress-Strain Diagram for Specimen 4



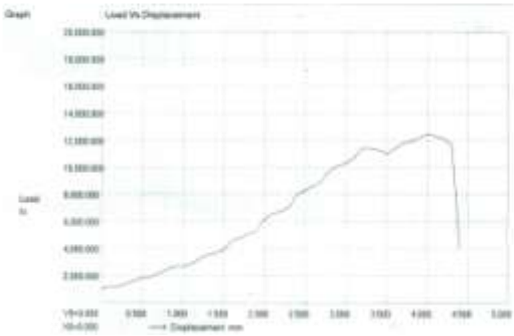
Graph 5.Stress-Strain Diagram for Specimen 5



Graph6.Stress-Strain Diagram for Specimen 6



Graph 7.Stress-Strain Diagram for Specimen 7

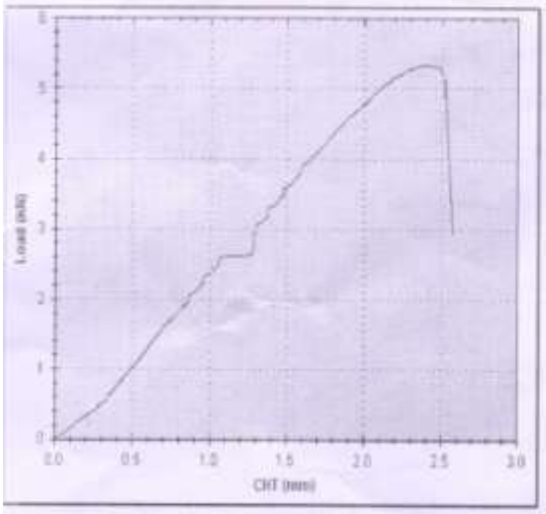


Graph8.Stress-Strain Diagram for Specimen 8

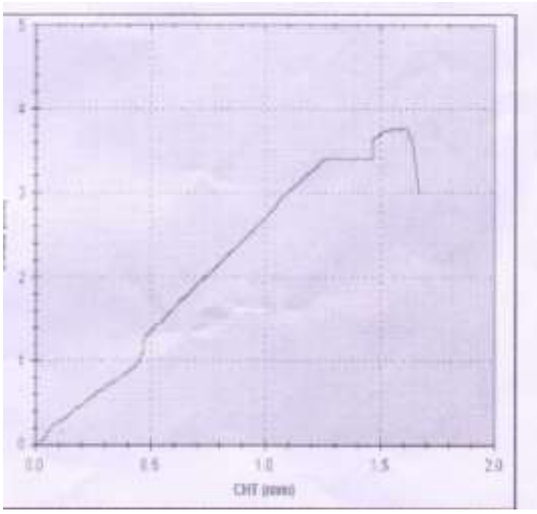
11.3 Notch Tensile Test

The specimens prepared for notch tensile test as shown in fig 10(a).The Failure of the specimens during notch tensile test as shown in fig 10(b). The yield strength, ultimate tensile strength & %elongation during notch tensile test for all the specimens are tabulated in table (6). The stress-strain Graphs during notch tensile test as shown below. Notch Tensile test is carried on TUE-600(C).The ASTM test samples are prepared. The tensile strength is decreasing when weld speed decrease. Stress Strain diagrams for specimens as shown in graphs 9-12. Comparison of notch ultimate tensile stress, notch yield stress and % elongation with parent metal as shown in figures 11(a), 11(b) and 11(c).

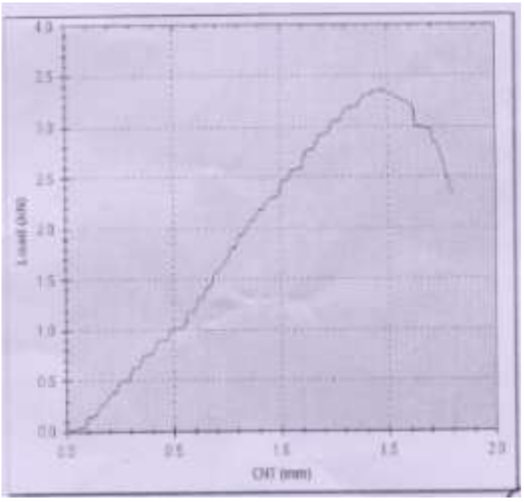
Fig (10) a) Notch tensile test specimens **b) Notch tensile test specimens after failure**



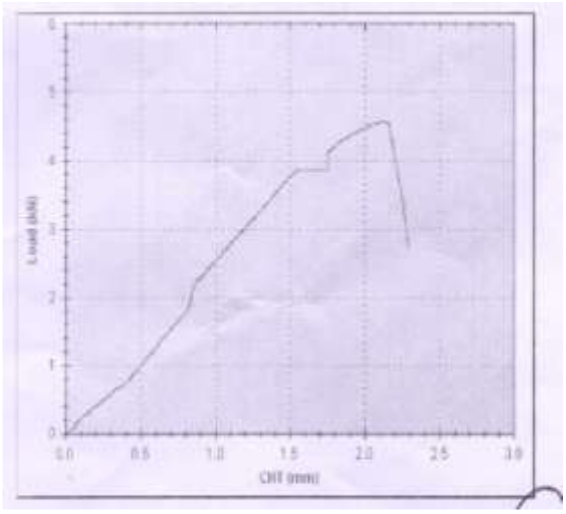
Graph 9.Stress-Strain Diagram for Specimen 1



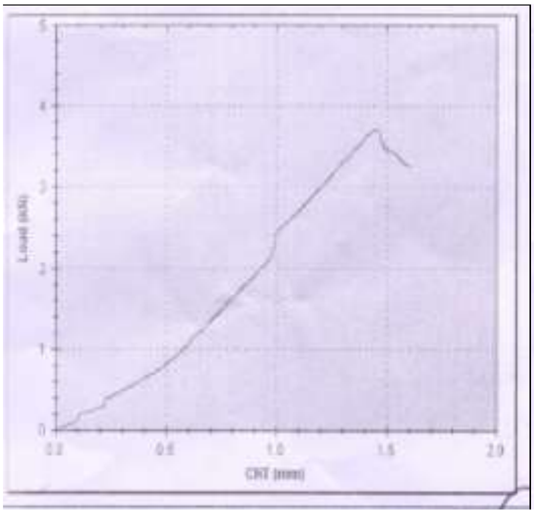
Graph10.Stress-Strain Diagram for Specimen 2



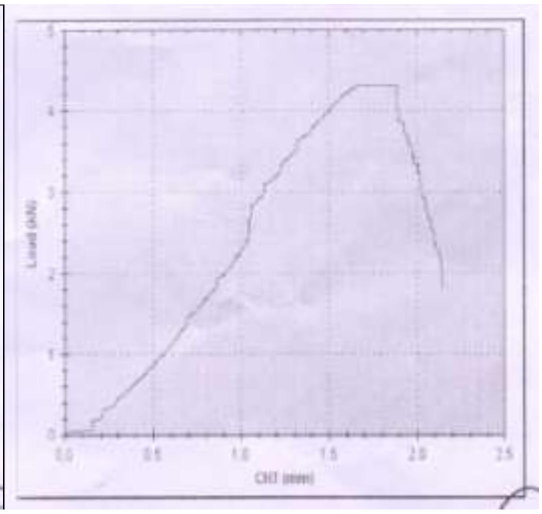
Graph 11.Stress-Strain Diagram for Specimen 3



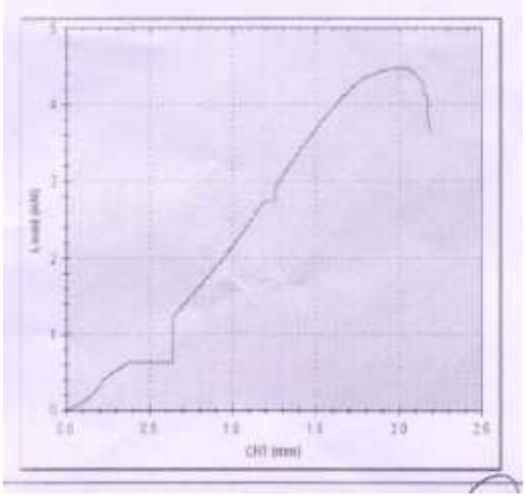
Graph12.Stress-Strain Diagram for Specimen 4



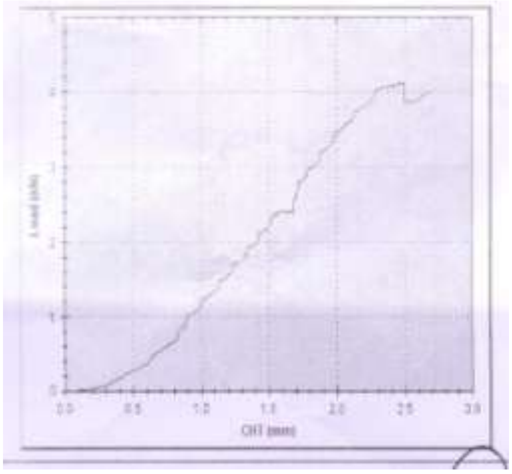
Graph 13.Stress-Strain Diagram for Specimen 5



Graph14.Stress-Strain Diagram for Specimen 6



Graph 15.Stress-Strain Diagram for Specimen 7



Graph16.Stress-Strain Diagram for Specimen 8

The ultimate tensile strength, yield strength and % elongation of the specimens are tabulated in table 6.

Table 6: Ultimate Tensile Strength, Yield Strength and % Elongation of the Specimens

	PM	Specimen1	Specimen2	Specimen 3	Specimen 4	Specimen 5	Specimen 6	Specimen 7	Specimen 8
Ultimate tensile strength in N/mm^2	343.03	189.5	138.9	124.8	170.7	135.3	149.8	179.5	146
Yield strength in N/mm^2	292.4	168.6	124.9	96.4	143.7	107.6	128.6	153.9	116.5
% elongation	0.93	2.9	1.23	2.27	3.87	0.9	4.1	2.83	2.77

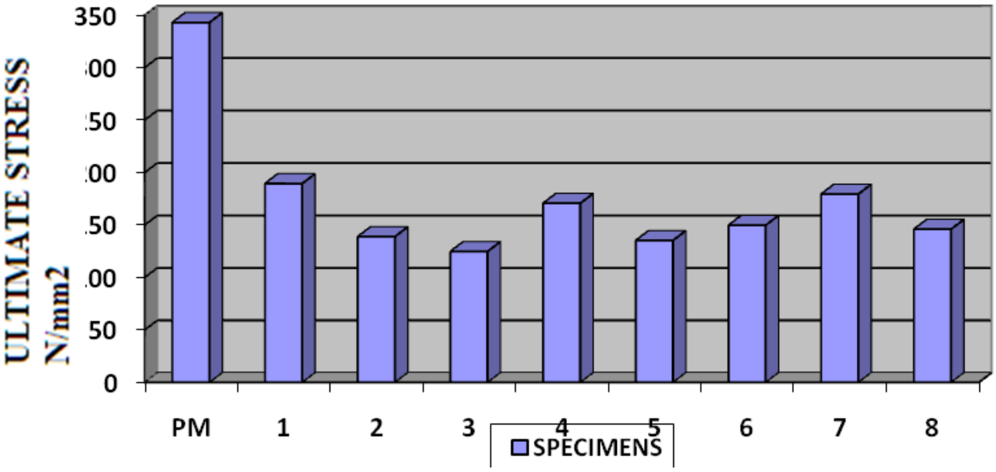


Fig11 (a). Comparison of Notch Ultimate Tensile Stress

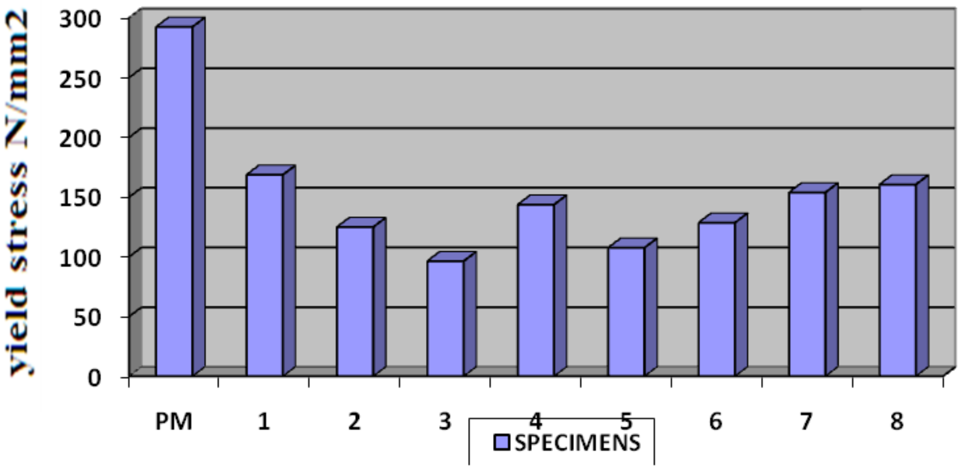


Fig11 (b). Comparison of Notch yield stress

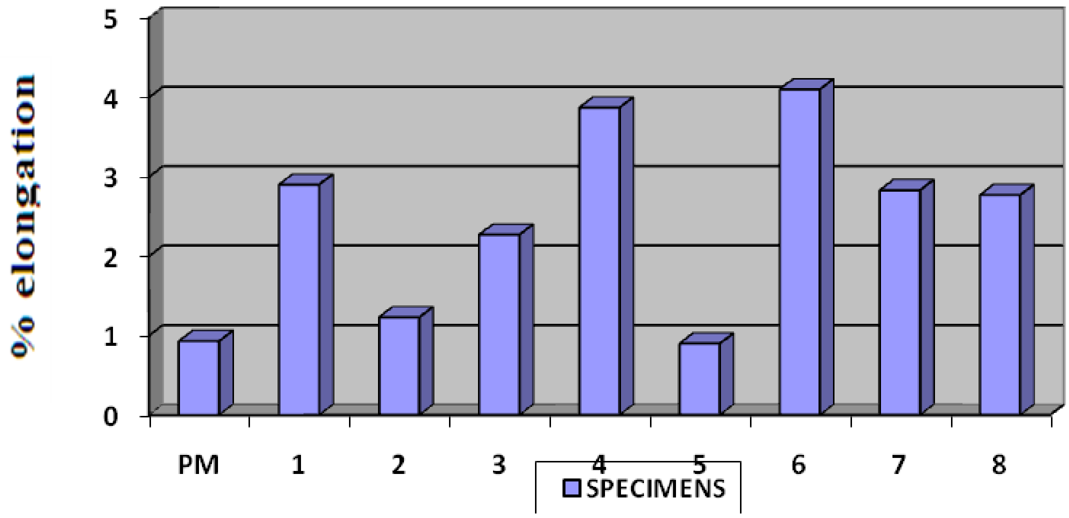


Fig11(c). Comparison of % Elongation

11.4 Bend Test

Root and face bend tests were used as an important tool to understand about the ductility and toughness of Friction Stir Welds.

As friction stir weld samples passes 90^0 bend as shown in fig 12(a). The root bend and face bend as shown in fig12 (b), 12(c). The results reveal that at low welding speeds the specimens withstands maximum bending load. The comparison of bending load on the root side and face side with parent metal as show in fig13 (a) and 13(b).

Fig 12 (a) Bend test set up (b) Root bend (C) Face bend

Table 7: Details of Bend Test for Root & Face bends comparing with parent metal

	PM	Specimen1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Specimen 6	Specimen 7	Specimen 8
Root Bend	8KN	7.85KN	7.8 KN	7.9 KN	7.95 KN	7.9 KN	7.7 KN	7.9 KN	7.8 KN
Face Bend	8KN	7.8 KN	7.8 KN	8 KN	7.9 KN	8.5 KN	7.9 KN	8 KN	8 KN

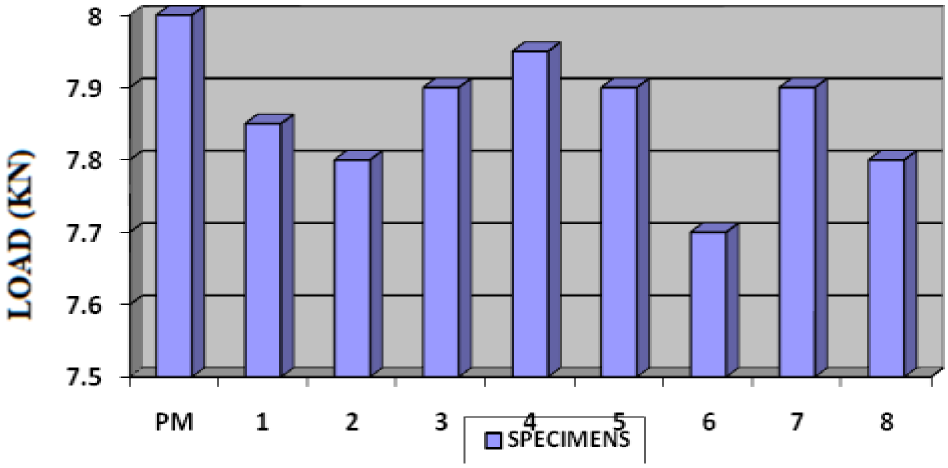


Fig 13(a) Comparison of Bending Load on Root Side

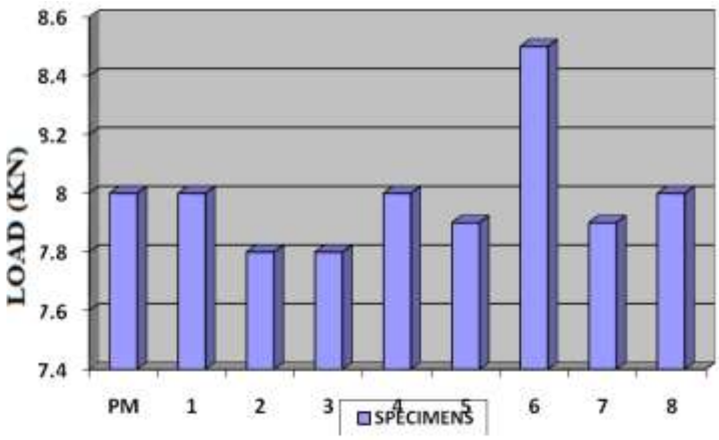
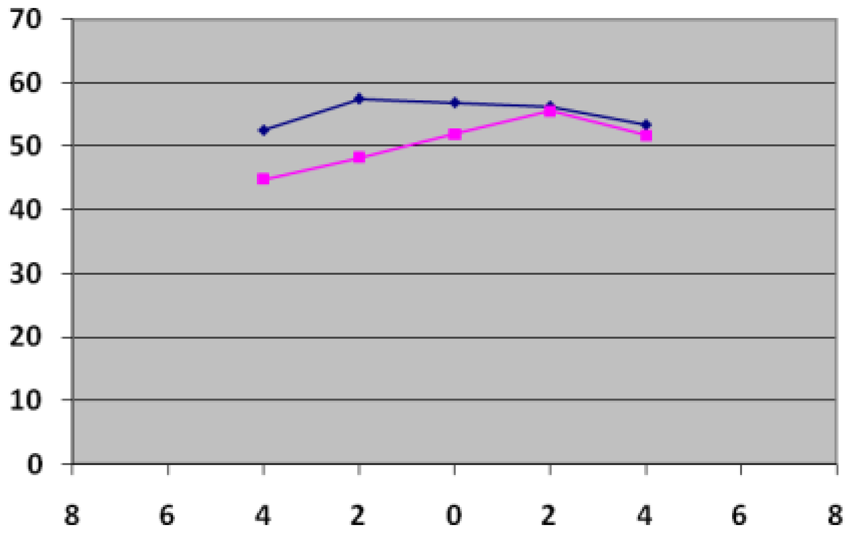


Fig.13 (b) Comparison of Bend Load for Face Side

11.5 Vickers Hardness Test

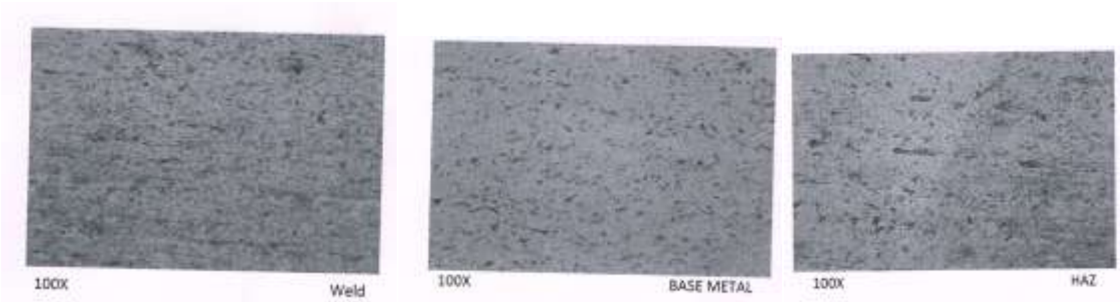
The results obtained are plotted against the rotational speed of 800 Rpm & 1500 Rpm & weld speed of 30 mm/min & 80 mm/min. It is observed that the hardness is min at the weld centre as shown in graph 17 below.



Graph17 Hardness Distribution

11.6. Micro Structure Analysis

The micro structures reveal that there are four zones along the traverse direction, as in the fig 14, near the stirred region, the grains are very fine. This is attributed to dynamic recrystalization; this is normally referred to nugget (zone D). This region adjacent to this zone, the grains are straightly inclined because of force exerted on the plasticized materials by the tool shoulder. This is normally referred to as thermo mechanically affected zone (TMAZ). Region adjacent to TMAZ along the traverse direction away from interface it is reported that the grains are coarse because of extreme heat conditions (Zone C). This is normally referred of a heat affected zone (Zone B). Next adjacent to this zone is base metal (zone A). Schematic fig 14(a), 14(b) and 14(c) as shown all these zones [6]. The microstructure of Parent metal as shown in fig (15)



(a) (b) (c)

Fig 14. Various Zones Microstructures in FS Weld No.7

The solid-state nature of the FSW process, combined with its unusual tool and asymmetric nature, results in a highly characteristic microstructure.

Fig 15. Micro structure of Parent Metal AA 6061

By comparing all microstructures, with parent metal, the formation of very fine grain microstructure, uniformly distributed fine precipitates and higher stir zone hardness are obtained in joint 7 at 800 RPM, 30mm/min feed at 20 mm/min.

11.7 IMPACT TOUGHNESS

Table 8, Gives the results of Charpy V-Notch impact toughness of the Friction Stir Welded Aluminum alloy using cylindrical pin profile including that of the parent material. The comparison of the impact specimens and specimen's after failure as shown in fig 16(a) & 16(b). Impact toughness values for specimens including parent metals as shown in table 8. The comparison of impact toughness of the welds with parent metals as shown in fig 17.

Fig 16 a) impact test specimens b) impact test specimens after failure

Table 8: Impact Toughness of Friction Stir Welding

Metal	PM	Specimen1	Specimen2	Specimen3	Specimen4	Specimen5	Specimen6	Specimen7	Specimen8
Impact toughness in Joules	42	36	35	30	38	30	48	48	38

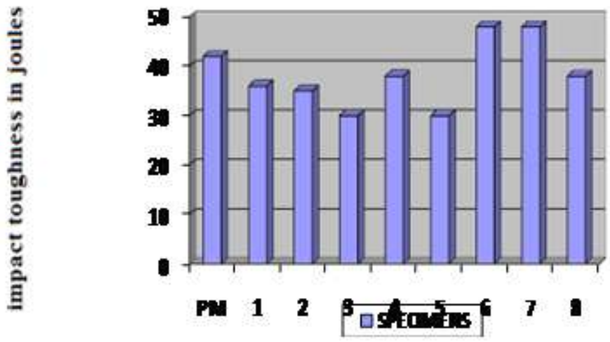


Fig 17: Comparison of Impact Toughness of the Welds

Maximum toughness is reported in weld specimens 6 & 7 were the spindle speed is 800 Rpm; it is about 114% as comparing with parent metal.

XI. CONCLUSION

1) FSW was successfully carried out on a CNC milling machine and the quality of the welded joints was found to be satisfactory.
2) Friction stir welding of AA6061 alloy resulted in a dynamically recrystalized zone, TMAZ and HAZ. A Softened region has clearly occurred in the friction stir welded joints of AA6061 alloy.
3) Mechanical properties of FS welded aluminum alloy AA6061 are influenced by process parameters.
4) Tensile strength of the FS welded joints is directly proportional to the travel speed, spindle speed and plunge speed.
5) The tensile strength, yield strength, percentage elongation, Hardness, notch tensile properties of the welded joints are lower than that of the parent metal.
6) The impact toughness of some of the specimens6 & 7 is more than that of the parent metal about 114%.
7) Bending load for face bend of specimen 4 is about 99.375% of parent metal. Where as bending load for root bend of specimen 5 is about 106% of parent metal.
8) Hardness drop was observed in the weld region. This softening was mostly evident in the HAZ on the advancing side of the welds. This zone corresponds to the failure location in tensile tests.
9) Maximum tensile strength is 134.6 N/mm^2 in Joint No.7 with a spindle speed of 800 Rpm, travel speed 30mm/min & plunge speed is 20 mm/min.
10) Maximum yield strength is 134.6 N/mm^2 in Joint No.7 with a spindle speed of 800 Rpm, travel speed 30mm/min & plunge speed is 20mm/min.
11) Maximum % elongation is about 4.7% in joint 4 with a spindle speed 1500 Rpm ,travel speed is 30mm/min & plunge speed is 10mm/min
12) Tool breakage was avoided
13) Maximum Notch tensile stress is 189.5 N/mm^2 in joint no.1 with a spindle speed of 1500Rpm, travel speed is 80mm/min & plunge speed is 20mm/min.
14) Maximum Notch yield stress is 168.6 N/mm^2 in joint no.1 with a spindle speed of 1500Rpm, travel speed is 80mm/min & plunge speed is 20mm/min.
15) Maximum % elongation is 4.1% in joint no.6 with a spindle speed of 800Rpm, travel speed 80mm/min, plunge speed 10mm/min.

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