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Friction Stir Welding of Dissimilar AI-Alloys at Different Welding Parameters: Experimental Testing and Finite Element Analysis

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ABSTRACT

Friction Stir Welding is a solid state welding technique that is proven to produce non-defective high-strength bonds utilizing the process frictional heating in combination to forging pressure. It produces a welded joint by transforming the metals from solid state into a plastic like state, and by mechanically stirring the materials together under high pressure.

Friction Stir Weld of two dissimilar aluminium alloy plates AA-6061 and AA-5052 in Butt configuration with variable factors such as tool rotation speed (RPM and tool pin profiles are considered. The produced samples are tested for their Ultimate Tensile Strength and Microstructural properties. Finite Element Analysis is undertaken to finally evaluate the combinational factors that produces an optimized welded joint.

Keywords:— *Friction Stir Welding, FSW on AA-6061 and AA-5052, Finite Element Analysis, Ultimate Tensile Strength, Microstructural analysis*

I. INTRODUCTION

Friction stir welding (FSW) is a solid-state welding process that gained much attention in research areas as well as manufacturing industry since its introduction in 1991. It is applicable and been marketed to industries such as automotive, aerospace, aircraft and shipbuilding. It can be used to join high-strength aerospace aluminum alloys and other metallic alloys that are hard to weld by conventional fusion welding. The main advantage of FSW over traditional welding processes is the fact that no melting of the work piece material is involved hence eliminating work piece material and tool material loss

FSW of AA-6061 and AA-5052 plates at different rotational speeds and tool pin profiles is undertaken on a Vertical milling machine. Tool pins of Hexagonal and Four sided probe are considered, their design and fabrication is done using Pro/Engineer. Rotational speeds of 1800, 1400, 1120, 900, 710 are inputted for the welding process. In total, 10 Friction stir welded samples of AA -6061 and AA-5052 with two different pin profiles and at five different rotational speeds are produced in this process. High Speed Steel (HSS) is the material used for this tool.

Tensile testing is done to find the maximum tensile strength exhibited by the produced samples. Microstructural analysis is done to observe the distribution of grain sizes in the weld sections of the samples. Structural analysis is done to find out the displacement and shear stress values of the samples. Thermal analysis is done to find out the heat flux on the samples.

The results obtained from the above tests are evaluated to find out the combination of rotational speed and tool pin profile that produces the best possible Friction stir welded joint of two dissimilar aluminium alloys AA-6061 and AA-5052.

II. DESIGN AND EXPERIMENTATION

2.1 Material Properties:

Aluminum alloys AA-6061 and AA-5052 are used in this experiment. Aluminum alloys are alloys in which aluminum (Al) is the predominant metal and the other alloying elements are copper, magnesium, manganese, silicon, tin and zinc.

AISI H13 is the most commonly exercised tool material for processing aluminum alloys. Due to its excellent combination of high toughness and fatigue resistance H13 is used more than any other tool steel in tooling applications.

Table 1: Material Properties of AA-6061, AA-5052 and H13 Steel Tool.

	AA-6061	**AA-5052**	**H13**
Density (ρ)	2.70g/cc	2.68g/cc	7.83g/cc
Young's modulus (E)	69.0 Gpa	69.3 Gpa	210 Gpa
Poisson's ratio (v)	0.33	0.33	0.30
Tensile strength	228 Mpa	268 Mpa	1990 Mpa
Yield strength (Ys)	193 Mpa	214 Mpa	1650 Mpa
Thermal conductivity (K)	167 W/m-K	138 W/m-K	24.3 W/m-K

2.2 Design:

The Design of Friction stir welding tools and the aluminum alloy plates is done using Pro/Engineer software.

Two rectangular plates with the dimensions of 50 mm x 70 mm and a thickness of 5 mm are inputted for the aluminum plates.

Two circles one with diameter of 18 mm and height of 55 mm and another with diameter of 5 mm and height of 5 mm are inputted to produce the tool tip.

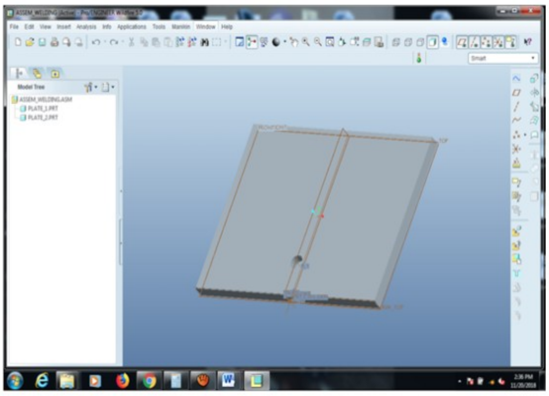


Figure 1: Rectangular plates assembled to represent welded joint.

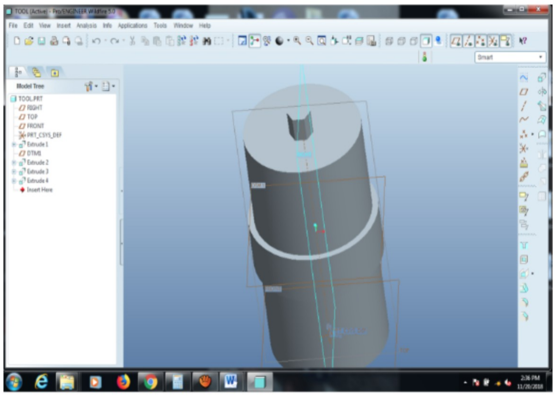


Figure 2: Hexagonal tool tip

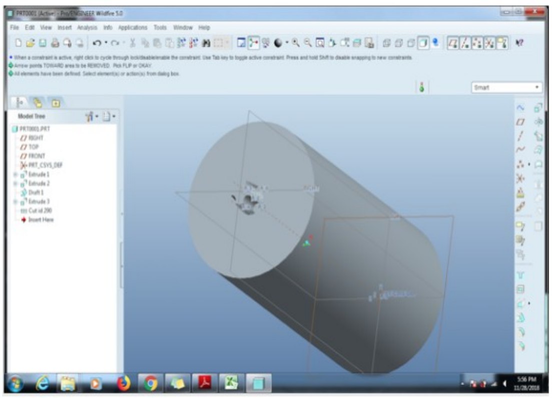


Figure 3: Four sided probe tool tip

2.3 Experimentation

Friction stir welding on two dissimilar aluminum alloys is undertaken in this experiment. The objective is to produce 10 welded samples of two dissimilar alloys AA -6061 and AA-5052 at different input parameters are shown in the Table 2.

Table 2: FSW Experimental Setup Parameters

Tools	Parameters
Work plate dimensions	70 mm x 50 mm x 5 mm
Work plate materials	AA-6061 and AA-5052
Tool Material	H13 steel
Tool Shoulder Radius	25 mm
Tool pin radius	5 mm
Tool pin height	5 mm
Tool Pin Profiles	Hexagonal, Four sided probe
Tool Rotational speed	1800, 1400, 1120, 900, 710
Tool transverse speed	20 mm/min, 25 mm/min
Tool Tilt Angle	0 degrees

The outcome samples from this experiment are categorized as below:—

- Sample 1: FSW of AA-6061 and AA-5052 plates at 1800 rpm using Four sided probe pin at a traverse speed of 25 mm/min
- Sample 2: FSW of AA-6061 and AA-5052 plates at 1400 rpm using Four sided probe pin at a traverse speed of 25 mm/min
- Sample 3: FSW of AA-6061 and AA-5052 plates at 1120 rpm using Four sided probe pin at a traverse speed of 25 mm/min
- Sample 4: FSW of AA-6061 and AA-5052 plates at 900 rpm using Four sided probe pin at a traverse speed of 25 mm/min
- Sample 5: FSW of AA-6061 and AA-5052 plates at 710 rpm using Four sided probe pin at a traverse speed of 25 mm/min
- Sample 6: FSW of AA-6061 and AA-5052 plates at 1800 rpm using Hexagonal pin at a traverse speed of 20 mm/min
- Sample 7: FSW of AA-6061 and AA-5052 plates at 1400 rpm using Hexagonal pin at a traverse speed of 20 mm/min
- Sample 8: FSW of AA-6061 and AA-5052 plates at 1120 rpm using Hexagonal pin at a traverse speed of 20 mm/min
- Sample 9: FSW of AA-6061 and AA-5052 plates at 900 rpm using Hexagonal pin at a traverse speed of 20 mm/min
- Sample 10: FSW of AA-6061 and AA-5052 plates at 710 rpm using Hexagonal pin at a traverse speed of 20 mm/min

Figure 4: AA-6061 and AA-5052 alloy plates

Figure 5: FSW process on AA-6061 and AA-5052

Figure 6: FSW sample with Hexagonal tool tip

Figure 7: FSW sample with Four sided probe tool tip

Table 3: Tensile Test Results of Four Sided Probe Tool Pin

RPM	Ultimate Load KN	Ultimate Tensile Strength N/mm2	Elongation %	Yield Load KN	Yield Stress N/mm2
1800	5.880	110.547	11.20	4.160	78.210
1400	6.400	118.959	13.600	4.640	86.245
1120	8.040	146.662	9.400	6.080	110.908
900	5.640	105.935	12.600	3.600	67.618
710	6.080	112.655	7.000	4.600	85.233

III. Testing and Analysis

3.1 Tensile Testing:

The tensile tests are conducted to determine the tensile strength values and percentage of elongation of the different Friction stir welded AA-6061 and AA-5052 work pieces produced at different rotational speeds and tool profiles. The tensile test specimens were cut using a power saw to dumbbell shapes as per standards on the 5mm thick plate. Feed rate of 400 KN is used for this Universal Tensile Testing.

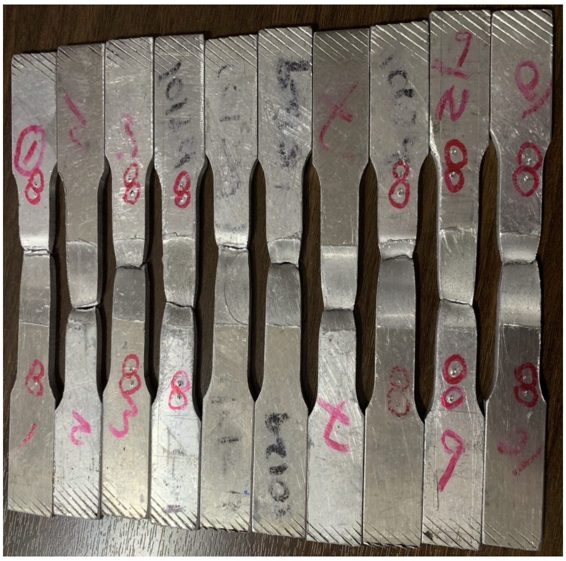
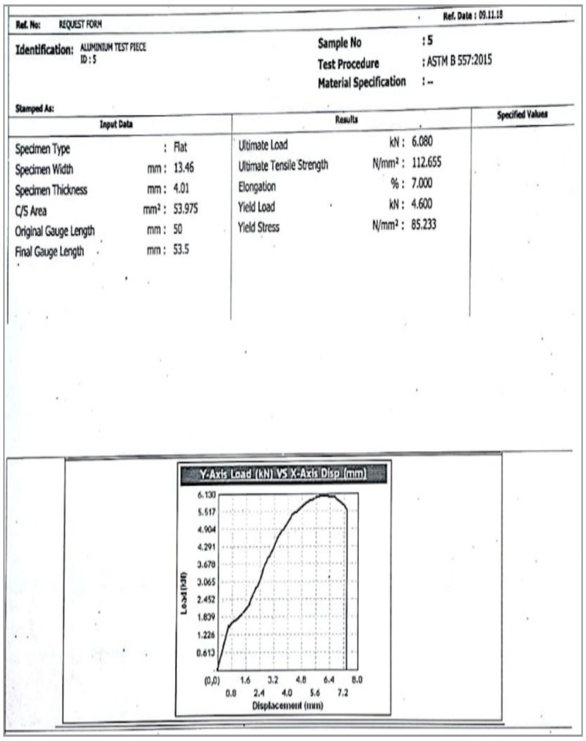


Figure 8: FSW samples that has been cut to dumbbell shape and undergone Tensile testing.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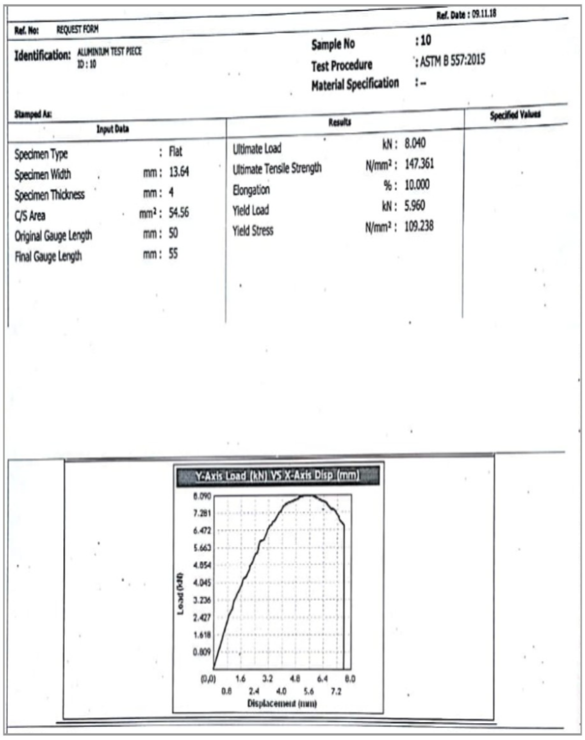
Ref. Date : 09.11.18
Identification: ALUMINIUM TEST PIECE ID : 5
Sample No : 5
Test Procedure : ASTM B 557:2015
Material Specification : --
Stamped As:

Input Data		Results		Specified Values
Specimen Type	: Flat	Ultimate Load	kN : 6.080	
Specimen Width	mm : 13.46	Ultimate Tensile Strength	N/mm² : 112.655	
Specimen Thickness	mm : 4.01	Elongation	% : 7.000	
C/S Area	mm² : 53.975	Yield Load	kN : 4.600	
Original Gauge Length	mm : 50	Yield Stress	N/mm² : 85.233	
Final Gauge Length	mm : 53.5			

Figure 9: Tensile test results of "Sample 5: FSW of AA-6061 and AA-5052 plates at 710 rpm using Four sided probe pin at a traverse speed of 25 mm/min"


Ref. No: REQUEST FORM
Ref. Date : 09.11.18
Identification: ALUMINIUM TEST PIECE ID : 10
Sample No : 10
Test Procedure : ASTM B 557:2015
Material Specification : --
Stamped As:

Input Data		Results		Specified Values
Specimen Type	: Flat	Ultimate Load	kN : 8.040	
Specimen Width	mm : 13.64	Ultimate Tensile Strength	N/mm² : 147.361	
Specimen Thickness	mm : 4	Elongation	% : 10.000	
C/S Area	mm² : 54.56	Yield Load	kN : 5.960	
Original Gauge Length	mm : 50	Yield Stress	N/mm² : 109.238	
Final Gauge Length	mm : 55			

Figure 10: Tensile test results of "Sample 10: FSW of AA-6061 and AA-5052 plates at 710 rpm using Hexagonal pin at a traverse speed of 20 mm/min"

Table 4: Tensile Test Results of Hexagonal Tool Pin

RPM	Ultimate Load KN	Ultimate Tensile Strength N/mm2	Elongation %	Yield Load KN	Yield Stress N/mm2
1800	8.080	148.366	10.000	6.360	116.783
1400	8.040	148.889	8.000	7.080	131.111
1120	6.240	115.727	12.000	5.360	99.407
900	5.880	109.294	16.000	4.600	85.502
710	8.040	147.361	10.000	5.960	109.238

3.2 Microstructural Analysis

A Microstructure analysis is used among the various industries to find the structure of the material at various stages of testing. Microscopic examinations and destructive examinations are carried out in cross-sections of the joints using Optical Microscope. They are typically performed at the stage of development of a tool or a technology. Cross-sections are usually sampled from the beginning, central or final part of the weld. The specimens are treated using a standard procedure for obtaining metallographic micro sections. Next, they are etched with a chemical etchant. The choice of the etchant is made depending on the purpose of the test.

In the case of aluminium alloys, Keller's reagent is most often employed to reveal the joint microstructure. Table 5 represents the composition of Keller's reagent used for this experiment.

Table 5: Keller's Reagent Composition used for Microstructure Analysis

Etchant	Conc.	Conditions	Comments
Keller's Reagent Distilled water Nitric acid Hydrochloric acid Hydrofluoric acid	190 ml 5 ml 3 ml 2 ml	10-30 second immersion	Used for most aluminum and aluminum alloys

Figure 11: Four sided probe and Hexagonal pin specimens for Microstructural Analysis

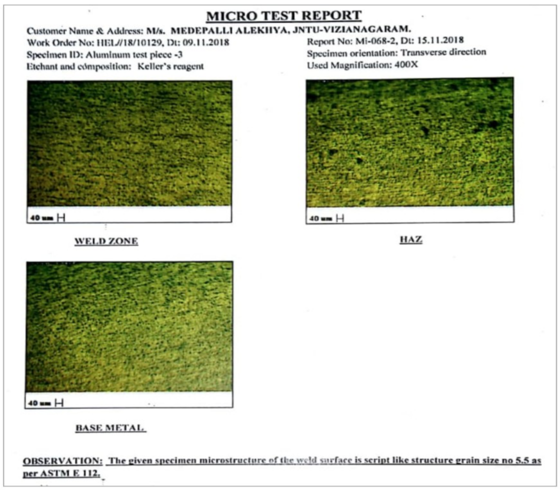


Figure 12: Microscopic test for Four sided probe tool pin

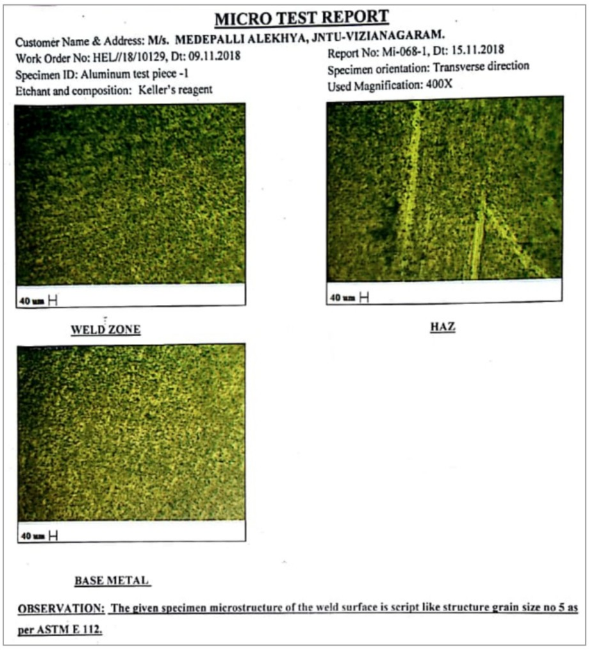


Figure 13: Microscopic test for Hexagonal tool pin

3.3 Thermal Analysis

Thermal analysis is a branch of materials science where the properties of materials are studied as they change with temperature. Developed models from Pro/ Engineer are imported into ANSYS to conduct the Thermal gradient and Thermal flux analysis. Temperature reading from the FSW experiment is taken and noted in the Table 6.

Table 6: Temperature Table From Experiment

Tool tip	RPM	Traverse speed	Tempera-ture K
Hexagonal	1800	20 mm / min	523
Hexagonal	1400	20 mm / min	483
Hexagonal	1120	20 mm / min	508
Hexagonal	900	20 mm / min	523
Hexagonal	710	20 mm / min	478
Four sided probe	1800	25 mm / min	518
Four sided probe	1400	25 mm / min	422
Four sided probe	1120	25 mm / min	523
Four sided probe	900	25 mm / min	509
Four sided probe	710	25 mm / min	493

The Temperature distribution, Thermal gradient and Thermal flux for "Sample 3: FSW of AA-6061 and AA-5052 plates at 1120 rpm using Four sided probe pin at a traverse speed of 25 mm/min" is shown in the Figures 14, 15 & 16".

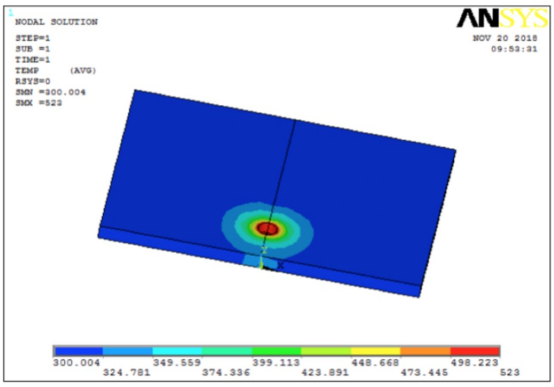


Figure 14: Temperature distribution on Four sided probe

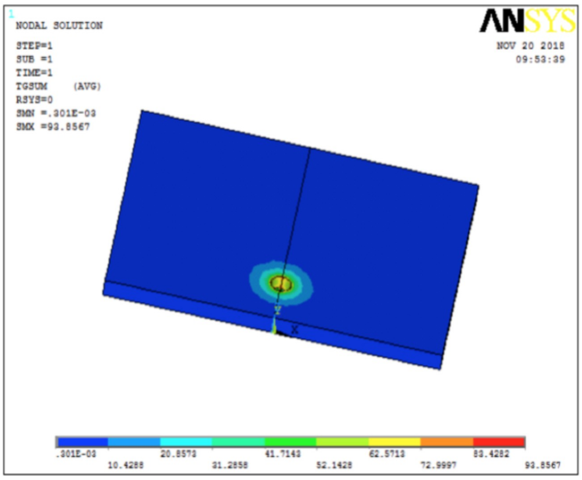


Figure 15: Temperature gradient on Four sided probe pin

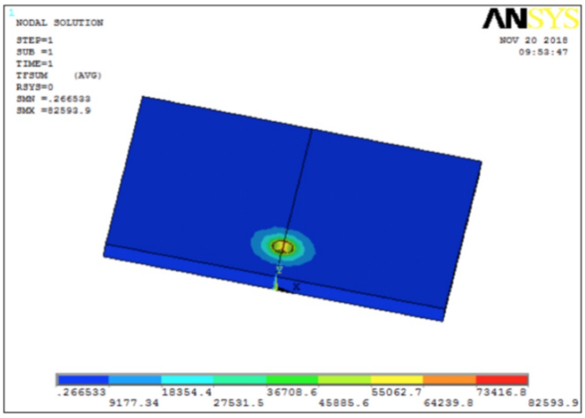


Figure 16: Temperature flux on Four sided probe pin

The Temperature distribution, Thermal gradient and Thermal flux for "Sample 10: FSW of AA-6061 and AA-5052 plates at 710 rpm using Hexagonal pin at a traverse speed of 20 mm/min" is shown in the Figures 17, 18 & 19".

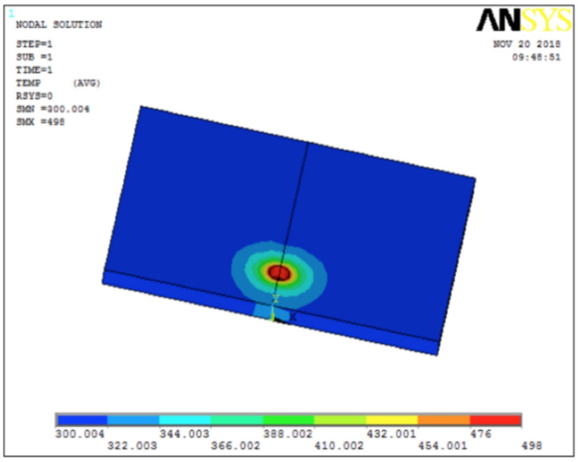


Figure 17: Temperature distribution on Hexagonal pin

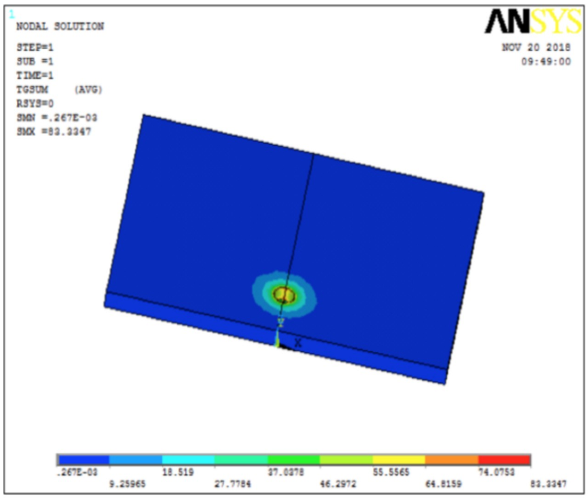


Figure 18: Thermal gradient on Hexagonal pin

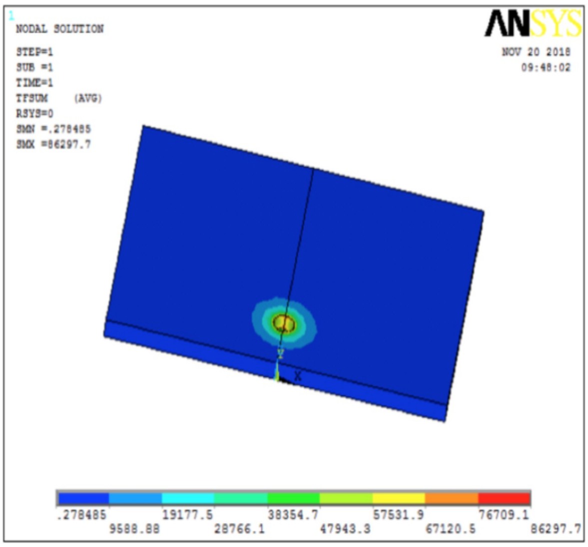


Figure 19: Thermal flux on Hexagonal pin

Table 8: Four Sided Probe Tool Tip Thermal Analysis

RPM	Temperature (K)	Thermal gradient	Thermal flux (W/m2)
1800	518	91.753	80742
1400	472	72.3917	63704.7
1120	523	93.8597	82593.9
900	509	87.9644	77408.7
710	493	81.2303	71482.6

Table 9: Hexagonal Tool Tip Thermal Analysis

RPM	Tempera-ture (K)	Thermal gradient	Thermal flux (W/m2)
1800	518	93.8567	82593.9
1400	472	77.0214	67778.9
1120	523	87.5435	77038.3
900	509	98.0656	73334.5
710	493	83.3347	86297.7

3.4 Structural Analysis

Structural analysis is done on understand the displacement along the XYZ axis to produce the Vector sum of the displacement. von-Mises stress and von-Mises strain are observed in this analysis.

The Displacement Vector Sum, von-Mises Stress and Von-Mises Strain are observed for the welded work pieces, which are produced at different rotational speeds and tool pin profiles.

Table 10: AA-6061 and AA-5052 Material Properties

	AA-6061	AA-5052	H13
Density (ρ)	2.70g/cc	2.68g/cc	7.83g/cc
Young's modulus (E)	69.0 Gpa	69.3 Gpa	210 Gpa
Poisson's ratio (v)	0.33	0.33	0.30

The Displacement Vector sum, von-Mises stress, von-Mises strain for "Sample 5: FSW of AA-6061 and AA-5052 plates at 710 rpm using Four sided probe pin at a traverse speed of 25 mm/min" is shown in the Figures 20, 21 & 22".

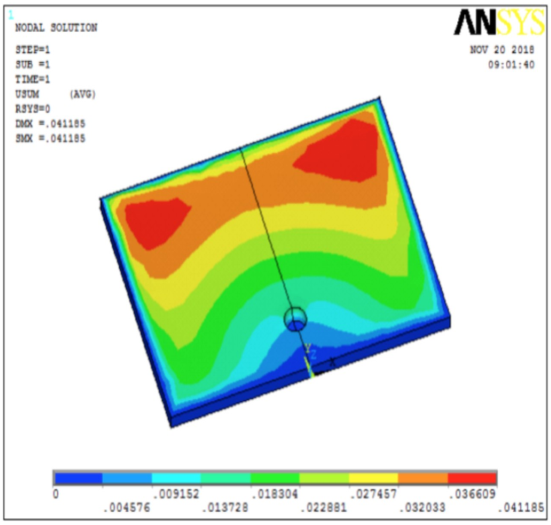


Figure 20: Displacement Vector sum on Four sided probe

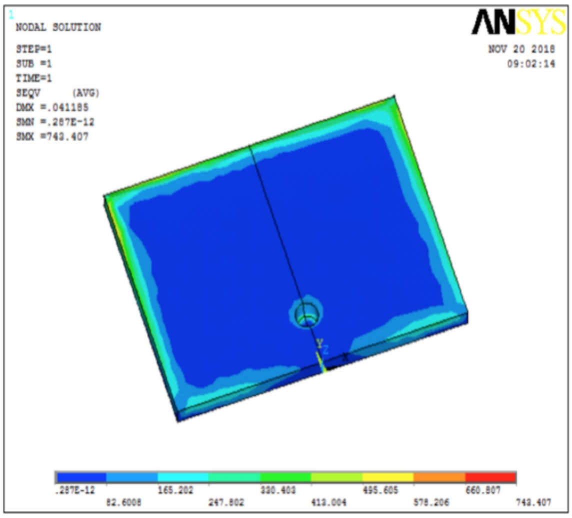


Figure 21: von-Mises stress on Four sided probe

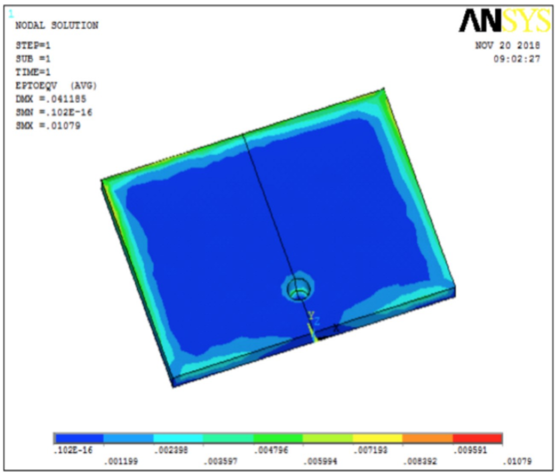


Figure 22: von-Mises strain on Four sided probe

The Displacement Vector sum, von-Mises stress, von-Mises strain for "Sample 10: FSW of AA-6061 and AA-5052 plates at 710 rpm using Hexagonal pin at a traverse speed of 25 mm/min" is shown in the Figures 23, 24 & 25".

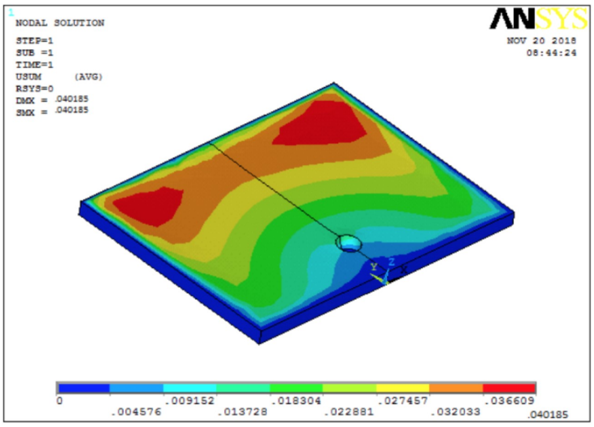


Figure 23: Displacement Vector sum on Hexagonal pin

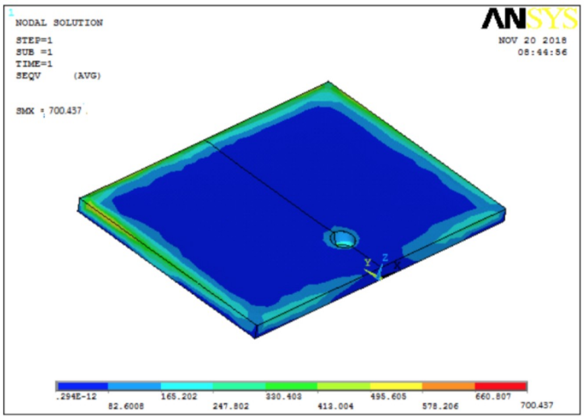


Figure 41: von-Mises stress on Hexagonal pin

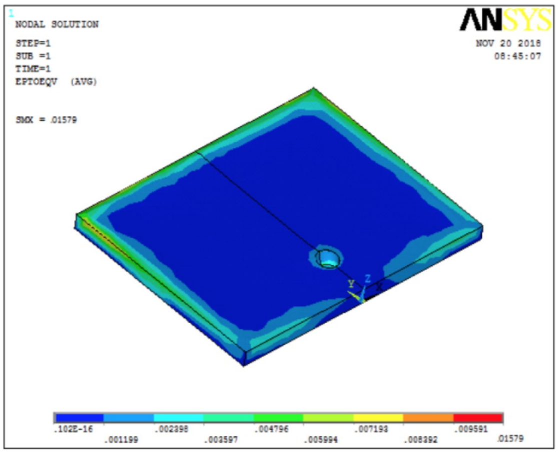


Figure 25: von-Mises strain on Hexagonal pin

Table 11: Structural Analysis of Four Sided Probe Tool Pin

RPM	Displace-ment Vector Sum (mm)	von-Mises Stress (N/ mm2)	von-Mises Strain
1800	0.264708	4778.1	0.06935
1400	0.160132	2890.45	0.041952
1120	0.102485	1849.89	0.02685
900	0.066177	1194.52	0.017337
710	0.041185	743.407	0.01079

Table 12: Structural Analysis of Hexagonal Tool Pin

RPM	Displacement Vector Sum (mm)	von-Mises Stress (N/ mm2)	von-Mises Strain
1800	0.235296	4578	0.06493
1400	0.138798	2510.37	0.035435
1120	0.099037	1940.23	0.02586
900	0.062177	1123.52	0.017337
710	0.040185	700.437	0.01579

IV. Conclusion

Friction stir weld of two dissimilar alloys AA-6061 and AA-5051 is done at different rotational speeds of 1800, 1400, 1120, 900 and 710 and tool pin profiles of Hexagonal and Four sided probe. Experimental testing for Tensile strength and Microstructural analysis are done to understand the maximum tensile strength and grain size distribution. Thermal and Structural analysis are done to find out the heat flux and stress on the work pieces. The following observations are made from the results obtained:—

- From the Tensile testing it is observed that the Hexagonal tool profile has exhibited high Tensile strength values at all the rmp's when compared to Four sided probe tool.

- From the Microstructural analysis the grain sizes observed are 5 for Hexagonal tool and 5.5 for Four sided probe
- In Structural analysis the Displacement and Shear stress values of 710 rpm is low when compared to the rest.
- In thermal analysis the Hexagonal tool profile's Heat flux is high in 710 rpm (86.297 w/mm) and for Four sided probe tool the Heat flux is high at 1120 rpm (82.593 w/mm)
- From the above observations it is evident that the Hexagonal tool profile at 710 rpm produces the best FSW welded joint for AA-6061 and AA-5052

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