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EFFECT OF TOOL PIN PROFILES AND HEAT TREATMENT PROCESS IN THE FRICTION STIR WELDING OF AA 6061 ALUMINIUM ALLOY

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Abstract: Friction stir linear welding (FSLW) uses a non consumable tool to generate frictional heat in the abutting surfaces. The welding parameters such as rotational speed, welding speed, axial force, tool tilt angle, etc., and tool pin profiles play a major role in deciding the joint properties. In this paper, an attempt has been made to study the effect of four different tool pin profiles on mechanical properties of AA 6061 aluminum alloy. Four different profiles have been used to fabricate the butt joints by keeping constant process parameters of tool rotational speed 1200RPM, welding speed 14mm/min and an axial force 7kN. Different heat treatment methods like annealing, normalizing and quenching have been applied on the joints and evaluation of the mechanical properties like tensile strength, percentage of elongation, hardness and microstructure in the friction stirring formation zone are evaluated. From this investigation, it is found that the hexagonal tool profile produces good tensile strength, percent of elongation in annealing and hardness in quenching process.

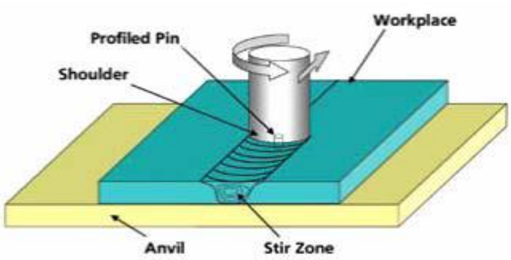
Key words: *Friction stir linear welding; AA 6061Aluminium; Tool profiles; constant process parameters; Heat treatment;*

I. INTRODUCTION

Friction Stir Welding (FSW) is a solid state welding process 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. This method relies on the direct conversion of mechanical energy to thermal energy to form the weld without the application of heat from conventional source. The big difference between FSW and fusion welding (other than the lack of melting) is the ability to manipulate peak temperatures by choice of different welding parameters. Welding parameters, tool geometry, and joint design make use of considerable effect on the material flow pattern and temperature distribution, thereby influencing the micro structural evolution of material. Tensile strength is higher with lower weld speed. This indicates that lower range of weld speed is suitable for achieving maximum tensile strength. Friction stir welding of Al 6061- O condition increases the strength of the weld joint as compared to that of the parent material in O-condition were studied by Ahmed Khalid Hussain et. al[1]. Mechanical properties substantially improve during Post Weld Heat Treatment[2]. R.palanivel, et al have studied the influences of tool pin profiles on the mechanical and metallurgical properties of FSW of dissimilar alloys [3]. FSW offers a quality advantage that leads the welds strength and ductility either identical or better than that of the base metal alloy were proposed by Nayi Li1, et al.[4]. J. Adamowski a, M. Szkodo b have been studied on the rotational speed, welding speed and tool profiles are directly influenced on the tensile strength of FS welded joints [5]. The tensile strength of the FS welded is affected by the tool pin profile. The grain structure within the FSP is fine and equiaxed compared to TMAZ [5].P. V. Gopal Krishna, et. al are investigated in the friction drilling using HSS tool [6]. Cabello Munoz et al. investigated the micro structural and mechanical properties of friction stir welded and gas tungsten arc welded Al-Mg-Sc alloy and reported that the yield strength of friction stir welded and gas tungsten arc welded joints are decreased 20% and 50 % respectively compared to the base metal[7]. Optimization of FSW parameters in different conditions of base material and the microstructures of the as-welded condition are compared with the post weld heat treated microstructures welded in annealed and T6 condition [9]. Elangovan K, Balasubramanian V, et. al are report on the influences of tool pin profile and axial force on the formation of Friction stir processing zone in AA6061 aluminium alloy [10]. Park HS, et.al have studied on microstructures and mechanical properties of AA 6061 alloy. FSW joints usually consist of four different regions. They are; (a) unaffected base metal; (b) heat affected zone (HAZ); (c) thermo mechanically affectd zone (TMAZ); and (d) friction stir processed (FSP) zone[11]. The formation of above regions is influenced by the material flow behavior under the action of rotating non consumable tool. However the material flow behavior is predominantly affected by the FSW tool profiles, tool dimensions, and FSW process parameters [12]. Hence in this paper an attempt was made to study the influence of different tool profiles by keeping the constant process parameters as tool rotational speed, welding speed and axial force and also investigate the post weld heat treatment like annealing, normalizing and quenching are performed on FSW joints of AA 6061 aluminum alloy followed by tensile test and micro hardness measurements. Microstructure testing is also done by Scanning Electron microscope.

II. EXPERIMENTAL DETAILS

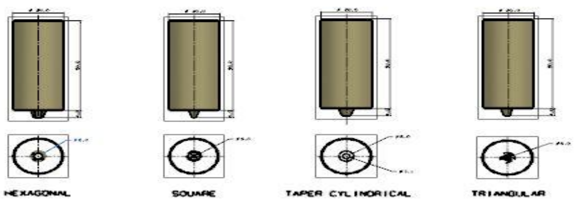
The specimens of the size of 200mmx100mmx5mm were machined from AA6061 aluminum alloy plates. The two plates of AA6061 aluminum alloy were Friction stir welded using four different tool profiles like taper cylindrical ,triangular , square and hexagonal made of high carbon high chromium steel. It comprises of 18mm shoulder dia, 6mm pin diameter and 4mm pin length under the constant process parameters of 1200 rpm, 14mm/min welding speed and 4kN axial force were applied in the butt configuration by using CNC vertical milling machine. The FSW procedure was based on the TWI procedure described in the patent by Thomas et al.(1991). The experimental set up is shown in Fig.1(a-d). The rotation of the tool resulted in stirring and mixing of material around the rotating pin and the linear movement of the tool moved the stirred material from the front to the back of the pin and finished the welding process. The insertion depth of the pin into the work pieces was associated with the pin height (length). The tool shoulder contacting the work piece surface depends on the insertion depth of the pin, which results in generation of welds with inner channel, surface groove, and excessive flash.



(a).Schematic diagram of FSW joint

(b). Photo of the CNC vertical machine

(c). Processing of the joint



(d). FSW tool pin profiles

(e). Fabricated joints

Fig.1. Experimental details

12 FSW butt joints were made by vertical conventional milling machine as shown in fig 1(e). Tensile tests were carried based on ASTM standard. The FSW joint plates were sawed into the dimension 200x20mm. The tensile tests were carried out by universal testing machine to find maximum loading and percentage of elongation. Percentage of elongation is defined as ratio of deformation to original length of 50mm. Hardness tests were carried out on Rockwell hardness machine at a force of 60kgf. The microstructure characterized by light microscopy, SEM in the base materials and in the weld nugget zone. Properties of aluminum alloy AA 6061 are given in the tables (1&2) and uncontrollable process parameters and tool dimensions are shown in the table (3).

Table1: Percentage of chemical composition AA 6061 alloy

Mg	Si	Fe	Cu	Zn	Ti	Mn	Cr	others	Al
0.8 -1.2	0.4-0.8	0.7	0.15-0.4	0.25	0.15	0.15	0.04-0.35	0.05	98.7

Table2. Mechanical and physical properties of AA 6061 alloy

Young's modulus	Yield strength	Ultimate tensile strength	% of elongation	Density	Hardness	Melting range	Thermal conductivity	Sp.heat
(G Pa)	(M Pa)	(M Pa)		Kg/m³	BHN	⁰ C	W/m-k	J/kg-⁰c
68.9	235	283	26.4	68.9	107	582-652	167	0.896

Table 3: Selected welding parameters and tool dimensions

Process parameters	**Values**
Rotational speed (RPM)	1200 rpm
Welding speed (mm/min)	14mm/min
Axial force	7 kN
Tool material	High carbon High Chromium with 60-62 HRc
Tool dimensions	Shoulder dia 18mm, pin dia 6mm and pin length 5.5mm.
Tool pin profiles	Taper cylindrical
	Triangular
	Square
	Hexagonal

III. INFLUENTIAL FACTORS OF WELD QUALITY

Factors affecting the weld quality include: tool material, tool configuration, rotation speed, welding speed, Axial force of tool on work pieces and the kind of work materials.

3.1. Tool material and configuration:

The tool of FSW is composed of two parts: a tool body and a probe. The tool technology is the heart of friction stir welding process. The tool shape determines the heating, plastic flow and forging pattern of the plastic weld metal. The tool shape determines the weld size, welding speed and tool strength. The tool material determines the rate of friction heating, tool strength and working temperature, the latter ultimately determines which materials can be friction stir welded. Each of these tool technology aspects will be studied to try and establish a combination that will produce sound welds and the best tolerance to process parameters at the required working temperature. In some references, the shape of probe was a slandered British system screw, but in many references it was special [13-15].

The radius of the tool body's shoulder is almost three times of that of the probe. If the radius of the shoulder is too small, the friction heat is not enough to plasticize the materials beneath the shoulder. On the other hand, the friction heat may too large to make the temperature of the materials beneath the shoulder reach or excess the melt point, consequently reduce the weld strength and raise the irregularity of the weld surface.

3.2. Rotating speed of the tool:

According to the thermal analysis of FSW, the average frictional heat input (q) per unit area and per unit time is given by Frigard [16]

$$q = \int_0^R \omega 2\pi\mu P r^2 \mathrm{d}r \qquad (1)$$

where, q is the net power intensity(in Watts/m^2), ω the angular velocity (in rad/s), μ the coefficient of friction, R the radius of the tool's shoulder (in meters), P the pressure across the interface (here assume constant). By substituting $\omega = \frac{1}{30}\pi n$ into equal, we get:

$$q = \int_0^R \frac{2}{30}\,\pi^2 \mu P n r^2 \mathrm{dr} \quad = \frac{1}{45}\,\pi^2 \mu P n (R^3 - r^3) \qquad (2)$$

where, n is the rotating speed of the tool (in rad/min).

From eqn 2, it is obvious that the rotating speed is one of the main factors affecting the frictional heat. If the rotating speed is too low, the frictional heat is not enough to induce plasticized flow, the metal in the weld cannot diffuse and recrystallize, and there are holes in the weld. Along with an increase of the rotating speed, the frictional heat increases, the plasticized layer increase from top to the underside, the holes in the weld become smaller. When the rotating speed reaches a certain number, the holes in the weld becomes tightness. But if the rotating speed is too high, the temperature of materials beneath the tool's shoulder and around the probe will excess the melt point, and the weld is no long a solid-state joint.

3.3 Welding velocity:

From equation 2, we can understand that the net power intensity is constant only when the structure of the weld tool and the rotating speed are confirmed. So, when the welding velocity is too small, the frictional heat makes the temperature in the weld too high (may reach or excess the melt point), the materials will be porous, inducing fluidification crack, and the weld surface will be irregular. On the other hand, when the welding velocity is too large, the frictional heat is not enough to plasticize the materials beneath the tool' s shoulder and around the probe, the work pieces can' t be welded[17-19].

3.4 Axial force of tool on the work pieces:

The press force of tool on work pieces affects the contact state, whereas the contact state affects the forming of weld. When the press force is not enough, the surface metal of the weld "floats" upward and overflows the surface of work pieces, resulting in holes at the bottom of the welding. When the press force is too large, the frictional force between the tool's shoulder and the work pieces’s surface increases, the tool's shoulder will cohere with the materials of work pieces and there will be flashes and burs on the weld face.

IV. HEAT TREATMENT METHODS

4.1.Annealing Process:

In this method, The butt weld joints are heated in the muffle furnace up to 580^0 C and holding the same temperature for a period of 2-3 hrs in order to get the homogeneous structure and then cooled in the furnace to attain the room temperature .

4.2.Normalizing Process:

In this method, The butt weld joints are heated in the muffle furnace up to 580^0 C and holding the same temperature for a period of 2-3 hrs in order to get the homogeneous structure and then cooled in the air to attain the room temperature .

4.3. Hardening Process:

In this method, The butt weld joints are heated in the muffle furnace up to 580^0 C and holding the same temperature for a period of 2-3 hrs in order to get the homogeneous structure and then cooled in the water to attain the room temperature .

V. MECHANICAL TESTS

From each of the heat treatment processes, the specimens are taken and tested for mechanical properties like tensile test, Vickers hardness test and microstructure.

5.1. Tensile test:

American Society for Testing of Materials (ASTM) guidelines are followed for preparing the test specimens. Tensile test has been carried out in 20 kN, Universal Testing Machine as shown in fig 2. The specimen finally fails after necking which occurs in the friction stirred region (FSP).

Fig 2: Universal Testing machine

5.2. Hardness test:

Rockwell hardness testing machine has been employed for measuring the hardness across the joint and perpendicular to the joint with 60 kg load. The hardness have been evaluated for Taper cylindrical, triangular , square and hexagonal tool pin as shown in fig(3).

Fig 3: Rockwell Hardness Tester

5.3. Microstructure:

Samples for microstructure observations were cut from both the FSW plates. The cut samples, 0.5 in. square in cross-section, were mounted in Bakelite and then dry ground on progressively finer grades of silicon carbide impregnated emery paper. Fine polishing to a perfect mirror-like finish of the surface was achieved using disc polishing kerosene solution as the lubricant.

The polished aluminum alloy sample of Plates was etched using Keller's reagent (a solution mixture of 1 drop hydrofluoric acid, 25ml concentrated nitric acid, 25ml hydrochloric acid and 25ml methanol). The etched surface of each sample containing the weld region was observed in an optical microscope and photographed using a bright field illumination (AVER CAP software) technique as shown in fig(4).

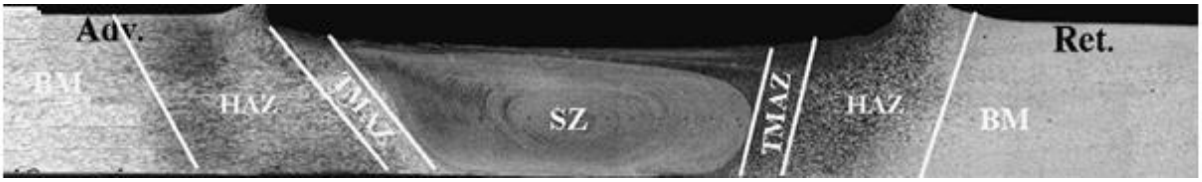


Fig.4 Typical macrograph showing various regions of the FS welded plates of AA 6061 alloy on AS, RS.

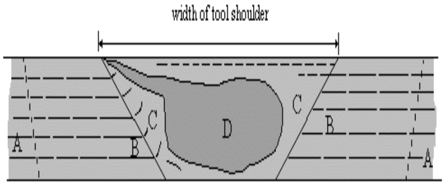


Fig 5. Schematic illustration diagram of various friction stirred zones of AA 6061 alloy

A: Unaffected material **B**: Heat Affected zone (HAZ) **C**: Thermo-Mechanically Affected Zone (TMAZ) **D**: Weld Nugget (Part of thermo-mechanically affected zone)(SZ)

Unaffected material or parent metal (A): This is material remote from the weld, which has not been deformed, and which although it may have experienced a thermal cycle from the weld is not affected by the heat in terms of microstructure or mechanical properties.

Heat affected zone (HAZ) (B): This is region which will lie closer to the weld centre; the material has experienced a thermal cycle which has modified the microstructure and/or the mechanical properties. However, there is no plastic deformation occurring in this area, which is referred to as the heat affected zone or thermal affected zone. Thermo-mechanically affected zone (TMAZ) (C): In this region, the material has been plastically deformed by the friction stir welding tool, and the heat from the process will also have exerted some influence on the material. However, subsequent work on other materials has shown that aluminum behaves in a different manner to most other materials, in that it can be extensively deformed at high temperature without recrystallisation. In other materials, the distinct recrystallised region (the nugget) is absent, and the whole of the TMAZ appears to be recrystallised. This is certainly true of materials which have no thermally induced phase transformation which will in itself induce recrystallisation without strain. Weld Nugget or Stir Zone (SZ): The recrystallised area in the TMAZ in aluminum alloys has traditionally been called the nugget. It has been suggested that the area immediately below the tool shoulder (which is clearly part of the TMAZ) should be given a separate category, as the grain structure is often different here. The microstructure here is determined by rubbing by the rear face of the shoulder, and the material may have cooled below its maximum.

VI. RESULTS AND DISCUSSIONS:

Successfully joints were obtained by FSW processes for the all the process parameters used in the investigation. Typical example of FS welds is shown in Fig. (3), in which the upper and bottom surfaces of the weld are seen at the process condition of; 1200 rpm rotational speed, 14mm/min of welding speed, 7kN axial force. Visual and macroscopic inspection of the weld surfaces has showed no observed superficial macroscopic defects. Usually, the FSW process leaves a pin hole at the weld end, as can be seen in Fig. (3.a), and the design of the weld is done in such a way that the part with the hole is cut and not used for further processes. The mechanical properties of AA 6061 alloy FSW joints of such ultimate tensile strength, percentage of elongation and hardness are evaluated. At each condition three specimens are tested and average of the results of three specimens is presented in the table 4.

6.1. Effect of Tool pin profiles on Ultimate tensile strength for different heat treatment process

Table 4: Mechanical properties obtained for Taper Cylindrical tool pin profile

	Taper cylindrical		**Triangular**		**Square**		**Hexagonal**	
Heat treatment Process	**UTS (N/mm^2)**	**% Elongation**	**UTS (N/mm^2)**	**% Elongation**	**UTS (N/mm^2)**	**% Elongation**	**UTS (N/mm^2)**	**% Elongation**
Annealing	145	28.34	170	26.56	198	24.78	210	20.9
Normalizing	130	18.8	145	20.3	187	22.5	195	24.3
Quenching (water)	120	9.6	125	9.5	124	8.9	130	10.3

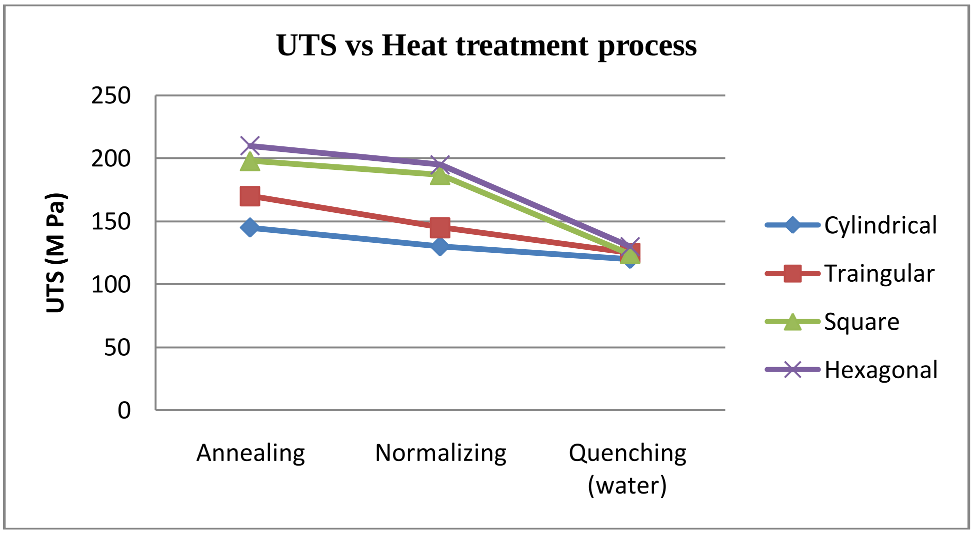


Fig.6: Effect of tool profile on Ultimate tensile strength for different heat treatment process

Fig 6. Shows that the variation of UTS for various profiles with respect to different heat treatment processes of annealing, normalizing and quenching. It can be inferred that tool pin profile has influenced on the ultimate tensile strength and percentage of elongation. Of the four profiles, it is observed that the maximum ultimate tensile strength occurred for hexagonal tool pin profile for annealed condition compared to the other profiles due to the grain refinement of the FSW joint. Similarly square pin profile also showing almost matching the properties of the hexagonal tool profile. The taper cylindrical pin profile tool exhibited inferior tensile properties compared to the counters. The percentage of elongation is maximum for the taper cylindrical pin profile for annealing condition. Similarly the triangular pin profile showed the matching properties of taper cylindrical pin profile. It is found that FSW softens the joints of the present alloy because the strengthening precipitates dissolved and grew during the weld thermal cycle which results degradation of the mechanical properties.

6.2: Effect of Tool pin profiles on microstructure for heat treatment process:

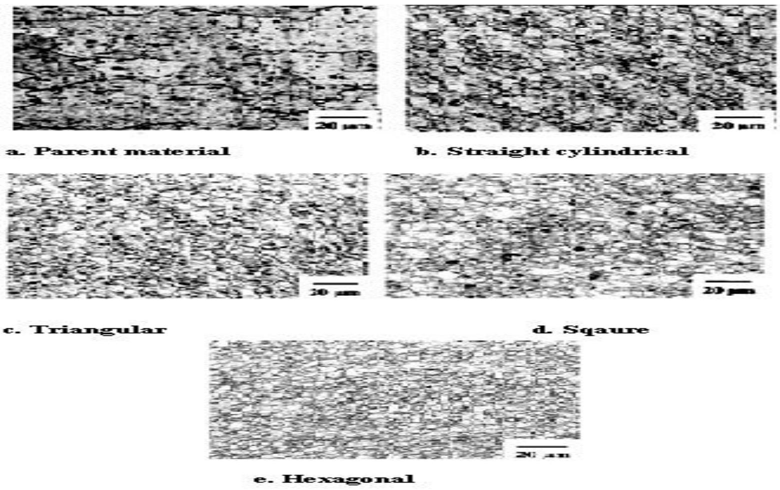


Fig 7(a-e): Microstructures showing different tool profiles at weld zone. (400x). Dark particles of Mg_2Si are embedded in a matrix of Aluminum rich solid solution etched by Keller's reagent

From Fig 7(a), it is shown that the base metal microstructure basically consists of elongated grains and the strengthening particles are uniformly distributed throughout the matrix. Few considerable variations in grain size and distribution of strengthening particles Mg_2Si are clearly visible in micrographs. From fig 7(b), The elongated grains are changed into equi-axed grains from the base metal microstructure in the Stirred zone (SZ) friction stirred process region, irrespective of tool pin profiles used to fabricate the joints. Due to the absence of pulsating action and insufficient working of the plasticized material, the grain size is comparatively higher in the SZ than the base metal produced by taper cylindrical pin. From fig 7(c-e), Pins with flat faces like triangular, square and hexagonal produced the pulsating stirring action and caused reduction in grain size and homogenous redistribution of second phase particles throughout the matrix at Nugget zone. It is observed that the more redistribution of the second phase particles in the matrix and reduction grain size occurred in hexagonal tool pin profile with annealing process resulting in better tensile strength.

6.3. Effect of Tool pin profiles on Hardness for different heat treatment process

Table 5(a): Hardness varying with Taper Cylindrical tool pin profile

Distance from weld center, mm	**Vickers's Hardness, (RV)**		
	Annealing	Normalizing	Quenching (water)
-40(AS)	78	82	84
-30(AS)	75	80	85
-20(AS)	74	79	79
-10(AS)	70	78	78
0(NZ)	67	73	77
10(RS)	70	79	73
20(RS)	74	80	73
30(RS)	77	81	84
40(RS)	79	82	85

Table 5(b): Hardness varying with Triangular tool pin profile

Distance from weld center, mm	**Rock well Hardness, (HBN)**		
	Annealing	Normalizing	Quenching (water)
-40(AS)	80	82	94
-30(AS)	82	85	93
-20(AS)	81	70	90
-10(AS)	78	68	88
0(NZ)	74	65	84
10(RS)	79	67	89
20(RS)	80	73	91
30(RS)	81	84	92
40(RS)	80	85	94

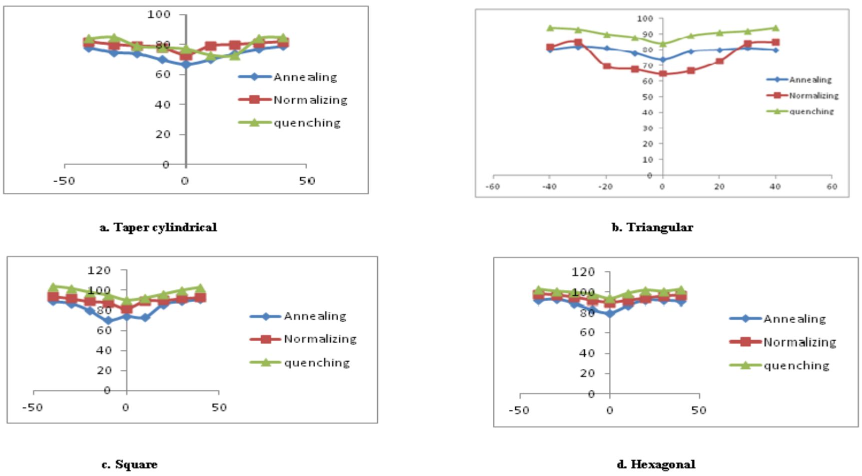
Table 5(c):: Hardness varying with Square tool pin profile

Distance from weld center, mm	**Rock well Hardness, (HBN)**		
	Annealing	Normalizing	Quenching (water)
-40(AS)	89	94	104
-30(AS)	87	92	102
-20(AS)	80	89	98
-10(AS)	70	88	95
0(NZ)	74	82	90
10(RS)	73	89.5	92
20(RS)	86	90	96
30(RS)	89	92	100
40(RS)	91	93	103

Table 5(d): Hardness varying with Hexagonal tool pin profile

Distance from weld center, mm	**Rock well Hardness, (HBN)**		
	Annealing	Normalizing	Quenching (water)
-40(AS)	92	98	103
-30(AS)	93	97	101
-20(AS)	89	95	100
-10(AS)	83	92	98
0(NZ)	80	90	94
10(RS)	87	92	99
20(RS)	92	94	102
30(RS)	92	96	101
40(RS)	91	97	103

AS: Advanced side RS: Retreating side NS : Nugget Zone



a. Taper cylindrical b. Triangular c. Square d. Hexagonal

Fig 8(a-d): The Hardness distribution and comparison at various zones of different profiles with different heat treatment Process.

From fig 8(a-d), it is shown that the hardness values are decreasing from advanced side to Nugget zone and further it is increasing till retreating side for different heat treatments like annealing, normalizing and quenching varies with respect to different tool pin profiles. It is observed that the maximum hardness occurs at quenching process with hexagonal tool profile which gave the fine grain structure and more Mg_2Si particles distributed in the aluminum alloy.

VII. CONCLUSIONS:

The joints fabricated using different tool pin profiles like Taper cylindrical, triangular, square and hexagonal tool with a rotational speed of 1200RPM, weld speed of 14mm/min and axial force of 7kN. The following important conclusions were made for the present investigation.

1. Of the four tool profiles, The maximum tensile strength and % of elongation of 210M Pa and 20.9 respectively was observed on Hexagonal pin profile tool with annealing process.
2. The tensile strength and percent of elongation of the hexagonal tool profile with annealing process has reached about 90% and 80% respectively of the parent metal.
3. The hardness of FSP zone fabricated using hexagonal profile tool with quenching is higher compared to other type of tool profiles.
4. The microstructure of FSP region contained fine equiaxed grains and very fine uniformly distributed strengthening precipitates(Mg_2Si) throughout the matrix of hexagonal pin profile. This may be the reason for superior tensile properties of these joints.

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