IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

INVESTIGATION OF DISSIMILAR AL-BASE ALLOYS BY USING DIFFERENT PIN PROFILES

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Abstract: Aluminum alloys have different applications (e.g. Al 5083 and Al 6082: marine, automotive and aeronautical components). Regarding the application, it is necessary to check the poor weldability of the conventional connection in which two aluminum alloys are connected in the liquid state due to the different chemical, mechanical and thermal properties of the connected material and the formation of hard intermetallic growths. Great brittleness occurs, which leads to a reduction in the mechanical strength of the connection.

Feasibility of friction stir welding (FSW) of Al 5083 and Al 6082 sheets with different pin profiles: straight cylindrical (Cy), threaded cylindrical (Th), triangular (Tr) and square (Sq) are studied, as cylindrical and threaded cylindrical generate regular stirring action whereas, triangular and square pin profiles produce pulsating stirring action in the flowing material due to their flat faces. Further investigations are underway to determine the effects of these tools pin on the microstructure, hardness, crystallographic structure, and tensile strength of the bonded specimens. All samples showed the lowest hardness value in the heat-affected zone on the side of AA 6082, and this zone also fractured during the tensile tests. Since all samples have comparable microstructures and hardnesses, only the threaded cylindrical sample has the lowest tensile strength because the heat-affected zone has the largest structural component in the tensile direction.

Index Terms: **Al 5083, Al 6082, friction stir welding, material testing and pin profile.**

I. INTRODUCTION

FSW (Friction Stir Welding) is a solid-state welding technology that is used to join materials that are similar or dissimilar. FSW is particularly well appropriate for joining aluminium alloys [1]. FSW is also considered for joining steel, titanium, Inconel, and magnesium alloys. These materials have a diverse set of uses in shipbuilding and marine industries, aerospace, automotive, rail and construction industries, oil and gas industries, and robotics. Aluminium alloys are precipitation hard-enabled alloys, joining aluminium alloys using fusion welding is challenging. there is a chance of dissolution of precipitate during the fusion welding, which leads to the loss of strength. The friction stir welding process (FSW), was devised and patented by The Welding Institute, in England, in 1991. It's a ground-breaking joining technique based on solid-state plastic deformation of materials [2].

The basic working principle of FSW is shown in Fig 1. Two plates are brought together, positioned on a holding plate, and tightly secured. The parts are inserted with a specially developed non-consumable tool that is made up of a shoulder of a large diameter and a smaller pin. The movement of the tool shoulder (which is in close interaction with the workpiece's top surfaces) and during welding the pin generates a lot of agitation and frictional heat, which causes the plate material to become plasticized. Plasticized plate material is agitated and forged behind the trailing face of the tool pin as the tool moves along the weld line, this will form a joint behind the tool. After the joining process, the tool is separated Friction stir welding (FSW) creates strong welds with low distortion and residual stresses [6]. The process parameters like tool rotational speed, weld speed, and axial force significantly affect the joint quality as well as strength [7].

The Friction Stir Welding process has been widely used in automobile engineering and mechanical engineering since its introduction. In earlier ages, it is used to weld soft alloys such as aluminium alloys and magnesium-based alloys. With the development of improved tools in recent years, FSW has been able to weld metals with high hardness, such as steels...etc [8].In most of the studies, the FSW uses the tool with a pin size of 0.1–0.6 mm diameter [9]. The FSW tool pin profile has a significant influence on material flow and weld quality [10]. Various researchers have used pin profiles of different shapes. Straight-cylindrical, threaded-straight cylindrical, square, taped-cylindrical, and triangular are some of the commonly used tool pin profiles, in recent works some new tool pins types have also been invented such as polygonal, hybrid polygonal, threaded taper profiles [11], [12]. Weld joints benefit from tool geometry because it improves their properties as well as quality. During the joining process, the FSW tool serves two purposes. The tool pin stirs the material while the tool shoulder rubs the material and generates heat. The power required to move the tool along the joint line is reduced when the tool is designed properly [13]. Based on literatures, it is found that the popularity of investigation on pin profiles has grown. This aims to review the impact of different pin profiles on the mechanical properties of the joint.

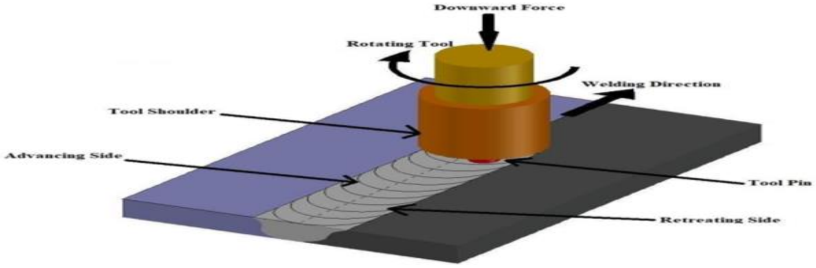


Fig.1. Working of FSW [5]

1.1 WORKING PRINCIPLE

As depicted in a traversely fed cylindrical-shouldered tool with a profiled nib is continuously rotated and fed into a butt joint between two clamped pieces of butted material. The tool shoulder rides at the top of the work surface, and the nib is just a little bit shorter than the needed weld depth. The process two movements namely initial downward movement of tool outside the workpiece and lateral movement of the tool along the work piece.

Frictional heat is produced between the work parts and the wear resistant welding components. The heat produced by the stirring action causes the materials to soften without melting, combined with heat from the mechanical mixing process and internal adiabatic heat. A unique design on the pin's leading face drives plasticized material to the back as it is advanced, where clamping force helps to forge the weld into place.

1.1.1 Work piece materials:

1. Work piece dimensions: Two dissimilar aluminum plates (AA 5083 and AA 6082) of thickness 6mm, have been cut into required size of (150 mm x 50 mm) by power saw as well as NC milling for face milling to remove extra scraps from work piece.

2. Composition and Mechanical Properties of Al alloys: The chemical composition and measured mechanical properties are given in Table 1.1.

Table 1.1. The chemical composition and mechanical properties of Al alloys

Alloys	Si (wt%)	Mn (wt%)	Mg (wt%)	UTS (MPa)	0.2 % yield (MPa)	Elongation to Failure %	Hardness (HV)
5083	0.4	0.4-1.0	4.0-4.9	256	203	8.96	75
6082	0.7-1.3	0.4-1.0	0.6-1.2	328	315	18.11	110

1.2 Tool design

1. Tool material: Non consumable tool material for fabrication of weld joint is H13 tool steel which is selected from variety of other tool materials like high speed steel, tool steel, high carbon high chromium steel (HCHCr), carbide, tungsten etc. because of its high hardness, high strength, tough, good oxidation resistance, low thermal conductivity, easy in manufacturing process, low cost and easy availability in the market.

2. Different tool pin profiles: Fabrication of different pin profiles is done by lathe and NC milling machine by using indexing and are shown in fig 1.2. After the manufacturing of all, tools are oil hardened up to a hardness of 48HRc to 52HRc

Fig.1.2 : different pin profiles; (a) Straight cylindrical. (b) Threaded. (c) Triangular (d) Square

3. Tool dimensions and welding process parameters: Tool dimensions and welding process parameters are given in Table 1.2. Tool have a shoulder diameter of 18mm and the diameter of the two column pins and the diameters of circumscribed circle of the triangular and square were 6mm and for threaded pin, a right hand 0.6 mm pitch thread is used and pin length of 5.5 mm.

Table 1.2.Optimized welding parameters used for all pin profiles

Pin profile used	Rotation speed (rpm)	Welding speed (mm/min)	Shoulder Dia. (mm)	Pin Dia (mm)	Pin length (mm)	Tilt angle (deg)	Plunge depth (mm)
Cylindrical (Cy), Thread (Th), Triangular (Tr), Square (Sq)	900	70	18	6	5.5	2	0.2

ETA Friction Stir Welding (FSW) machine is used to weld work piece sheet or plates by different pin profile. This machine provide a rotation speed in the range between 70 rpm to 3000 rpm and traverse speed range between 0.1mm/min to 2000mm/min with up to 100 KN axial force. Optimized welding parameter for welding are achieved by visual inspection and optical microscopy observations of each FSW joint and try to get sound (defect free) joint. The welded sample is cut on the transverse section perpendicular to the welding direction by precision cutting machine (Secotom) of the dimension 50 mm x 10 mm x 6 mm for hardness and microstructural measurement. Further grinding is performed on the transverse section by 800 and 500 Grit SiC paper and fine polishing by 9µm, 6µm, 3µm, 1µm diamond colloidal solutions followed by etching and electro polishing according to the requirements. The FSW specimens were etched with Keller's regent and electro polishing with a mixture of 30% nitric acid in methanol, for 15 to 25 seconds at 12V. Their optical images were taken using optical microscopy with a magnification of 5X.

Fig.1.3.Experimental setup for FSW

First of all hardness is measured perpendicular to weld line in the transverse section at the middle of thickness by Vickers hardness with a load of 0.3 kg at regular interval of 1mm. After that optical images were taken on the transverse section of the specimens and several zones like interface or nugget or stir zone, Thermo-mechanically affected zone (TMAZ), heat affected zone (HAZ), and base material were identified. Further microstructural characterization using Scanning Electron Microscope- Electron Backscattered Diffraction (SEM-EBSD) is performed at the various locations of the welded samples such as at Nugget, (TMAZ), (HAZ), and base materials.

1.3 Plunge depth

At the preliminary stage of using designs the plunge depths used were 3.5mm the plunge depths varied from one shoulder diameter to the other, because of the different sizes of the shoulder diameters used. From literature, it was reported that when the tool is tilted, it gives rise to a shoulder plunge, Shoulder plunge, p can be calculated as:

$$P = 0.5\ D \sin \theta$$

Where, P = Shoulder plunge

D = Shoulder Diameter

θ = Tilt angle

The effective plunge depth is the sum of the nominal plunge depth and the shoulder plunge depth. The effective plunge depth used for the final weld matrix was 3.5 mm, as calculated below. The plunge rate is 0.5 mm/min and the position control setting was used to make all the welds.

For the 18 mm shoulder diameter tool,
the shoulder plunge is: $P = 0.5 \times 18 \sin 30 = 0.47$ mm
The nominal plunge depth used for welding was 2.65 mm,
The effective plunge depth = 2.65 mm + 0.47 = 3.12 mm.

II. RESULTS & DISCUSSION

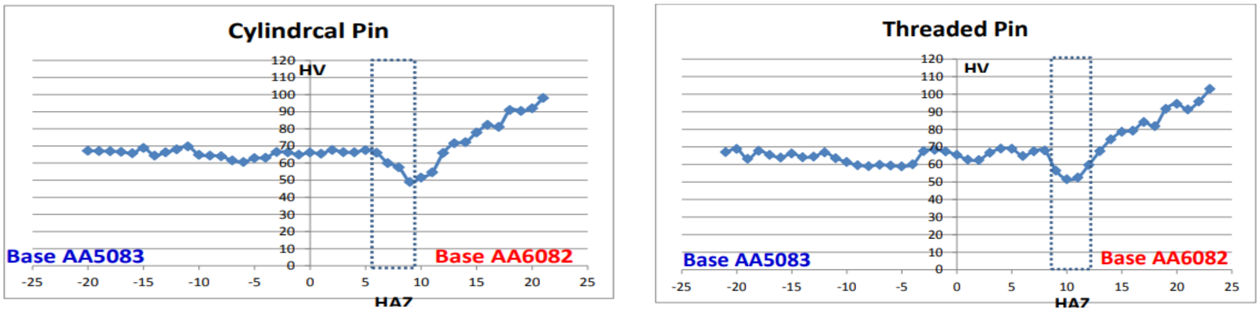
Friction Stir Welding was used to make butt joint between AA5083 – AA6082 with 4 types of tool shapes. Mechanical tests like tensile test, bending test and hardness were conducted to evaluate their property. Also changes in microstructure were studied. All the results are discussed in detail in this chapter.

2.1 WELDING PROCESS

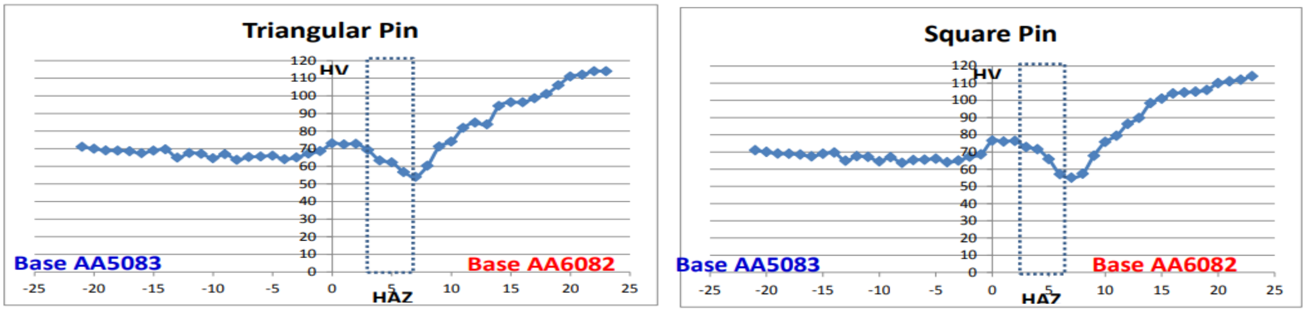
The tool often has a shoulder and a square pin on it. The pin's length is just a little bit less than the thickness of the plates that will be welded. In FSW, however, there are only three process variables; i.e., rotational speed, transverse speed and pressure that need to be controlled. Therefore, due to the excellence performance in welding technology as compared to fusion methods, FSW has been successfully used in many applications such as aerospace, shipbuilding, aircraft, and automobile industries.

2.2 Vickers micro-hardness test profile for different pins

Their micro-hardness profiles for all four different pins in the transverse section are given in Fig.2.1. There is less variation noted in the hardness profile of AA 5083 side. The base material AA5083 has hardness of 75HV and has not varied towards the nugget zone. This might be due to the annealed state of the base aluminum alloy with stable microstructure undergoing no further softening in the heat-affected Zone (HAZ). However, there noticed variation in hardness profile in the retreating AA 6082 side (shown in Fig.2.1). The base material AA 6082 has hardness of 110HV



(a) Cylindrical Pin Profile (b) Threaded Pin Profile



(c) Triangular Pin Profile (d) Square Pin Profile

Fig.2.1: Vickers micro-hardness for all four different pin profiles (a) Cylindrical (b) Threaded (c) Triangular (d) Square

2.2.1 Combined micro-hardness profile for all four tool pin profiles:

Combined micro-hardness profiles for all four different pin profiles are given in figure 2.2. This shows that square pin profile gives maximum hardness at the interface which is due to most fine grains (will be shown in next section) and there is a shifting of the minimum hardness value in the HAZ also.

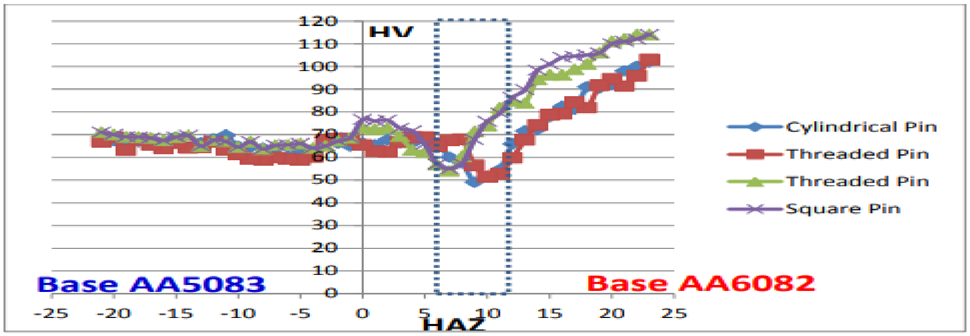
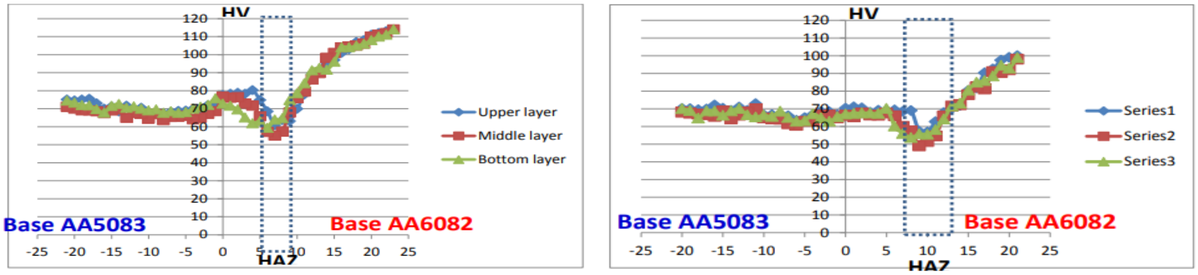


Fig.2.2: Combined micro-hardness profile for all four pin profiles

It can be seen that for all the four specimens the minimum hardness is obtained in between 7 mm to 10 mm from the center of the nugget zone depending on the pin profile used (Fig.2.2). For straight cylindrical and threaded cylindrical pin welded specimens the minimum hardness is located between 9 to 10 mm but for triangular and square pin welded specimens the minimum hardness is obtained between 7 to 7.5 mm.

2.2.2 Hardness along the thickness in the transverse section:

Hardness along the thickness in the transverse section for square and cylindrical pin profiles is shown in fig 2.3. These hardness profiles are measured at distances of 1.5 mm, 3 mm and 4.5 mm from the top surface of the welded sample.



(a) Square pin profile (b)Cylindrical pin profile

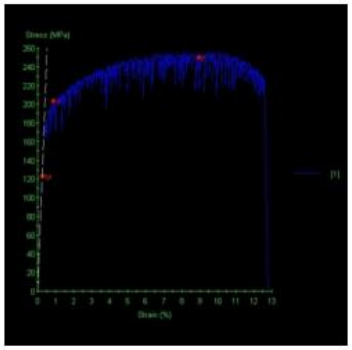
Fig.2.3 : Hardness along the thickness in the transverse section for (a) Square and (b) Cylindrical pin profile

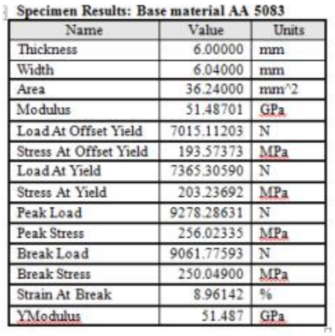
The nature of the hardness profile for three layers is almost similar but only the value of minimum hardness and the position of minimum hardness vary. As middle layer gives minimum hardness than other two layers and minimum hardness shifted towards interface line from top layer to bottom layer.

2.3 Tensile Tests:

2.3.1 Base Material AA 5083 and AA 6082:

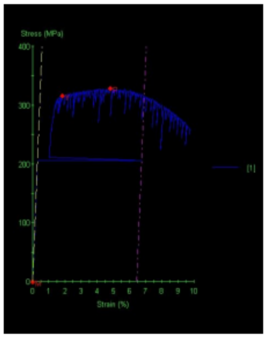
The various tensile values obtained from the base materials (AA 5083 and AA 6082) and given below in Fig.2.3:

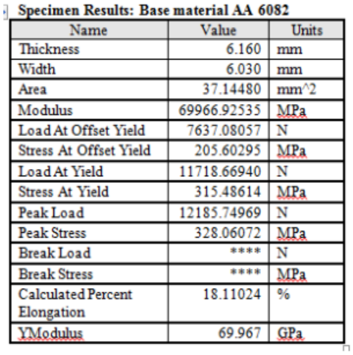




Specimen Results: Base material AA 5083

Name	Value	Units
Thickness	6.00000	mm
Width	6.04000	mm
Area	36.24000	mm^2
Modulus	51.48701	GPa
Load At Offset Yield	7015.11203	N
Stress At Offset Yield	193.57373	MPa
Load At Yield	7365.30590	N
Stress At Yield	203.23692	MPa
Peak Load	9278.28631	N
Peak Stress	256.02335	MPa
Break Load	9061.77593	N
Break Stress	250.04900	MPa
Strain At Break	8.96142	%
YModulus	51.487	GPa





Specimen Results: Base material AA 6082

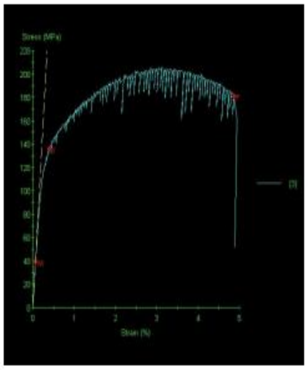
Name	Value	Units
Thickness	6.160	mm
Width	6.030	mm
Area	37.14480	mm^2
Modulus	69966.92535	MPa
Load At Offset Yield	7637.08057	N
Stress At Offset Yield	205.60295	MPa
Load At Yield	11718.66940	N
Stress At Yield	315.48614	MPa
Peak Load	12185.74969	N
Peak Stress	328.06072	MPa
Break Load	****	N
Break Stress	****	MPa
Calculated Percent Elongation	18.11024	%
YModulus	69.967	GPa

(a) Base material 5083 (b)Base Material 6082

Fig.2.3: Tensile properties of base materials (a) AA 5083 (b) AA 6082

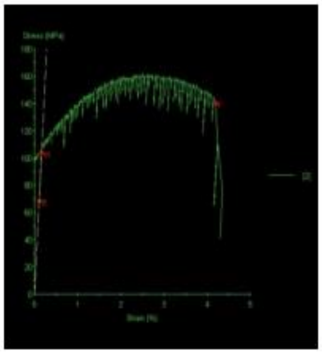
2.3.2 Tensile tests on different pin profiles specimens:

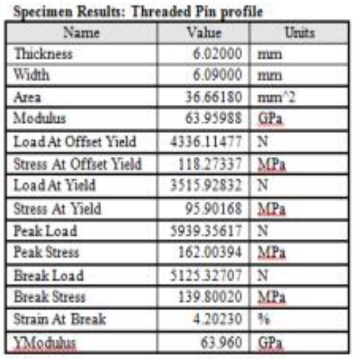
To check the strength of the welded joints, tensile tests on the four specimens are performed and are compared with the base materials. The tensile properties of the weld joints are shown in Fig.2.4 and their values are given in Table 2.1.



Specimen Results: Cylindrical Pin profile

Name	Value	Units
Thickness	6.07000	mm
Width	6.19000	mm
Area	37.57330	mm^2
Modulus	63.48648	GPa
Load At Offset Yield	5232.16997	N
Stress At Offset Yield	139.25234	MPa
Load At Yield	5104.14721	N
Stress At Yield	135.84506	MPa
Peak Load	7728.50398	N
Peak Stress	205.69138	MPa
Break Load	6799.38032	N
Break Stress	180.96309	MPa
Strain At Break	4.86689	%
YModulus	63.486	GPa

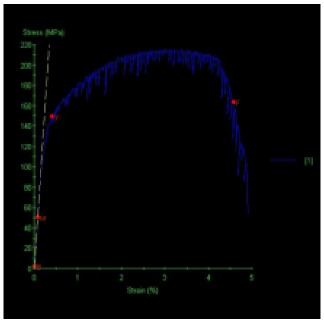


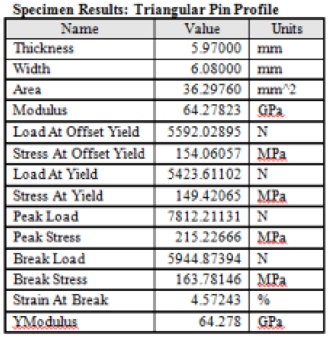


Specimen Results: Threaded Pin profile

Name	Value	Units
Thickness	6.02000	mm
Width	6.09000	mm
Area	36.66180	mm^2
Modulus	63.95988	GPa
Load At Offset Yield	4336.11477	N
Stress At Offset Yield	118.27337	MPa
Load At Yield	3515.92832	N
Stress At Yield	95.90168	MPa
Peak Load	5939.35617	N
Peak Stress	162.00394	MPa
Break Load	5125.32707	N
Break Stress	139.80020	MPa
Strain At Break	4.20230	%
YModulus	63.960	GPa

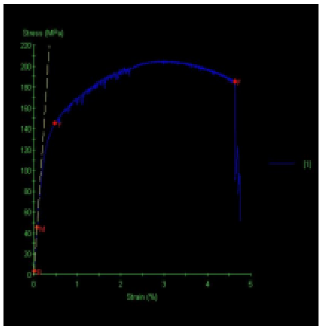
(a)Cylindrical pin (b)Threaded pin

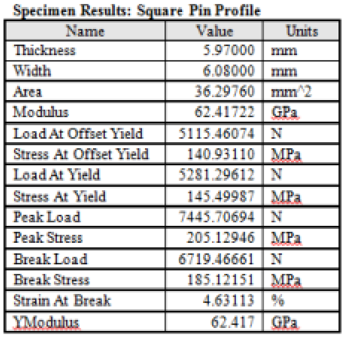




Specimen Results: Triangular Pin Profile

Name	Value	Units
Thickness	5.97000	mm
Width	6.08000	mm
Area	36.29760	mm^2
Modulus	64.27823	GPa
Load At Offset Yield	5592.02895	N
Stress At Offset Yield	154.06057	MPa
Load At Yield	5423.61102	N
Stress At Yield	149.42065	MPa
Peak Load	7812.21131	N
Peak Stress	215.22666	MPa
Break Load	5944.87394	N
Break Stress	163.78146	MPa
Strain At Break	4.57243	%
YModulus	64.278	GPa





Specimen Results: Square Pin Profile

Name	Value	Units
Thickness	5.97000	mm
Width	6.08000	mm
Area	36.29760	mm^2
Modulus	62.41722	GPa
Load At Offset Yield	5115.46074	N
Stress At Offset Yield	140.93110	MPa
Load At Yield	5281.29612	N
Stress At Yield	145.49987	MPa
Peak Load	7445.70694	N
Peak Stress	205.12946	MPa
Break Load	6719.46661	N
Break Stress	185.12151	MPa
Strain At Break	4.63113	%
YModulus	62.417	GPa

(c)Triangular Pin Profile (d)Square pin

Fig.2.4: Tensile properties of four different pin profiles (a) Cylindrical (b) Threaded (c) Triangular and (d) Square

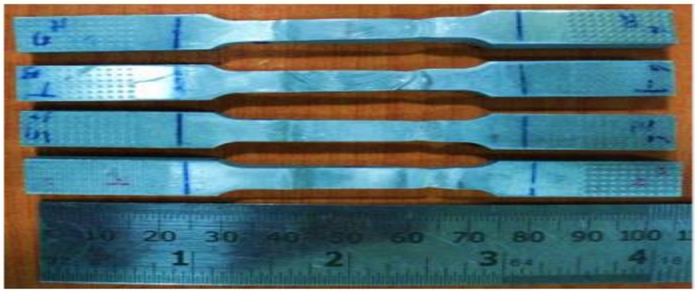


Fig.2.5: Fractured Samples after tensile test

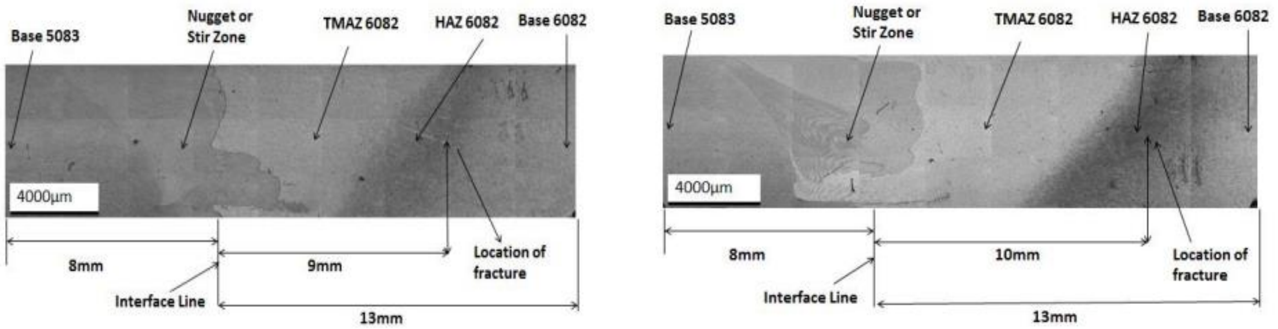
The cylindrical and the threaded welded specimens fractured at 9.0 mm and 10.0 mm and the triangular and the square welded specimens fractured at 7.5 and 7.0 mm respectively, all when measured from the center of the nugget zone. Figure 2.5 shows fractured samples after tensile test.

Table.2.1: Tensile Properties for dissimilar material weld by four different pin profile

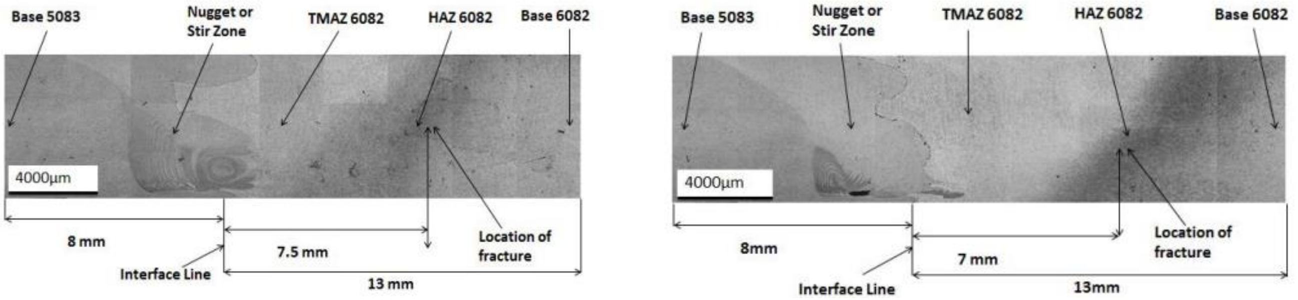
Pin Profiles	**UTS (MPa)**	**0.2%Yield (MPa)**	**Elongation to Failure (%)**	**Location of Failure (mm) from Interface**
Cylindrical	205	136	4.86	9.0
Threaded	162	96	4.20	10.0
Triangular	216	150	4.57	7.5
Square	206	145	4.63	7.0

2.4 Optical micro-graphs of the welded sample for all four different pin profiles:

The optical images of the FSW specimens joined with four different pin profiles are given in Figure 2.6. The optical image of the welded zone is divided mainly into four different regions: nugget or stir zone, thermo mechanically affected zone (TMAZ), heat affected zone (HAZ) and base materials. All optical images are taken with a same magnification of 5x and from same area as 8mm in AA 5083 region and 13 mm in AA6082 region from the interface or center line. The reason for these different distances is due to no microstructural changes (TMAZ and HAZ) observed in the AA 5083 region. Creating edges in the pins, it's static to dynamic ratio increases i.e. decrease in the contact area with the work piece but in turn increase in the pulsating stirring action [8]. Hence, the triangular and the square pin welded specimens are expected to generate lower distance HAZ from the nugget zone than the cylindrical and the threaded cylindrical welded specimens.



(a) Cylindrical Pin (b) Threaded Pin



(c) Triangular Pin (d) Square Pin

Fig2.6: Optical images of welded samples with distinct regions with distance of fracture from interface line for (a) Cylindrical pin (b) Threaded pin (c) Triangular (d) Square.

2.5 CONCLUSIONS

In conclusion, defect-free welds (sound joints) through friction stir welding were achieved on two dissimilar aluminum alloys by all the four different pin profiles (cylindrical, threaded cylindrical, triangular and square).

SEM characterization at the welded nugget zone showed the development of fine grain microstructure with all the pin welded specimens which is due to proper mixing and hence, indicating better joint strength. Irrespective of generating better welds, during tensile tests, all the specimens failed earlier than the base materials at their fragile heat affected zone (HAZ) in the AA 6082 side containing lower hardness values. The location of fracture or minimum hardness of the welded sample varies for different pin profiles. The cylindrical and the threaded welded specimens fractured at 9 mm and 10 mm and the triangular and the square welded specimens fractured at 7.5 and 7 mm respectively. Out of all the four specimens, the threaded pin welded specimen showed the least ultimate tensile strength due to the presence of higher amount of ||tensile direction texture component which rendered low Taylor factor and hence, poor strength.

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