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FRICTION STIR WELDING OF ALUMINIUM ALLOYS AA2014 AND AA6082 AND FINITE ELEMENT ANALYSIS

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Abstract: The present work investigates the friction stir welding of aluminium alloys AA6082 and AA2014 and its simulation in Ansys software. In this test initially 100×50×8mm dimensioned plates of AA6082 and AA2014 are Friction Stir Welded with Tools rotated on the edge of two plates attached together on a milling machine. Here two different types of Tool Tips are used for experimentation The Stir welded part is wire cut machined to ASTM E8 standard i.e. Dog Bone Shape. Further Tensile Test, Fatigue test, Microstructural characterisation and Hardness measurements were carried out to understand the welded materials. A comparison is made between the obtained practical test readings and the same simulation test performed on the Ansys Software19.2 version. On the software platform Structural Analysis was carried out. The maximum peak stress obtained was 155 MPa and Maximum Microhardness obtained as 90 VH. After all experimentation it was found that the weld joint obtained was strong enough and properties tested were all nearby the parental material. The Weld joint is strong enough in application of Truss, automobile body parts, Construction of roof, internal parts of ship buildings aeroplanes and aerospace industries etc.

Key Words: Friction stir welding, Tool, Tensile Test, Microhardness, Finite Elemental Analysis.

1. INTRODUCTION

FRICTION STIR WELDING (FSW) was first stepped on earth in 1991 at The Welding Institute of the UK as a non-consumable solid-state metal joining process initially for aluminium alloys. Friction stir welding employees non- consumable rotating tool running forward through the joint generating heat much below the melting temperature of the base metals and the tool with designed pin and shoulder inserted into the edges of two plates to be joined and traversed along the joint line for the tool and work piece as shown in Fig.1.Advancing and retreating side of tool rotation and travel directions plays a important role in joining process. By rotating the tool and moving it along the weld line to be joined, the softened and recrystallized material is stirred together with the help of friction forming a weld joint without melting the material. These welding process without the use of filler materials and also without distortion of the joining material. Initially developed for non-ferrous materials such as aluminium and also by further modification of the tool material process has been applied to harder material like steel and titanium alloy etc.

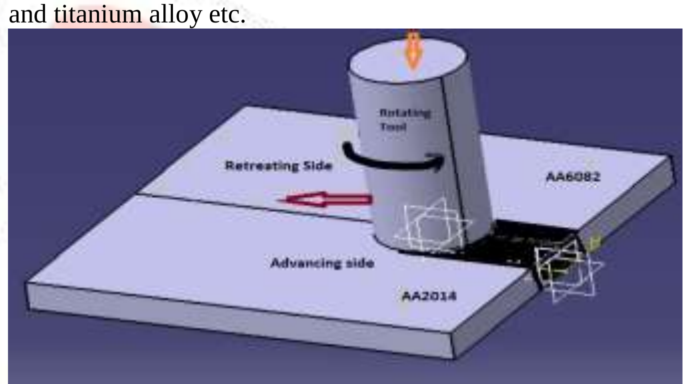

Fig.1 Friction Stir Welding Process

1.1: Literature review:

Many experiments have been conducted regarding FSW and results are obtained telling the benefits and advantages of FSW over other conventional welding. Dr.Ch..S.Naga Prasad et al[4] tells the FSW process relating butt joining of same Aluminium alloy to Aluminium Alloy (AA6351 with AA6351) and dissimilar Aluminium alloy of AA6351 with AA5083 and the Tensile test and Hardness test were also investigated that the maximum Yield stress value obtained is 51.2MPa for different Aluminium Alloys. Naveen Kumar et al [6] tells that from his experimentation Tool Running with speed more than 700rpm and below 1500rpm provides better results for Aluminium Alloy's FSW. In this Paper, FSW of AA2014 and AA6082 is conducted at two RPM 1120 and 900rpm and also with Two different Tools. Here Tensile and Microhardness tests were carried out to study the analysis.

2. METHODOLOGY

Materials:

The material used here are AA6082 and AA2014, both are Friction Stir Welded, and a joint is formed. The AA6082 contains 95% of Pure Aluminium and Silicon (Si), Magnesium (Mg) and Manganese (Mn) in remaining percent. Similarly, AA2014 contains 95% of pure Aluminium and Copper (Cu) nearly 5%.

Tools used in FSW of AA2014 and AA6082:

1. Tool with Hexagonal pin with Hexagonal rings on it.

2. Tool with Circular pin with Circular rings on it.

The Tool used here is made up of H13 Tool Steel and made to above design shown in the fig: 2 on a CNC machine and the tool used here is capable of bearing high temperature nearly 1600℃. So best one to be used while friction stir welding of aluminium alloys where maximum temperature may rise nearly to 500℃ to 600℃.

Fig.2 Showing Tools used 1) Tool with Hexagonal Pin with Hexagonal ring 2) Tool with Circular Pin with Circular rings.

Out of 16 pairs of weld specimen 8 pairs of are done with Hexagonal pin with hexagonal rings on pin as shown in the fig.2 and similarly next 8 weld specimen pair are welded with Circular tool pin with Circular rings on it .Temperature are recorded while conducting Friction stir welding using these Tools at equal distanced location that is 14cm distance from each reading. The dimension of plate used here are 100mmX50mm and 8mm thick both AA6082 and AA2014 individually. Before FSW the rectangular plates which is to be welded are trimmed to exact dimensions into a rectangular plate with smooth edge.

Fig.3 Friction Stir welded Specimen

After conducting of Friction Stir welding using the both Tools the final obtained Weld is shown in the fig.3 While FSW temperature were noted at both Tools used at 7 locations particularly and the reading was done with help of an industrial temperature gun and the readings are shown in table.1

While performing the FSW the workpiece is clamped to the worktable of Vertical milling machine. The tool running over it goes straight along the joint of the two pieces. The tools rotation and the plunge depth of both Tools employed should made unchanged throughout the FSW.

The weld joint produced here was very precise and strong strength and was nearly equal to the properties of the parental material.

Tool Rpm; Weld Speed mm/min; Tilt Angle	T1 ℃	T2 ℃	T3 ℃	T4 ℃	T5 ℃	T6 ℃	T7 ℃
900;16;1.5	120	140	142	146	145	142	141
900;25;1.5	134	155	170	171	165	163	160
1120;16;1.5	130	150	154	157	153	152	152
1120;25;1.5	145	160	163	167	165	161	160
900;16;2.0	132	149	152	160	156	153	152
900;25;2.0	139	145	154	162	158	155	155
1120;16;2.0	142	159	170	171	165	160	158
1120;25;2.0	155	158	166	175	168	165	163
900;16;2.0	145	180	190	194	184	174	170
900;25;2.0	149	185	192	202	199	194	188
1120;16;2.0	153	175	187	193	181	173	170
1120;25;2.0	174	192	202	210	199	197	190
900;16;1.5	151	164	173	189	178	170	160
900;25;1.5	159	185	197	203	196	188	177
1120;16;1.5	174	196	208	211	202	199	195
1120;25;1.5	180	205	206	204	203	202	200

Table.1 Shows Temperature recorded while Friction stir welding. (First 8 readings are of Hexagonal Pin with Hexagonal rings and next 8 are of Circular pin with Circular rings.)

After the FSW of AA6082 and AA2014 was formed the joint was made to E8-Tensile specimen on an EDM wire cut machine as shown in fig.4.

Fig.4 Specimen Prepared on EDM wire cut

After the E8-tensile specimen is prepared two tests are carried out in this paper:

1. Tensile test
2. Micro Hardness test.

1.Tensile Test:

A tensile test can also be called as tension_test is most essential and regular types for mechanical testing of material. In tensile test a pulling force is applied to a material and finds out the specimen's response to the stress created in it. By conducting tensile tests one can know how strong a material is to load applied to it and how much it can elongate with the load applied. Tensile tests are mainly conducted on UTM-Universal Testing Machine as shown in the figure 5. The test results are plotted on a graph where this data results in a stress/strain curve which tells how the Specimen reacted to the forces applied to it. In tensile test the point of break or failure is very crucial point to be noted, other important properties along with break or failure point is the elasticity, peak stress, peak load, yield strain, yield load, upper yield stress, lower yield stress etc. The Tensile Specimen has 40mm gauge length and 42mm^2 of area along the gauge length.

Fig.5 Mounted Tensile test specimen on Digital Hydraulic UTM.

The above figure.5 shows clearly the experimentation of tensile test on an ITE BISS The NANO PLUG n PLAY that is a Nano Servo Hydraulic UTM. The specification and standard features of the UTM machine is detailed shown below:

-5/10/15/25 KN Force Rating.
-Plus, or Minus 25mm actuator stroke.
-0-100 Hz cycling frequency.
-Frame stiffness 600 KN/mm
-Fully Digitalized.
-weight=160kg
-Column Clearance=400mm
-Total Frame height=1500mm
-Total Dimension=600 X 600mm

The reading obtained while performing the Tensile test are shown below in table 2:

Tool rpm; Weld Speed mm/min; Tilt angle	Peak stress MPa	UYS MPa	LYS MPa	%elongation at break using strain
900;16;1.5	136.25	103.851	99.9	15.125
900;25;1.5	119.92	59.191	46	13
1120;16;1.5	111.25	51.9	49.8	10
1120;25;1.5	109.1	47.3	44.2	7.5
900;16;2.0	153.3	62.06	59.2	5
900;25;2.0	96.5	46.4	43.96	5
1120;16;2.0	155.8	98.4	95.17	13.3
1120;25;2.0	114.7	43.09	41.9	16.6
900;16;2.0	131.4	131.4	127.2	17
900;25;2.0	56.47	31.97	30.4	4.4
1120;16;2.0	70.7	36	34.2	5.7
1120;25;2.0	113.04	45.8	43.3	10
900;16;1.5	145.94	117.9	113.7	15
900;25;1.5	54.237	51.125	48.9	4
1120;16;1.5	100.8	38.7	37.199	7
1120;25;1.5	104.425	40.3	37.3	14

Table.2 Tensile Test data Recorded on UTM

Fig.6 The above fig shows the tensile test specimen after UTM test

2. Microhardness Testing:

Metallographic Microhardness examination was carried on sixteen flat tensile samples of thickness 8mm and overall length of 100mm and gauge length of 40mm are used for metallographic examination to study the Microhardness of the specimen. The welded sample is trimmed or machined based on the required dimension for conducting the Metallographic test to study microhardness on an EDM wire cut machine in such a way that better microhardness can be revealed. The polished samples were etched with Keller's Etching agent used for Aluminium for 15 minutes to reveal microstructure and also for Microhardness study. These different zone in specimen study were primarily characterized into (a)Weld zone or Nugget Zone and b) TMAZ c) HAZ zone and finally the parent material Zone as shown in fig 8. Preparation of samples for Microstructural and Microhardness study involves the following steps:

1. Grinding
2. Polishing (coarse and fine)
3. Etching
4. Testing

Microhardness Testing is a technique of defining a material's hardness or resistance to penetration when test samples or specimen are very small, thin and when small regions in a composite sample or plating are to be investigated or measured. Microhardness test can provide precise and detailed data about surface features of materials that have a fine microstructure, multi-phase, non-homogeneous and also prone to cracking. By microhardness test one can measure precisely surface to core hardness on carburized and case-hardened parts, as well as surface conditions such as grinding burns, carburization or decarburization.

Microhardness test specimen testing is carried on the specimen on which the Microstructure study is carried out. Specimen prepared is shown in fig.7.

The testing machine (Digital Microstructure tester) is primarily used for analysis of welds and surface coating, this equipment is versatile for micro-hardness measurements on diverse metallic and non-metallic material. Features like fully automated load-hold-release mechanism and multi-line/random measurements are accompanied with data accuracy as per ASTM standards.

1. Measuring Modes: HV & HK
2. Load range: 5gf-1000gf
3. Magnification: 100X & 400X
4.Test-Table size: 100mm X 100mm (max stroke of 25mm along X &Y axis)
5. Dwell time: Variable form 5-99 sec (with 1sec internals).

Fig.7 Specimen Prepared to perform Microhardness Test

Fig.8 Magnified Microstructural View of Microhardness Specimen

3. Tensile Test simulation in Ansys Software 19.2:

The ANSYS Software have many finite element analysis abilities from simple, linear, static analysis to a complex analysis like nonlinear, transient dynamic analysis. ANSYS finite element analysis software allows to achieve the following tasks such as apply functional loads or other design performance conditions, Study physical responses like stress levels, temperature distributions, electromagnetic fields etc., We can do prototype testing in environments in Ansys where cost reduction comes into picture. Ansys is very user-friendly software. Here initially the tensile specimen is crafted in Catia 5.0 software an then converted to IGS format to open it in Ansys software19.2 for simulation.

Here the analysis was carried out by applying Yield load on the specimen and the Von-Mesis equivalent stress was found. The equivalent stress obtained was nearly to the peak stress obtained during the Tensile test on UTM. The figure from 9 to 14 shows the Ansys work carried and the result was compared with the result obtained from UTM tensile test.

3.1 Hexagonal Tool pin:

3.1.1 Maximum Stress:

1.Eqivalent(von-mesis) stress at 1120rpm,16 mm/min weld speed and 2.0 tilt angle:

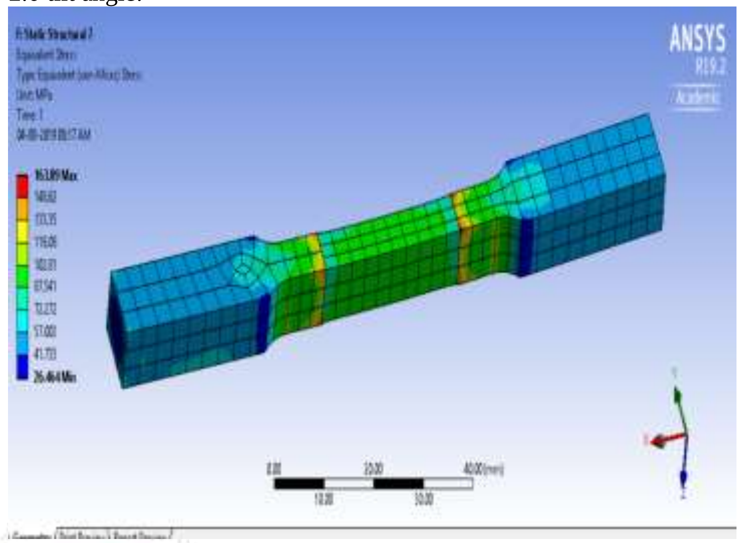

Fig.9 Finite Elemental Analysis at 1120rpm ,16mm/min

2. Maximum Peak stress at 1120rpm,16 mm/min weld speed and 2.0 tilt angle:

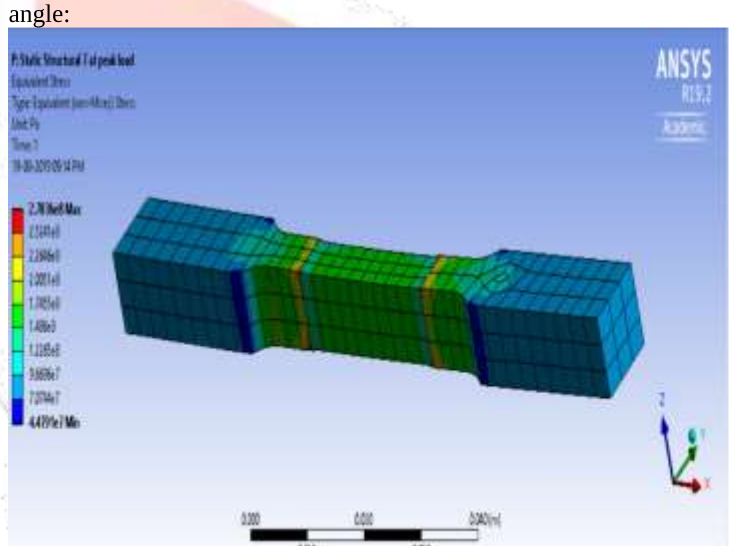

Fig.10 Finite Elemental Analysis at 1120rpm ,16mm/min.

3.1.2 Minimum Stress:

At 900rpm, 25mm/min weld speed and 2.0 tilt angle:

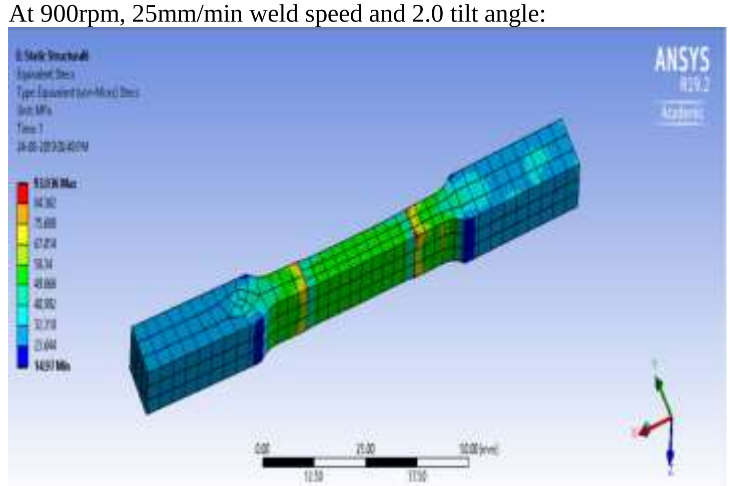

Fig.11 Finite Elemental Analysis at 900rpm, 25mm/min.

3.2 Circular Tool Pin:

3.2.1 Maximum Stress

1. Equivalent (von-mesis) stress at 900rpm,16 mm/min weld speed and 1.5 tilt angle:

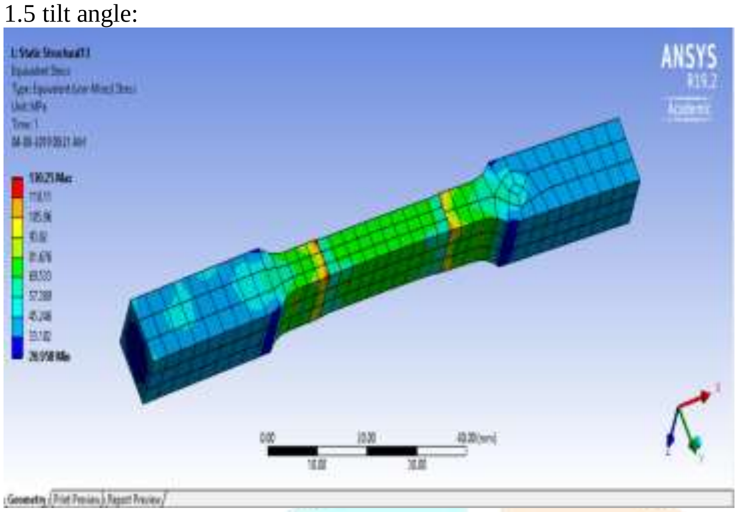

Fig.12 Finite Elemental Analysis at 900rpm, 16mm/min.

2. Maximum Peak stress at 900rpm,16 mm/min weld speed and 1.5 tilt angle:

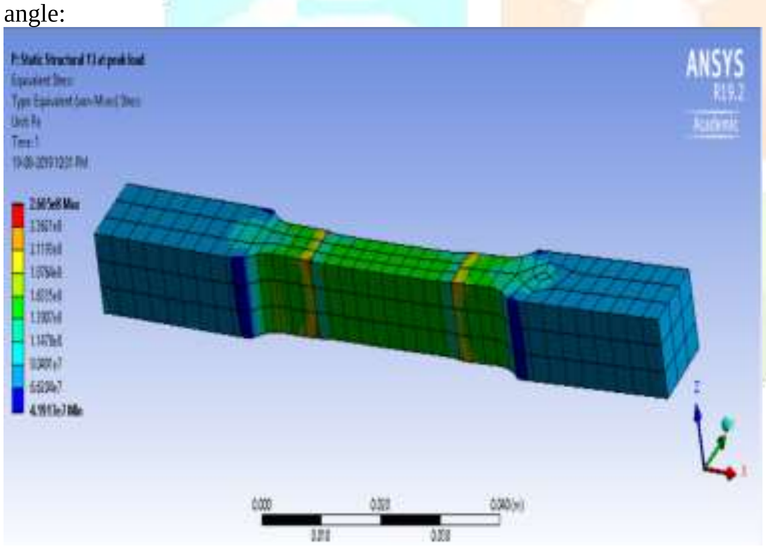

Fig.13 Finite Elemental Analysis at 900rpm, 16mm/min.

3.2.2 Minimum Stress:

Equivalent (von-mesis) stress at 900rpm,25 mm/min weld speed and 1.5 tilt angle:

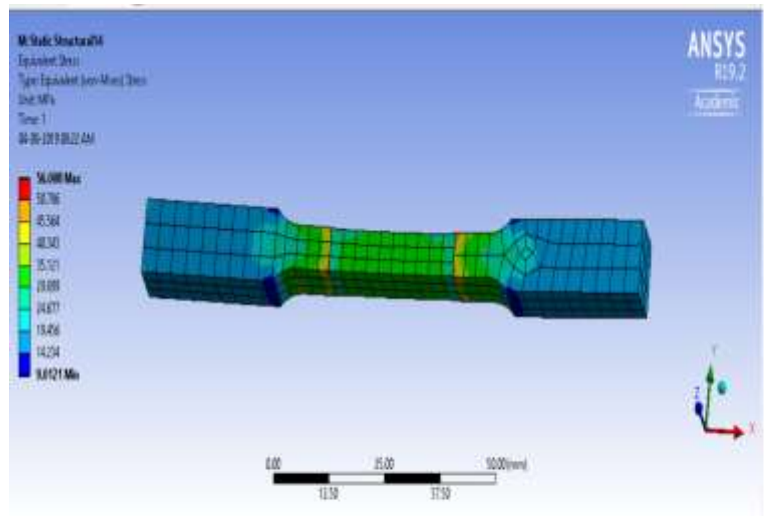

Fig.14 Finite Elemental Analysis at 900rpm, 16mm/min.

4. RESULTS AND DISCUSSION:

The main objective study was to develop and validate 3-D thermal models of friction stir welding for butt joints for experimental cases and investigation of varying process parameters and analysis such as Structural Analysis both practically and simulation in Ansys. In order to better understand the process an initial detailed study into butt welds was performed. The developed models would be validated against the published experimental results. Such process parameter studies covering parametric conditions not found in the literature would provide insights for further testing and analysis needed for development of process specifications for FSW butt welds.

4.1Tensile Test:

After conducting Tensile test for 16 Friction Stir Welded specimen the Maximum obtained Stress out of all and similarly the Minimum stress out of all and also the better tool for conducting the FSW is all discussed below.

Tool	Tool Rpm; Weld Speed mm/min; Tilt Angle	Maximum temperature°C
Hexagonal Tool Pin	1120;25;2.0	175
Circular Tool Pin	1120;16;1.5	211

Table.3 Maximum Temperature recorded for both Tools.

Tool	Tool Rpm; Weld Speed mm/min; Tilt Angle	Maximum stress-MPa
Hexagonal Tool Pin	1120; 16; 2.0	155.8

Circular Tool Pin	900; 16; 1.5	145.94

Table.4 Maximum stress recorded for both Tools.

Tool	Tool Rpm; Weld Speed mm/min; Tilt Angle	Minimum stress-MPa
Hexagonal Tool Pin	900; 25; 2.0	96.5
Circular Tool Pin	900; 25; 1.5	54.237

Table.5 Minimum stress recorded for both Tools.

4.1.1 Finite Element Analysis of Tensile Test:

Tool	Tool Rpm; Weld Speed mm/min; Tilt Angle	[Maximum stress-MPa (UTM results)] X	Force Applied N (value taken from Tensile Test data)	[FEM Stress Results] Y	% Difference of X-Y
Hexagonal Tool Pin	1120; 16; 2.0	155.8	4500=Yield Load	163.89	5%
Circular Tool Pin	900; 16; 1.5	145.94	3500=Yield Load	130.25	10.75%

Table.6 Comparing results of Maximum Stress for both the Tools.

Tool	Tool Rpm; Weld Speed mm/min; Tilt Angle	[Minimum stress-MPa (UTM results)] X	Applied Force N (value taken from Tensile Test data)	[FEM Stress Results] Y	% Difference of X-Y
Hexagonal Tool Pin	900; 25; 2.0	96.5	2500=Yield Load	93.5	3%
Circular Tool Pin	900; 25; 1.5	54.237	1505=Yield Load	56.08	3%

Table.7 Comparing results of Minimum Stress for both the Tools.

From Table.4 we can clearly notice that Highest peak stress is 155.8 MPa for Hexagonal Tool Pin at 1120 rpm, 16mm/min weld speed,2.0 tilt angle on UTM and Highest peak stress obtained in Ansys is 163.89 MPa. For Circular Tool at 900 rpm, 16mm/min weld speed and 1.5 tilt angle the maximum bearable stress obtained is 145.94MPa. Similarly, From Table.5 we can clearly notice that Minimum stress is 96 MPa for Hexagonal Tool Pin at 900 rpm, 25mm/min weld speed,2.0 tilt angle on UTM and Minimum stress for Circular tool pin is 54.237 MPa. From the above result we can clearly say that Hexagonal Tool Pin has better FSW than Circular Tool Pin because by using Hexagonal tool pin better mixing of material takes place while performing FSW.

From fig.6, it shows the necking point or the break point performed on UTM. As we observe the figure the breaking or necking is at mainly at the HZA zone or zone near to the base metal. From this we can clearly say the weld quality and strength.

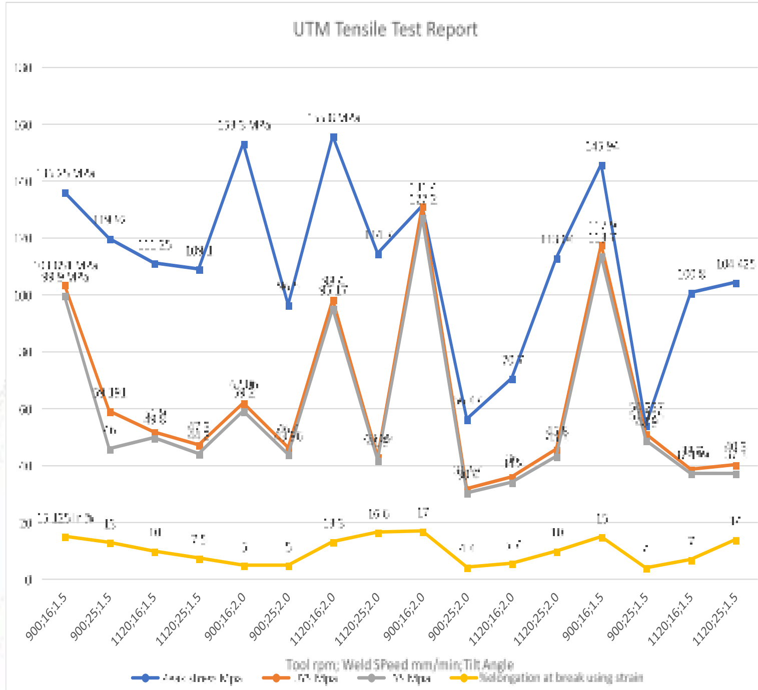

Table.15

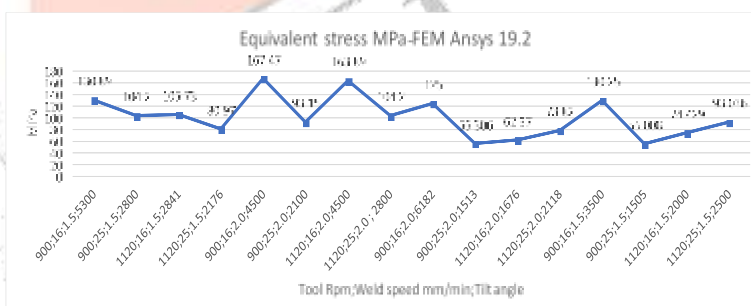

Table .16

(Table.15 shows the Digital Hydraulic UTM Tensile Test Report and Table.16 shows the Finite Element Analysis Report carried on Ansys Software 19.2.)

4.1.2: %Elongation at break using strain:

From Tensile Test which was carried on a Digital Hydraulic UTM the %elongation at break using strain was found from the result data. From this result data the Maximum and Minimum %elongation for both the tool is shown below:

Tool	Maximum% elongation (%El)	Minimum %elongation (%El)	L_f at Maximum %El	L_f at Minimum %El
Hexagonal Tool	16.6	5	47.67 mm	42.105mm
Circular Tool	17	4	48.192mm	41.6 mm

Table.8 Showing the %elongation at break using strain

In this paper as already mentioned the Initial gauge length (L_o) is 40mm and from that %El = [(L_f -L_o)/ L_f] x 100 where L_f is length of the gauge section at fractur, we can find the L_f.

4.2 Microhardness

The Following results of Microhardness reading was obtained after it is conducted on the Digital Microhardness tester.

1. Maximum Hardness for Hexagonal Tool Pin:

At 1120rpm;16mm/min weld speed; 2.0Tilt angle	HAZ@2014	76.2HV& 77HV
	TMAZ@2014	89.5HV & 90HV
	NZ	75.8HV& 76.2HV
	TMAZ@6082	54.8HV& 55.7HV
	HAZ@6082	59.1HV& 59.7HV

Table.9

2. Minimum Hardness for Hexagonal Tool Pin:

At 1120rpm;25mm/min weld speed; 2.0Tilt angle	HAZ@2014	41.1HV&41.4HV
	TMAZ@2014	45.2HV&45.8HV
	NZ	54.1HV&54.5HV
	TMAZ@6082	44.1HV&44.3HV
	HAZ@6082	54.1HV&54.5HV

Table.10

(Table .9 & Table.10 shows the Microhardness results of Hexagonal Tool pin with Hexagonal rings)

3. Maximum Hardness for Circular Tool Pin:

At 900rpm;25mm/min weld speed; 1.5Tilt angle	HAZ@2014	60.7HV&61HV
	TMAZ@2014	62HV & 66.7HV
	NZ	51HV & 54.9HV
	TMAZ@6082	51.5HV&52.3HV
	HAZ@6082	50.6HV& 53HV

Table.11

4. Minimum Hardness for Circular Tool Pin:

At 1120rpm;25mm/min weld speed; 2.0Tilt angle	HAZ@2014	42HV& 42.6HV
	TMAZ@2014	51.5HV&57.5HV
	NZ	46.8HV&48.3HV
	TMAZ@6082	50.8HV&51.2HV
	HAZ@6082	54.1HV&56.5HV

Table.12

(Table .11 & Table.12 shows the Microhardness results of Circular Tool pin with Circular rings)

6.CONCLUSION

From the Investigation data and from the Methodology study the values obtained practically were similar to the values obtained through the Ansys Software 19.2. The following data were concluded from the Investigation:

1.From the Tensile Test report the Maximum Peak stress obtained was 156MPa on a digitally Automated UTM machine at 1120 rpm and 16mm/min weld speed by using hexagonal tool pin.

2. From the Tensile Test report the Minimum Peak stress obtained was 55MPa on a digitally Automated UTM machine at 900rpm and 25mm/min weld speed by using Circular tool pin.

3. From % elongation at break using strain in this paper found that maximum length of the gauge at facture was found 48.192mm and minimum was 41.6mm.

4. From Microhardness Test is conducted at two point in each location and it is observed that Maximum Hardness is obtained to specimen that is FS welded at 1120rpm;16 mm/min weld speed and 2.0 tilt angle. The obtained hardness is at TMAZ@ AA2014-89.5HV & 90 HV, at NZ-75.8HV&76.2HV and at TMAZ@AA6082-54.8HV & 55.7HV. Lowest Hardness is obtained at Weld specimen which is welded at 1120rpm ,25mm/min weld speed and 2.0 tilt angle, the obtained Hardness is at HAZ@AA2014-41.1HV & 41.4HV and at NZ is 54.1HV & 54.5HV all above for Hexagonal Tool Pin.

5. From Circular Tool pin report, Maximum hardness is obtained at 900rpm;25mm/min weld speed and 1.5Tilt angle that is at TMAZ@2014-62 HV & 66.7HV.Minimum hardness is obtained at 1120rpm,2 5mm/min weld speed and 2.0 Tilt angle and that is at HAZ@2014-42HV & 42.6HV.

6. On an overall study the best Friction Stir Welded was done using Tool with Hexagonal pin which gave better results.

7. Among Tool speed of 1120rpm and 900 rpm, better results were obtained for tool running at 1120 rpm.

Abbreviations:

FSW: Friction Stir Welding;
RPM (rpm): Revolution Per Minute
FSW: Friction Stir Welding
UTM: Universal Testing Machine
EDM: Electro Discharge Machining
AA: Aluminium Alloy
HAZ: Heat affected Zone
TMAZ: Thermo Mechanical affected Zone
NZ: Nugget Zone
UYS: Upper Yield stress

LYS: Lower Yield Stress

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Competing interests:
The authors declare that they have no competing interest

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