Friction Stir Welding (FSW) studies of dissimilar Al-based alloys using different pin profiles

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Department of Materials Science and Engineering

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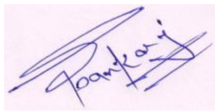

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Approval Sheet

This thesis entitled – **Friction stir welding (FSW) studies of dissimilar Al-based alloys using different pin profiles** by **Mr. Pankaj** is approved for the degree of Master of Technology from IIT Hyderabad.

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PANKAJ

Dedicated to

My Family members:

My Father- Mr. Ram Maher Singh

My Mother- Mrs. Rajbeeri Devi

My Brothers- Yogendra and Pawan Sahlot

Because they believe in me, whatever I am doing that is good for us that's why every time their trust motivate me to work hard and honestly

Abstract

The feasibility of friction stir welding (FSW) of Al 5083 and Al 6082 sheets using 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 in-depth investigations are made to understand the effects of these tool pin profiles on microstructures, hardness, crystallographic texture and tensile strength of the welded specimens. All specimens showed minimum hardness values in their heat affected zone in the AA 6082 side and they fractured as well in this region during the tensile tests. Having comparable microstructures and hardness values in all the specimens, only the threaded cylindrical joined specimen showed the lowest tensile strength due to the presence of maximum <001>||tensile direction texture component in its heat affected zone.

There are varied applications of aluminum alloys (for e.g. Al 5083 and Al 6082: marine, automobile, and aeronautical applications). For the application point of view the conventional welding involving liquid state joining of two dissimilar aluminum alloys is not desirable because of poor weldability due to difference in chemical, mechanical, thermal properties of welded materials and formation of hard and brittle intermetallic phases in large quantity, leading to decrease in mechanical strength of the welded joint.

To overcome this problem, there exists a relatively new welding technique known as friction stir welding (FSW), an energy efficient and eco-friendly solid state joining process invented by The Welding Institute (TWI) of Cambridge, England in 1991. FSW appears to offer a number of advantages over conventional fusion welding techniques, such as no need for expensive consumable filler materials, good mechanical and metallurgical properties of the resultant joint, absence of solidification crack, no porosity, low distortion and less energy consumption.

Nomenclature

FSW	-	Friction Stir Welding
TWI	-	The Welding Institute
TMAZ	-	Thermo mechanically Affected Zone
HAZ	-	Heat Affected Zone
Cy	-	Cylindrical
Th	-	Threaded
Tr	-	Triangular
Sq	-	Square
NC	-	Numerical Control
CNC	-	Computer Numerical Control
MTS	-	Material Testing System
UTS	-	Ultimate Tensile Strength
OIM	-	Orientation Image Microscopy
SEM	-	Scanning electron Microscopy
EBSD	-	Electron Backscatter Diffraction
IPF	-	Inverse Pole Figure
TD	-	Transverse and Tensile Direction
ND	-	Normal Direction
WD	-	Welding direction

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Chapter 1

Introduction

Metal joining:

Metal joining is a method to join two or more materials by the help of some external means. There are huge requirements of metal joining because of limitation to manufacture a large or complicated work piece design by conventional manufacturing processes such as casting, forging, rolling, extrusion etc. There are many methods exist to join materials as shown in Figure 1.1.

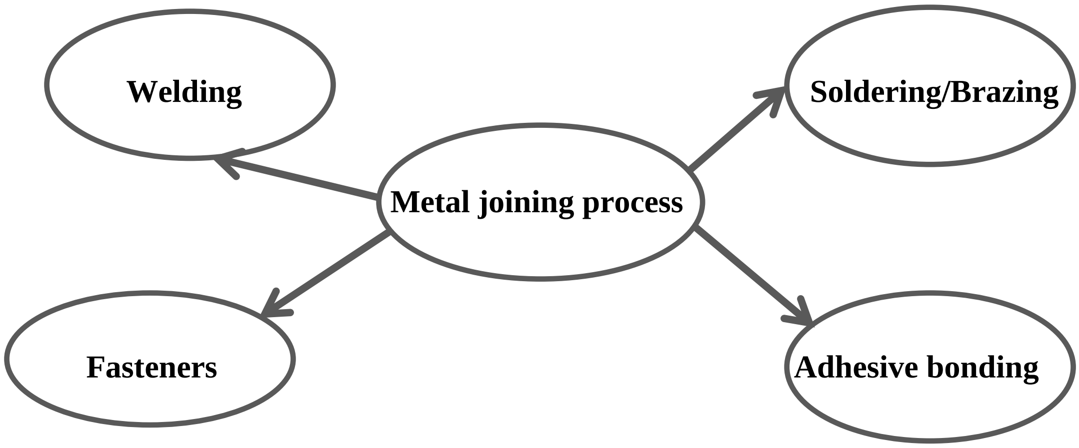


Figure 1.1: Different of methods of metal joining [1]

Welding:

Welding is a fabrication process that joins materials, usually metals or thermoplastics, by causing coalescence. Welding is one of the absolutely necessary and widely used manufacturing processes in any manufacturing/production industries. The main aim of welding technology is to achieve the optimal condition for defect free joint.

There exist mainly two types of welding; one is conventional fusion welding and other is solid state welding. In fusion welding a heat source is used to melt the material and after melting pressure is applied to join the materials but solid state welding is performed below the work piece's melting temperature such as friction stir welding (FSW). All types of welding processes are mentioned in Figure 1.2.

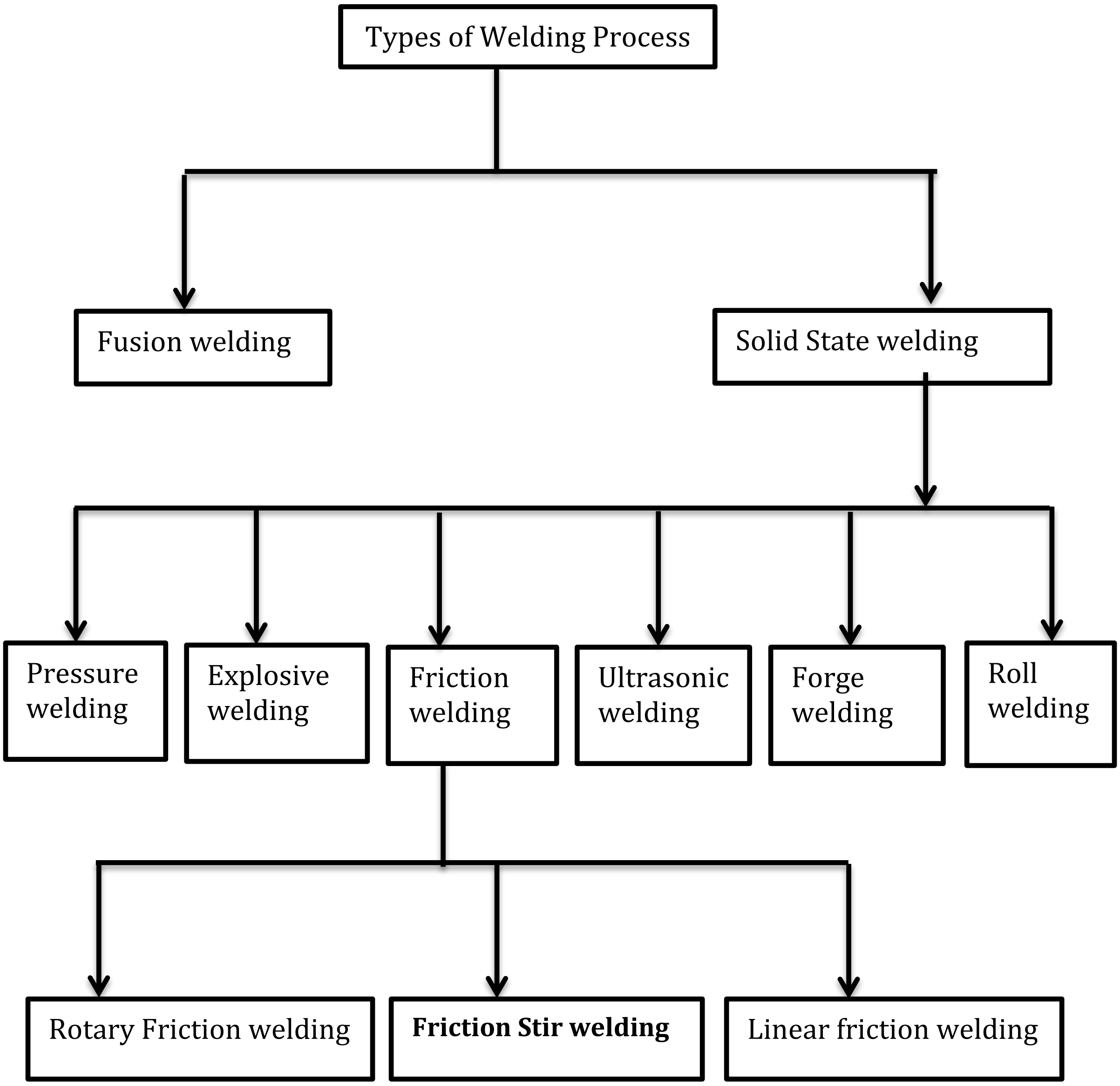


Figure 1.2: Flow chart of welding process [2]

There are general problems associated with fusion welding and these are [3,4]:

- Decline of mechanical properties due to melting & re-solidification.
- Presence of Hot cracking, solidification cracking and porosity.
- Inclusions of Hydrogen, Oxygen and Nitrogen from surrounding.
- Requirement of expansive consumable filler material.
- Application or use of flux and Shielding gas.
- Energy Consumption is high
- Environmental problems because of flue gases.

Certainly, solid state welding is advantageous over the above given reasons of fusion welding. Since my M.Tech. thesis work is on Friction stir welding (FSW), a solid state welding process so now onwards, FSW will only be explained in detail.

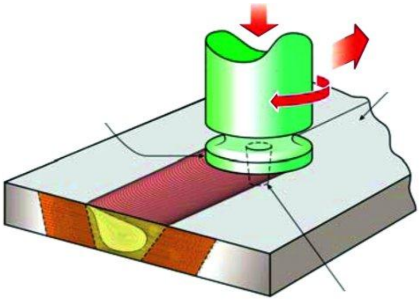
Friction Stir Welding:

Friction stir welding (FSW) is an emerging, energy efficient, attractive and eco-friendly solid state welding process invented in 1991 in England [4]. FSW appears to offer a number of advantages over conventional fusion welding techniques, such as no need for expensive consumables filler materials, good mechanical and metallurgical properties of the resultant joint, absence of solidification crack, no porosity, low distortion and less energy consumption [5]. In the beginning this emerging welding technique has been applied for aluminum [4] but later on it has been used for joining of magnesium [6], titanium [7], copper [8], and ferrous alloys [9] also.

Principle of Operation:

A non-consumable cylindrical-shoulder tool, with a threaded/unthreaded probe (pin) is rotated at a constant speed and is inserted/plunged in-between the two separate work piece sheets or plates to be joined and subsequently fed at a constant rate along the joint line shown in figure 1.3.

The tool serves mainly three functions: (i) Softening of material arising from heating of the work piece, (ii) movement of material or plastic deformation of material to produce the joint, (iii) forging of the hot material behind the tool shoulder [4-5]. Heat is generated within the work piece and tool due to friction between the rotating tool shoulder and pin with work piece and by severe plastic deformation of the work piece materials. Materials become soften around the pin and welding occurs while traversing along the welding direction. The main function of the non-consumable rotating tool pin is to stir the plasticized metal and move the same behind it to have sound (or defect free) joint [10]



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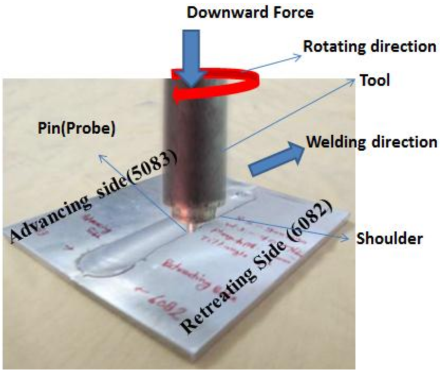


(ii)

Figure 1.3: FSW processing diagram. Ref. (i) http://katjakovanen.com/Slavic-force-and-friction-experiments-for-kids/ . (ii) Our own FSW experiment.

Advantages or Benefits of FSW

Due to the absence of parent (base) metal melting, the new FSW process is observed to offer several advantages over conventional fusion welding. Key benefits of friction stir welding with respect to the Metallurgical, Energy and Environment are listed below [5,11,12]

Metallurgical benefits

- Solid state joining process.
- Excellent mechanical and metallurgical properties in the joint region.
- Low distortion.
- Fine microstructure: Grain refinement process takes place and fine equiaxed grain is obtained.
- Absence of Hot cracking, solidification cracking and porosity.
- Residual stress is low.
- No loss of alloying elements.
- Good dimensional stability and repeatability.
- Dissimilar materials/alloys can be welded.

Energy benefits

- Improved materials-use (e.g., joining different thickness) allows reduction in weight.

- Decreased fuel consumption in light weight aircraft, automotive and ship applications.

Environmental benefits

- Expensive consumable materials such as filler, fluxes, and shielding gas are not required.
- No surface cleaning required.
- Eliminate grinding wastes.
- No harmful emissions.

There are certain limitations of FSW also and these are:

- Exit hole left when tool is withdrawn.
- Insufficient weld temperature, weld material is unable to accommodate the extensive deformation result in long, tunnel like defects.
- Large down forces required with heavy-duty clamping necessary to hold the plates together.
- Expensive equipment.

Distinct Regions of Weld Zones

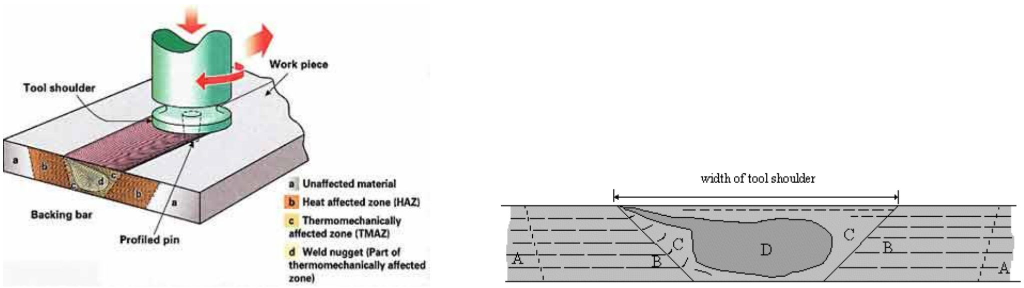
Weld zones of FSW is divided in four different regions [13,16] as shown in figure 1.4.

Weld nugget: In the central region of the weld which is fully recrystallized area and this region occupies fine equiaxed grains and, sometimes called the stir zone, refers to the zone previously occupied by the tool pin.

Thermomechanically affected zone (TMAZ): In this region, the FSW tool has plastically deformed the material, and the heat from the process will also have exerted some influence on the material and there is generally a distinct boundary between the recrystallized zone (weld nugget) and the deformed zones of the TMAZ.

Heat-affected zone (HAZ): In this region, material experience changes in microstructure and material properties from the heat of welding, but not from plastic deformation.

Unaffected material or base metal: Material may experience a thermal cycle from the weld but is unaffected in terms of structure or material properties.



(i) **(ii)**

Figure 1.4: Different regions of welded zones. Ref. (i) http://www.twi.co.uk, (ii) http://materialteknologi.hig.no/Lettvektdesign/joining%20methods/joining-welding-friction%20stir%20weld.htm

Welding Parameters and Their Role in Welding:

There are mainly three factor responsible for sound weld joint as shown in Figure 1.5.

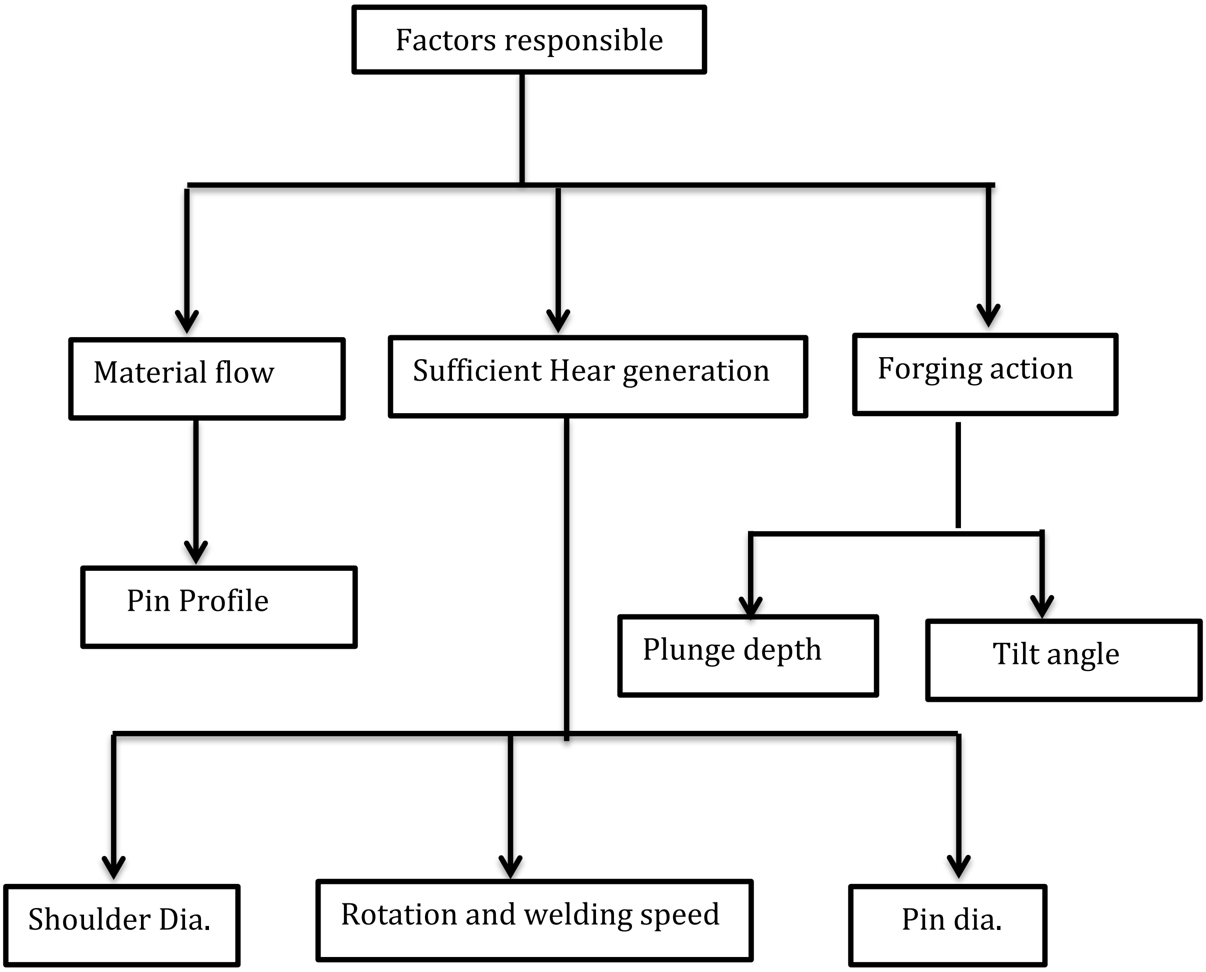


Figure 1.5: Factor responsible for a defect free joint

Heat generation:

During FSW, heat is generated within the work piece and tool due to friction between the rotating tool shoulder and pin with work piece and by severe plastic deformation of the work piece material. Heat generation is influenced by the weld parameters, weld tool geometry, thermal conductivities of the work piece materials, and backing anvil. Welding parameters responsible factor for heat generation are rotation and welding speed, shoulder diameter, plunge depth. Generally hot welds are produced with high rpm and low travel speed, and cold welds with low rpm and high travel speeds. For defect free weld we need sufficient heat generation. If the material is cold then voids or other flaws may be presented in the stir zone and in extreme cases the tool may break. At other end of the scale excessive heat input may be detrimental to the final properties of the weld [12,14].

Mainly frictional heat is generated between tool shoulder and work piece but some amount of heat also generate between the pin tool and the work piece due to friction or plastic deformation, depending on whether slide or stick conditions prevail at the interface. The amount of heat input from deformational heating around the pin tool has been estimated in the range from 2% to 15%.

Material Flow:

The localized heating softens the material around the pin and combination of tool rotation and translation leads to movement of material from the front of the pin to the back of the pin. However, the material flow behavior is predominantly influenced by the FSW tool profiles, FSW tool dimensions and FSW process parameters. Weld parameters, coupled with the pin tool design and materials, control the volume of metal heated, of which a portion is then swept by the mechanical working portion of the process [15].

Tool Rotation speed:

Tool rotation speed means how fast the tool is rotating. This welding parameter plays a crucial role to get a defect free joint. Tool rotation speed decides how much heat will generate during welding. . In general, if rotation speed is increased or traverse speed is decreased then heat input will increase and vice versa. If rotation speed is high it create void in the upper surface due to release of stirred material in the FSW zone but if rotation speed is less proper mixing will not take place due to lack of stirring action by tool pin.

Welding or Traverse speed:

Welding speed means how fast tool is moving along the joint line during welding. Welding speed also plays an important role in productivity of the welded joints. When the tool traveled at higher speeds, heat generation is less, which creates voids due to poor consolidation during forging of the welded materials. Generally, low transverse or welding speed results a weld with a higher strength.

Tool Design and its role in welding:

The design of the tool is a crucial factor for improvement of both the quality of the weld or resultant joint strength and the maximum possible welding speed cause progress in productivity. Tool design mainly consists of two parts shoulder and pin. During welding, major of heat is generated due to friction between shoulder and work piece during plunging of shoulder inside of work piece. This heat is help to soften the material and after softening, tool pin play a crucial role in welding. The primary function of the non-consumable rotating tool pin is to stir the plasticized metal and move the same behind it to have good joint. Pin profile plays a crucial role in material flow and in turn regulates the welding speed of the FSW process [16].

The pin generally has cylindrical plain, frustum tapered, threaded and flat surfaces. Pin profiles with flat faces (square and triangular) are associated with eccentricity. This eccentricity allows incompressible material to pass around the pin profile. Four different pin profiles are shown in figure 1.6.

Figure 1.6: Different pin profiles

Eccentricity of the rotating object is related to dynamic orbit which is the part of the FSW process. In addition, the triangular and square pin profiles produce a pulsating stirring action in the flowing material due to flat faces [17].

The square pin profile produces 60 pulses/s and triangular pin profile produces 45 pulses/s when the tool rotates at a speed of 900 rpm. There is no such pulsating action in the case of cylindrical, tapered and threaded pin profiles. The higher number of pulsating action experienced in the stir zone of square pin profile produces very fine microstructure and in turn yields higher strength and hardness [3,12].

Welding Forces:

There are a number of forces that act on the tool during welding and are given below [16]:

- **(i)** **Downwards force:** A *downwards force* is essential to maintain the position of the tool at or below the material surface. This force is increase when tool is plunged into the materialor mainly when shoulder touches the work piece.
- **(ii)** **Traverse force:** The *traverse force* acts parallel to the tool motion and is positive in the welding direction. Since this force arises as a result of the resistance of the material to the motion of the tool
- **(iii)** **Lateral force:** The lateral force may act perpendicular to the tool traverse direction and is defined here as positive towards the advancing side of the weld.
- **(iv)** **Torque:** Torque is required to rotate the tool, the amount of which will depend on the downward force and friction coefficient (sliding friction) and/or the flow strength of the material in the surrounding region (sticking friction).

Plunge Depth:

Plunge depth is a crucial parameter for ensuring weld quality. The plunge depth is defined as the depth of the lowest point of the shoulder below the surface of the weld plate and this helps to ensure sufficient forging of the material at the rear of the tool [18] as shown in figure 1.7.

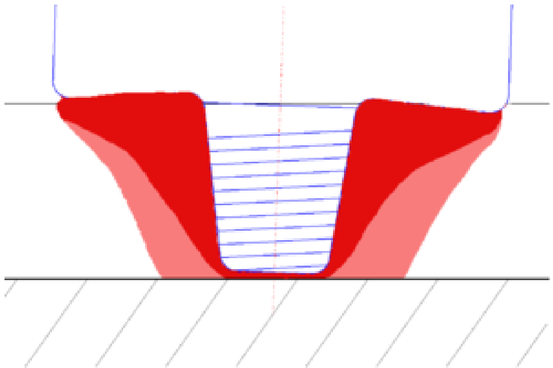


Figure 1.7: Plunge depth in FSW process. Ref. [http://sttechnica.blogspot.in/2011/04/weldment-technology-friction-stir.html]

Tool Tilt: Tilting the tool by 2-3 degrees, such that the rear of the tool shoulder is lower than the front and it has been found to assist this forging process [18]. Tilting of tool is shown in figure 1.8.

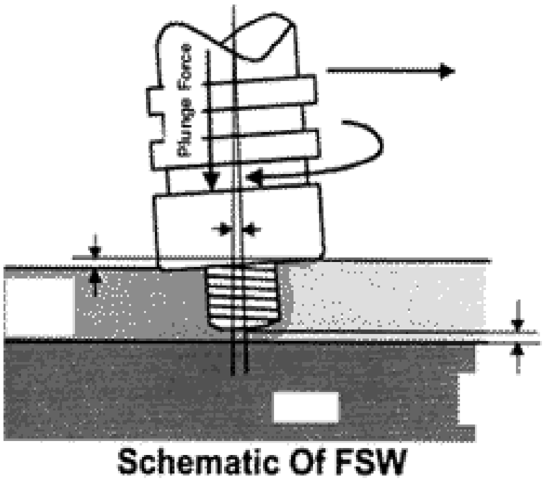


Figure 1.8: Schematic diagram of FSW. [http://www.aws.org/itrends/07-02/feature2.html

Dwell:

This is the time when tool is only rotating at a constant speed into the work piece material to generate a sufficient heat to soften the material before it to move in the direction of welding

Chapter 2

Literature Survey on FSW of Aluminum Alloys:

Before the invention of FSW in 1991, it was difficult to weld some of aluminum alloys with conventional fusion welding as it gives poor fatigue, fracture strength of these aluminum alloys due to poor solidification microstructure and porosity in the fusion zone. These alloys have limited application due to their poor weldability and fusion welding is not attractive joining process for aluminum alloys. To overcome this problem The Welding institute invented a new joining technique with a name Friction Stir Welding in 1991 in Cambridge, England. A US patent for ***FSW***, # 5,460,317, was filed in November 1992 with W. H. Thomas et al as inventors, assigned to TWI [4, 16].

Friction Stir Welding is an emerging, energy efficient and ecofriendly solid state joining process. Solid state joining means welding occurs below the melting temperature; generally temperature reach 80% of the melting temperature because of this solid state nature a high-quality weld is created. This characteristic greatly reduces the ill effects of high heat input, including distortion, and eliminates solidification defects. Friction stir welding also is highly efficient, produces no fumes, and uses no filler material, which makes this process environmentally friendly [16].

Initially this joining process applied on aluminum alloys but the rapid development of the FSW process in aluminum alloys and its successful implementation into commercial applications has motivated its application to other metals such as magnesium (Mg) , copper (Cu), titanium (Ti), ferrous alloys even thermoplastics. However, there is a high challenge for welding of high temperature materials such as Titanium and steel because of requirement of efficient tool material for welding [4-9].

Welding of two dissimilar aluminum alloys by conventional fusion welding is not desirable because of poor weldability due to difference in chemical, mechanical, thermal properties of welded materials and formation of hard and brittle intermetallic phases in large quantity, leading to decrease in mechanical strength of the welded joint [19]. So this problem is overcome by the invention of Friction Stir Welding because FSW is solid state joining process so welding is mainly occurs by deformation of materials below melting temperature.

Table given below shows the overview of the welding of two dissimilar alloys or metals by FSW [5].

Table 2.1

A summary of dissimilar alloys/metals FSW

Materials	Plate thickness (mm)	Rotation rate (rpm)	Traverse speed (mm/min)	References
2024Al to 6061Al	6.0	400–1200	60	[10,38,220]
6061Al to 2024Al	12.7	637	133	[36]
2024Al to 1100Al	0.65	650	60	[215]
5052Al to 2017Al	~5.3, 3	1000, 1250	60	[79,221]
7075Al to 2017Al	~5.3, 3	1000, 1250	60	[79,221]
7x1xAl (Sc) to 7x5xAl (Sc)	~5.3	1000	60	[221]
7075Al to 2017Al	3	1250	60	[79]
7075Al to 1100Al	3	1250	60	[79]
5083Al to 6082Al	5.0	–	170–500	[222]
2024Al to D357	–	–	–	[223]
6061Al to A356	4.0	1600	87–267	[225,226,228]
2024Al to 7075Al	25.4	150–200	76.2–127	[227]
20 vol.% Al_2O_3/6061Al to 10 vol.% SiC/A339	6.5	800	60	[215]
20 vol.% Al_2O_3/2014Al to 2024Al	4	1120	120	[224]
6061Al to copper	6.0	400–1200	60–180	[37,220]
2024Al to copper	6.5	650	60	[215]
2024Al to silver	6.0	650	60	[9]
Copper to brass	6.2	1000	60	[221]
1050Al to AZ31	6	2450	75	[229]
6061Al to AZ31B		800	75	[230]
6061Al to AZ91D		800	75	[230]
AZ91D to AM60B		2000	75	[230]
5083 Al to mild steel	2	100–1250	25	[231]
6061Al to AISI 1018	6	914	140	[232]

In FSW of dissimilar aluminum alloys, Peel et al. [20] used only one kind of pin profile (cylindrical threaded) for welding and this paper help to reach the optimization parameters and show that the possibility of the welding of two dissimilar aluminum alloys (AA 5083-AA 6082). They noticed minimum hardness is the location of fracture in the tensile test and this is the heat affected Zone (HAZ) and minimum hardness is because of coarsening of precipitate due to over aging.

In the FSW studies with different profiles, Elangovan et al. [17] used five kind of different pin profiles such as straight cylindrical, cylindrical taper, cylindrical threaded, triangular, square etc. on AA 6061 and observed the effect of all five different pin profiles.

In another investigation on the effect of tool shape on mechanical properties and microstructure of aluminum alloys by H. Fuji et.al. [21]. They used three types of pin profiles straight cylindrical, threaded cylindrical and triangular prism shape probes to weld three types of aluminum alloys 1050-H24, 6061-T6 and 5083-O.

In FSW of dissimilar aluminum alloys, R.PALANIVEL et al. [22] used five types of tool pin profiles straight cylindrical, threaded cylindrical, square, tapered square, and tapered octagon and investigate the effect on mechanical and metallurgical properties of dissimilar AA6051- AA5083H111.

Objectives

In this study, authors studied the feasibility of FSW joining of Al 5083 and Al 6082 sheets using different pin profiles: straight cylindrical (Cy), threaded cylindrical (Th), triangular (Tr) and square (Sq) and investigations are performed on the welds to study the pins profiles effects on microstructure, hardness, texture and tensile strength of welded joint dissimilar Al alloy (AA5083 and AA6082).

Chapter 3

Equipment's Used

3.1 Lathe Machine:

A **lathe Machine** (as shown in figure 3.1) is a machine tool which rotates the work piece on its axis to perform various operations such as cutting, knurling, drilling, or deformation with tools that are applied to the work piece to create an object which has symmetry about an axis of rotation. I used for the purpose to fabricate cylindrical shoulder tools.

Figure 3.1: Lathe Machine used for tool fabrication

3.2 Cut Saw:

A **saw** is a tool that uses a hard blade, or wire with a toothed edge to cut soft materials as shown in figure 3.2. We used electricity powered saw to cut the required size of work piece from a large sheet.

Figure 3.2: Saw used for cutting work piece from sheet.[http://www.mcfeelys.com/tech/ftplungecutsaws.htm]

3.3 Milling Machine:

A **milling machine** is a machine tool used to machine solid materials as shown in figure 3.3. The milling machine removes metal with a rotating cutting tool called a milling cutter. Milling machines can be used for boring, slotting, circular milling dividing, and drilling. I used this machine for sample facing and fabrication of tool pin profiles by the help of indexing. This machine can also be used for cutting keyways, racks and gears and for fluting taps and reamers.

(a)

(b)

Figure 3.3: Milling Machine used to prepare sample and tool (a) NC milling (IIT Hyderabad). (b) Manual control in IISc Banglore

3.4 Belt emery:

Belt emery is a mechanical grinding machine to remove the extra scrap which came after the milling of work piece sample. This machine consists of a belt of abrasive material as shown in figure.

Figure 3.4: Belt emery Machine used for grinding

3.5 ETA Friction Stir Welding (FSW) Machine:

This machine provides a rotation speed in the range between 70rpm to 3000rpm and traverse speed range between 0.1mm/min to 2000mm/min with up to 100KN axial force as shown in figure 3.5. Generally, FSW machines have vertical axis like as milling machine but we used horizontal axis CNC FSW machine. In this machine we can control three axis moments according to our requirement to get an appropriate condition for welding.

Figure 3.5: Friction Stir Welding (FSW) Machine

3.6 Cutting Machine:

Secotom (precision cutting) performs precise and fast deformation-free cutting for all types of materials like metals, ceramics, biomaterials, minerals as shown in figure 3.6. I used this machine to transverse section of the welded sample of dimension of 50 mm x10mm x6 mm.

Figure 3.6: Precise Cutting Machine

3.7 Grinding machine:

Grinding machine requires SiC grinding papers (180-500 Grit) which are rotated on a wheel (~300-800 rpm) and the sample is pushed face down while cooled and cleaned with water as shown in figure 3.7. Small SiC particles are glued to the grinding paper so these are also sometimes called fixed abrasives. While rotated these particles slowly remove chips from specimen surface.

Figure 3.7: Mechanical grinding machine

3.8 Polishing machine:

This polishing machine is same as grinding except the abrasive particles are loose and no water cooling is performed as shown in figure 3.8. Diamond suspension having particles 1 -

9μm diameter are used. This is an automatic polishing machine in which diamond suspension particles is supplied automatically according to the need.

Figure 3.8: Automatic polishing machine

3.9 Electropolishing and Etching:

STRUERS LectroPol-5 ® machine as shown in figure 3.9. is used for electropolishing of the cross section of the welded sample for EDSB. The FSW specimens were electropolishing with a mixture of 30 pct nitric acid in methanol, for 15 to 25 seconds at 12V and etched with Keller's regent.

Figure 3.9: Electro polishing machine

3.10 Optical Microscope:

The **optical microscope**, which often referred to as the "**light microscope**", is a type of microscope which uses visible light and a system of lenses to magnify images of small samples. I used hot stage automated upright microscope (Leica DM 6000M) as shown in figure 3.10.

Figure 3.10: Optical microscope

3.11 Vickers Micro hardness:

Micro hardness testing of metals, ceramics, and composites is useful for a variety of applications for which 'macro' hardness measurements are unsuitable. The term micro hardness test usually refers to static indentations made with loads not exceeding 1 kgf. Dura Scan 20 Emco- Test Vickers hardness with diamond pyramid shaped indenter was used and is shown in Figure 3.11.

Figure 3.11: Vickers microhardness

3.12 Electron Backscattered Diffraction (EBSD) attached in Scanning Electron Microscopy (SEM):

EBSD is a microstructural-crystallographic characterization technique used to examine the crystallographic orientation of crystalline materials, used to determine their texture or preferred orientation. I performed this on FEI Quanta-200HV SEM as shown in figure 3.12. A source of electron beam (from few 100 volts to 30 eV) when focused on a thick crystalline material, electron backscattered diffraction pattern also called Kikuchi pattern is generated which is then acquired by the camera and matched with the computer generated Kikuchi pattern of the input crystal system specification by the software and the crystal orientation is determined. When this step is repeated after regular interval of distance while scanning over the specimen surface, an orientation image map containing variety of crystallographic details is obtained.

Figure 3.12: SEM-EBSD

3.13 MTS Tensile Machine:

The **MTS Load Frame with** hydraulic operating machine is utilized for tensile, compressive and fatigue loading and is shown in Figure 3.13. Welded specimen of dog bone shape is fixed in the clamping device.

Figure 3.13: MTS Tensile machine

Chapter 4

Experimental procedure

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.

Table 4.1. 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

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 figure 2. After the manufacturing of all, tools are oil hardened up to a hardness of 48HRc to 52HRc.

Figure 4.1: 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 3. 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 4.2.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 electropolishing according to the requirements. The FSW specimens were etched with Keller's regent and electropolishing 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.

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.

Orientation Image Microscopy (OIM) is used for microstructural evaluation for pole figures, inverse pole figures and average grain size (obtained by the area fraction method determination) is determined.
Dog bone shaped tensile test specimens are prepared perpendicular to the welding direction by the help of wire EDM and tested is on MTS machine with a strain rate of 0.001/sec.

Chapter 5

Results

Variation in torque, downward force and welding position vs time:

Figure 5.1 given below shows, how downward force, torque, x- and z- position varies according to time during welding.

Variation in downward force and torque: As pin started to plunge in between the work piece, downward force and torque increased due to resistance of the material to deform but as pin reached inside the material, it become soft then downward force and torque decreased in some amount but as tool shoulder touch the work piece force and torque again increased and after some time material become soft and force and torque become constant for the remaining time.

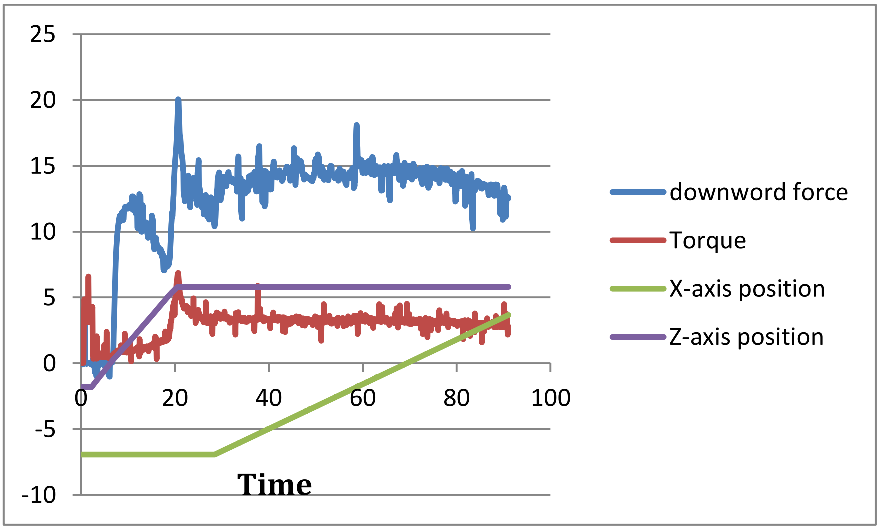


Figure 5.1: Variation in torque, downward force and welding position vs time:

Variation in x and z- axis positions:

At first all tools start moving down in z-direction for plunging and after the dwell time the tool moves in x- direction for welding, which is called welding direction.

Orientation Image Microscopy (OIM) images and Inverse pole figure (IPF) of base materials:

The orientation images of the two base materials on plane perpendicular to welding direction with their inverse pole figures of the base materials parallel to the tensile direction (TD) with the scale bar are shown in Figure 5.2 (a) and (b) respectively.

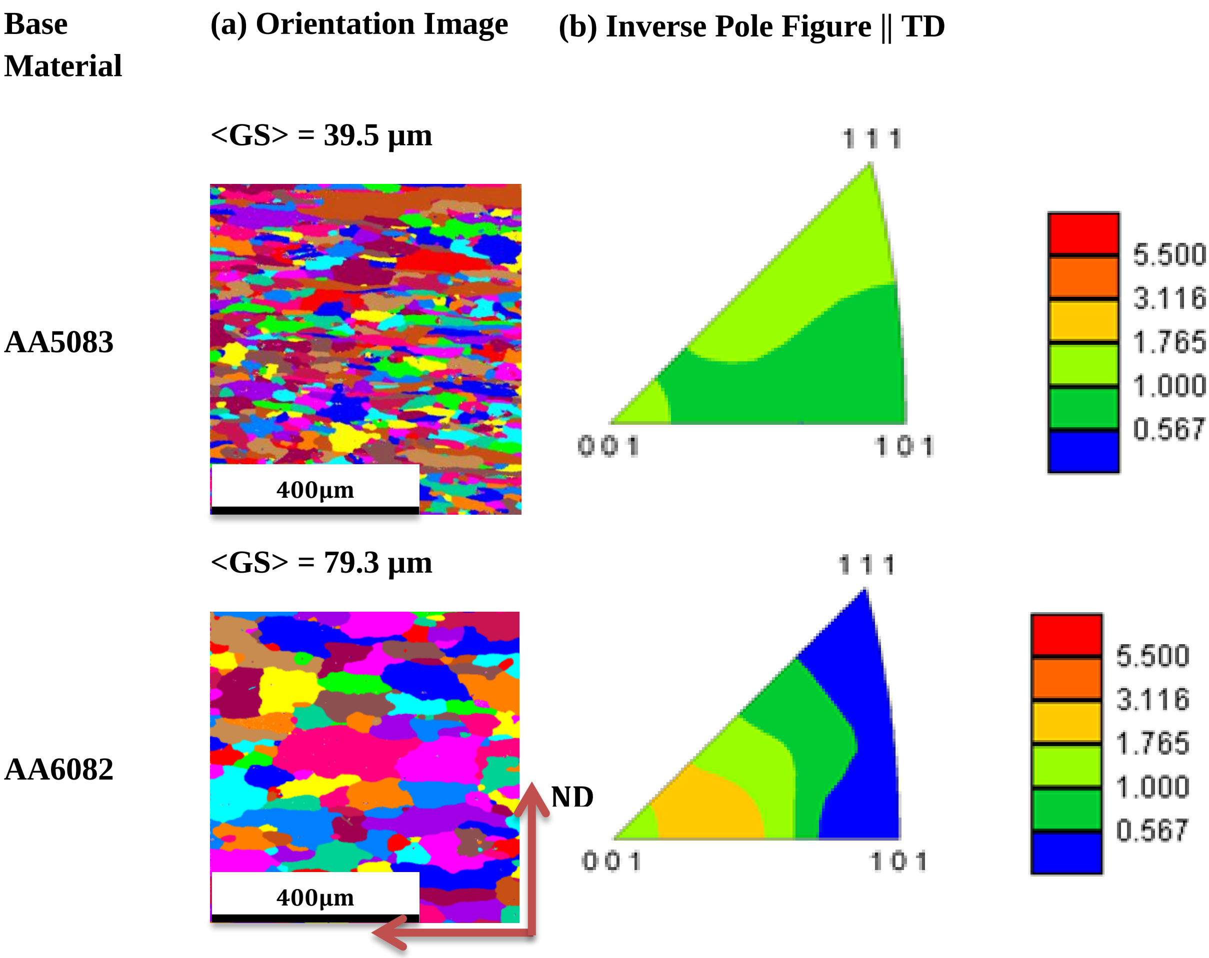


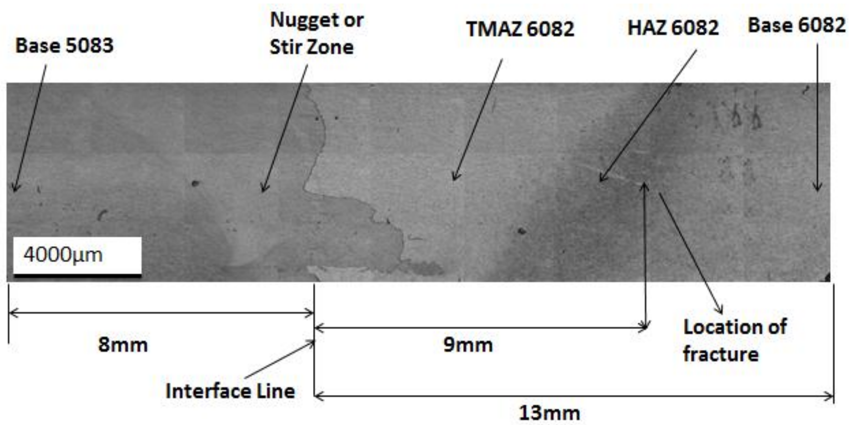
Figure 5.2. (a) Orientation image of base materials on the plane perpendicular to the welding direction. (b) Inverse pole figure (IPF) of the base materials parallel to the Tensile Direction (TD) with the scale bar. Their average grain sizes are also mentioned.

Average grain sizes of 39.5 µm and 79.3 µm are found in AA 5083 and AA 6082 respectively. Aluminum 5083 alloy has texture components TD(tensile direction)||<001> and TD||<112> to <111>. Whereas, AA 6082 base alloy contained crystallographic directions from <103> to <113> parallel to the TD.

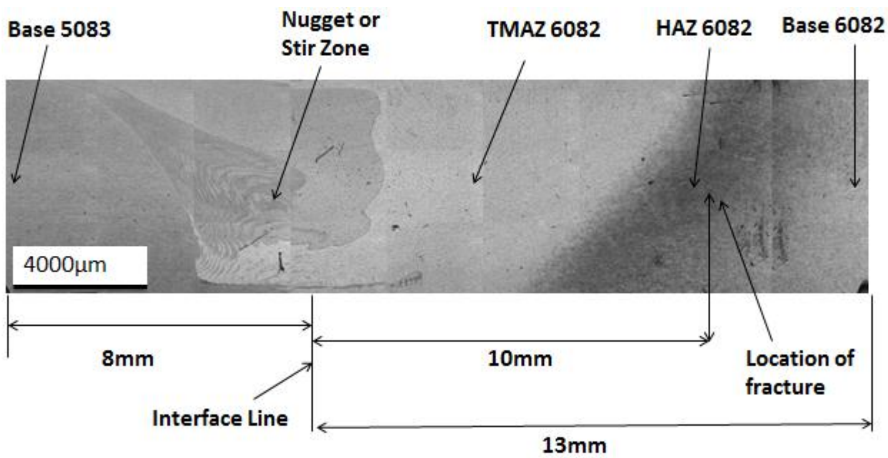
Optical micro-graphs of the welded sample for all four different pin profiles:

The optical images of the FSW specimens joined with four different pin profiles are given in Figure 5.3. The optical image of the welded zone is divided mainly into four different regions: nugget or stir zone, thermomechanically 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.

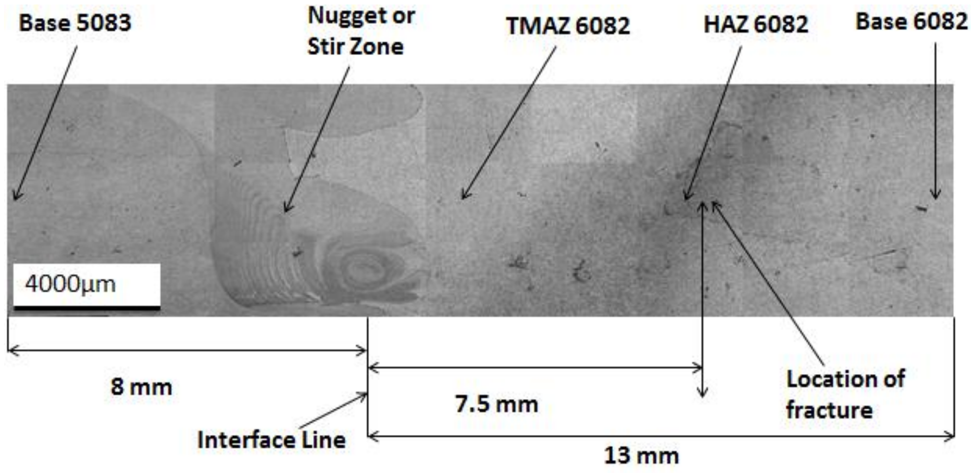
Creating edges in the pins, it's static to dynamic ratio increases i.e. decrease in the contact area with the work piece but in turn increase in the pulsating stirring action [8]. Hence, the triangular and the square pin welded specimens are expected to generate lower distance HAZ from the nugget zone than the cylindrical and the threaded cylindrical welded specimens.



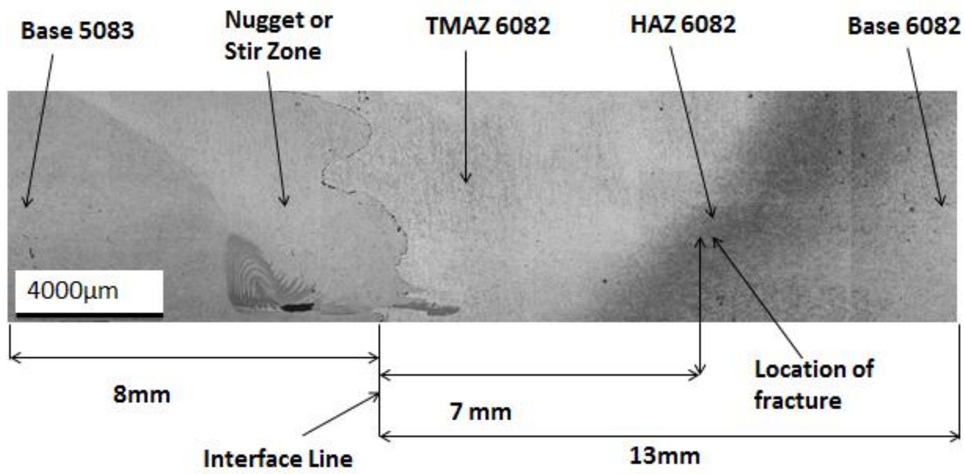
(a) Cylindrical Pin



(b) Threaded Pin



(c) Triangular Pin

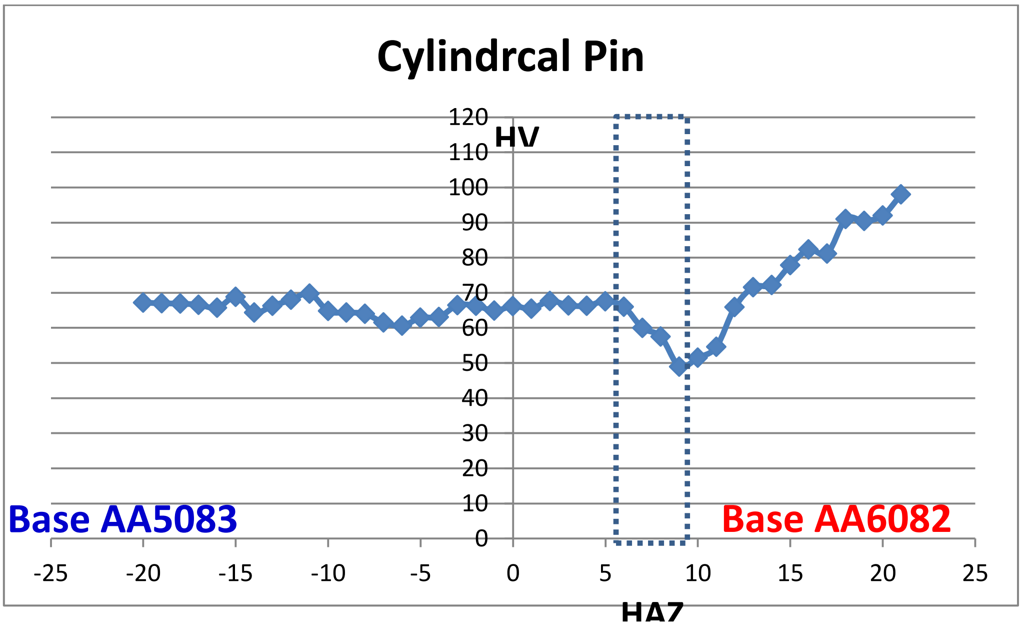


(d) Square Pin

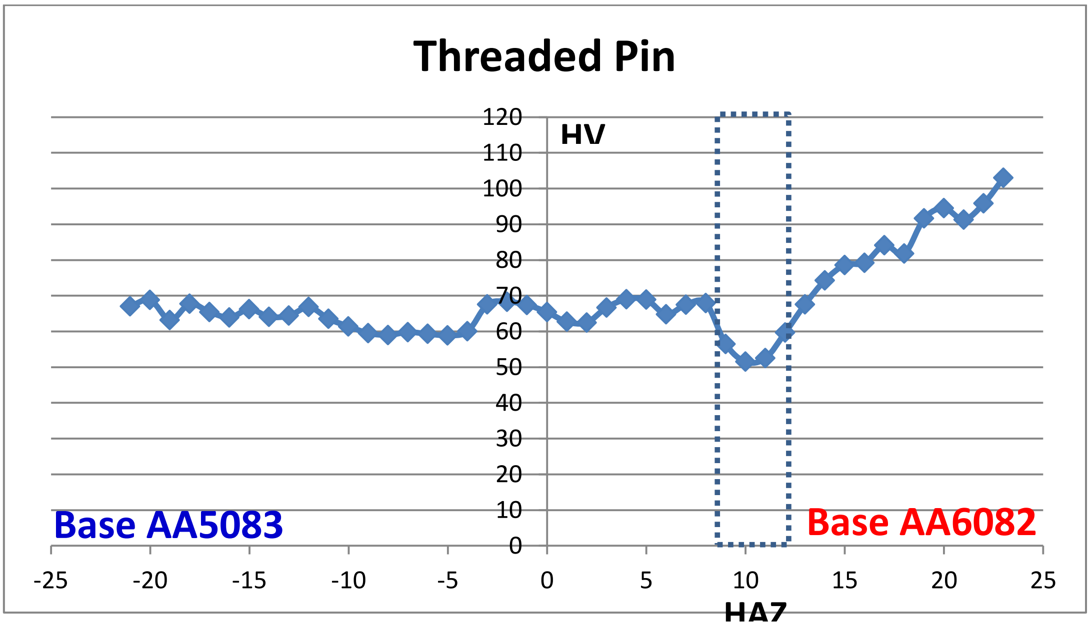
Figure5.3: Optical images of welded samples with distinct regions with distance of fracture from interface line for (a) Cylindrical pin (b) Threaded pin (c) Triangular (d) Square.

Vickers micro-hardness test profile for different pins:

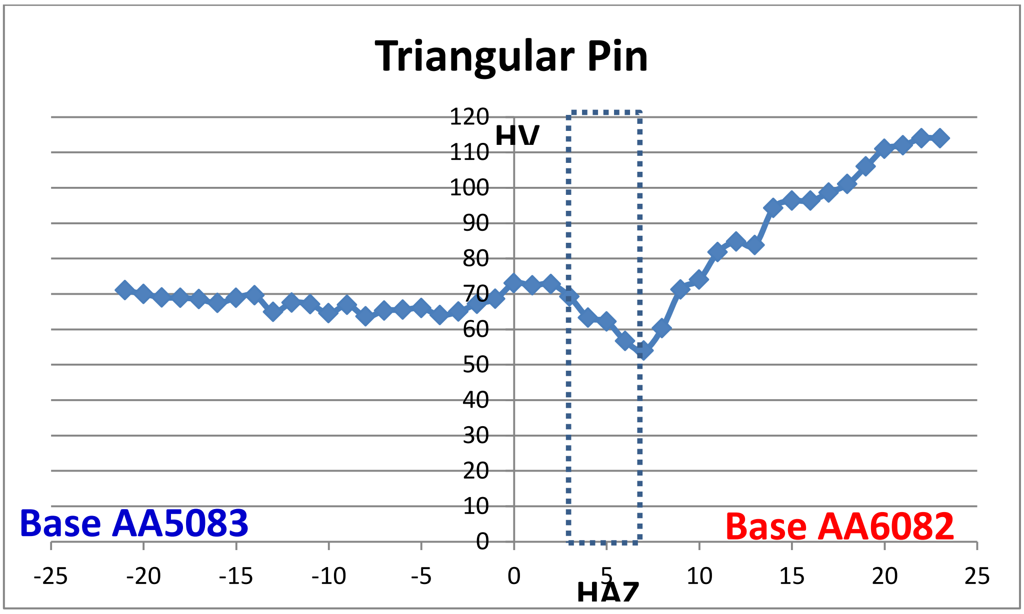
Their micro-hardness profiles for all four different pins in the transverse section are given in Figure 5.4. There is less variation noted in the hardness profile of AA 5083 side. The base material AA5083 has hardness of 75HV and has not varied towards the nugget zone. This might be due to the annealed 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 Figure 5.4). The base material AA 6082 has hardness of 110HV.



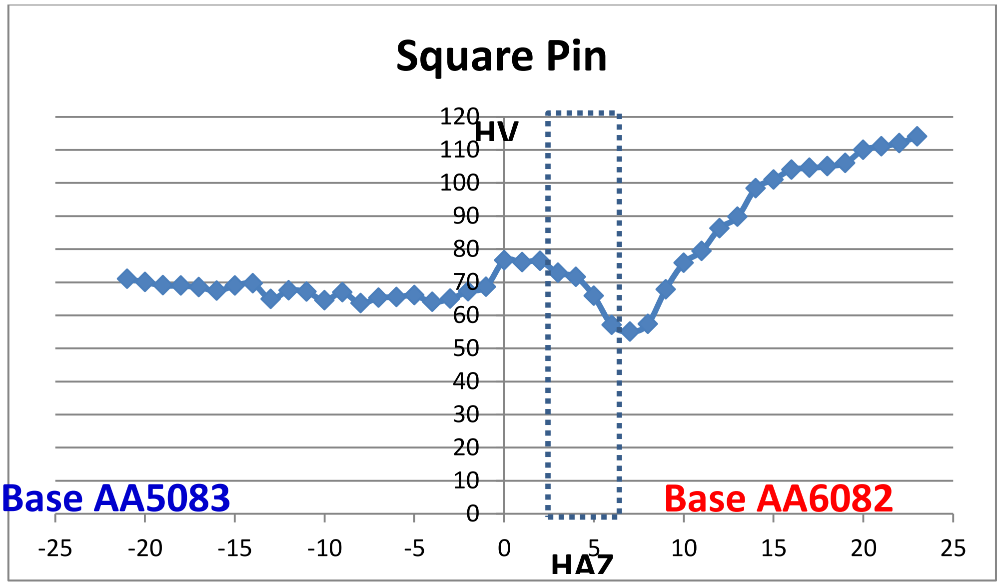
(a) Cylindrical Pin Profile



(b) Threaded Pin Profile



(c) Triangular Pin Profile



(d) Square Pin Profile

Figure5.4: Vickers micro-hardness for all four different pin profiles (a) Cylindrical (b) Threaded (c) Triangular (d) Square

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

Combined micro-hardness profiles for all four different pin profiles are given in figure 5.5. 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.

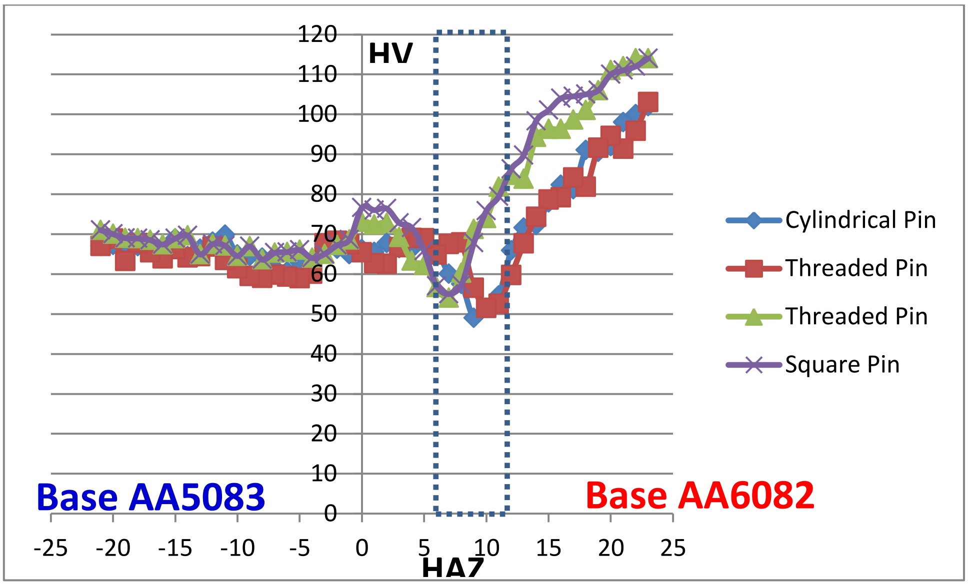
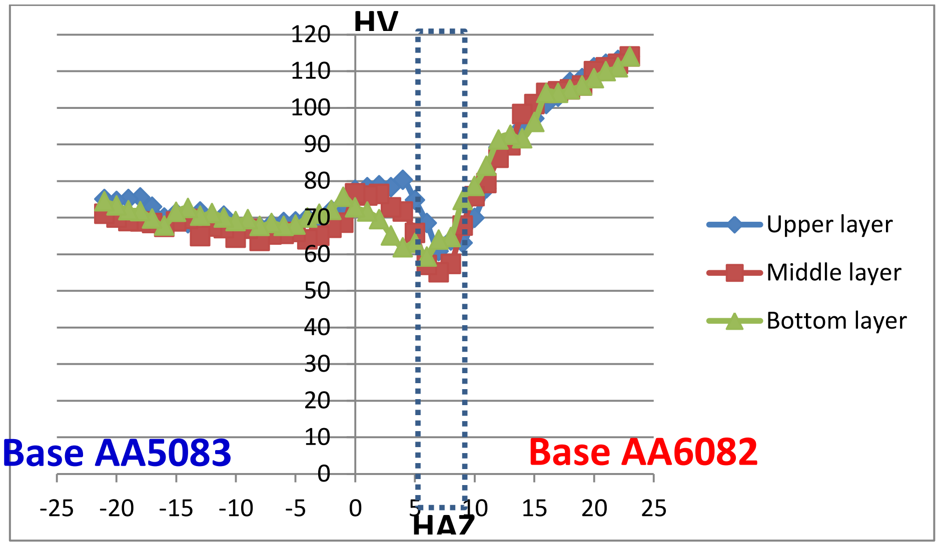


Figure 5.5: Combined micro-hardness profile for all four pin profiles

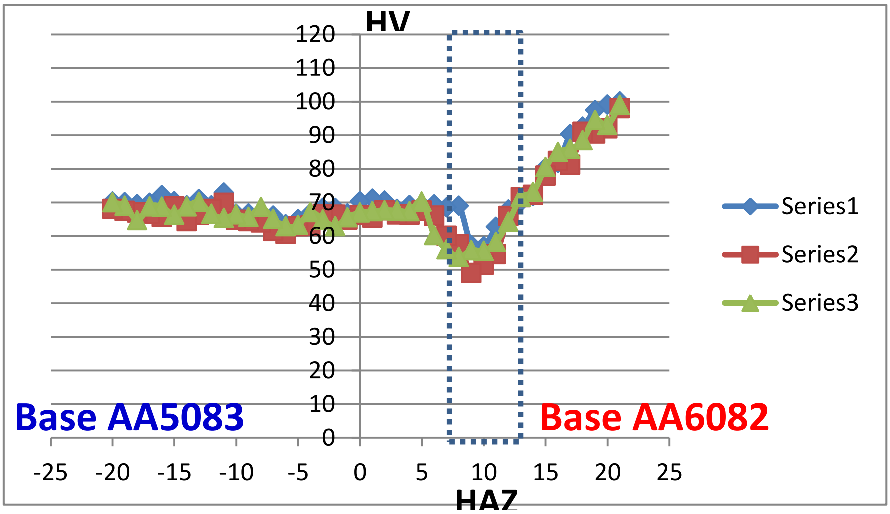
It can be seen that for all the four specimens the minimum hardness is obtained in between 7 mm to 10 mm from the center of the nugget zone depending on the pin profile used (Figure 5.5). For straight cylindrical and threaded cylindrical pin welded specimens the minimum hardness is located between 9 to 10 mm but for triangular and square pin welded specimens the minimum hardness is obtained between 7 to 7.5 mm.

Hardness along the thickness in the transverse section:

Hardness along the thickness in the transverse section for square and cylindrical pin profiles are shown in figure 5.6. 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. 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.



(a) Square pin profile



(b) Cylindrical pin profile

Figure 5.6: Hardness along the thickness in the transverse section for (a) Square and (b) Cylindrical pin profile

Orientation Image Microscopy (OIM) images for all four different welded samples:

OIM images from the nugget zone and the heat affected zone (HAZ) in the transverse section are also given in Figure 5.7. Their noticed grain refinement with decreased grain size in the nugget zones of all the four specimens suggesting better joining strength. In all welded samples, square pin welded specimen generating smallest grain size microstructure in the nugget zone (due to more number of sides and pulsating stirring action).

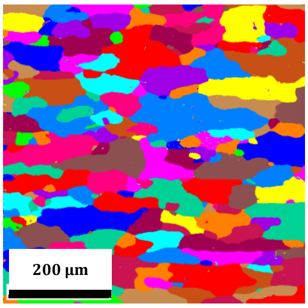
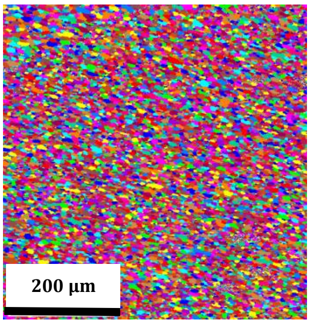
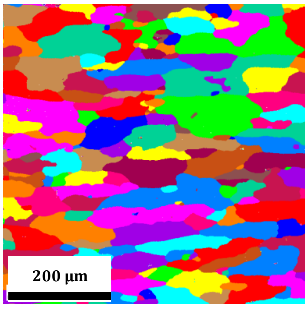
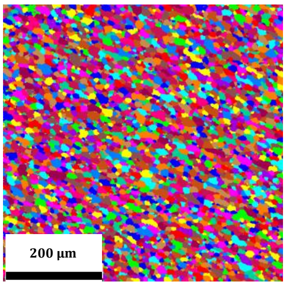
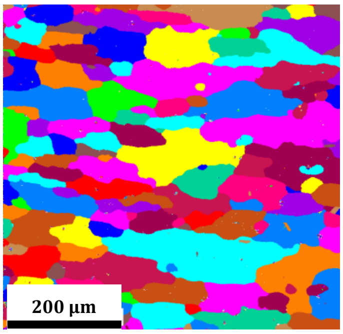
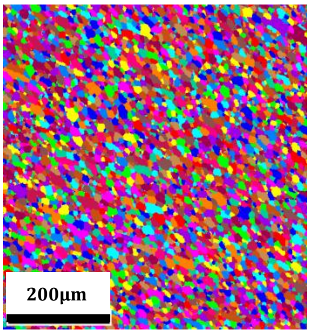
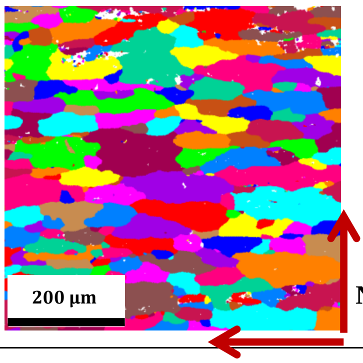
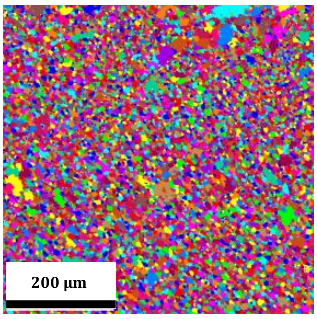
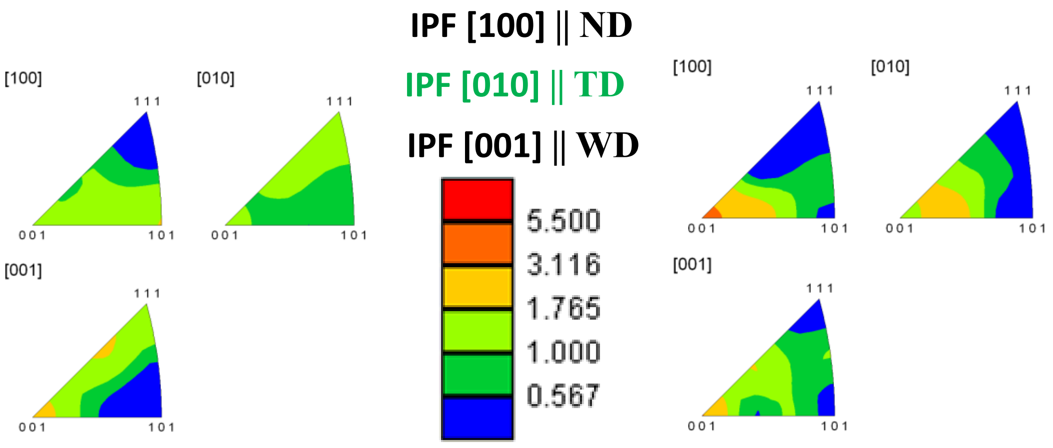
HAZ region Microstructure(a)	Nugget zone Microstructure(b)
Cy; <GS> = 72.42 µm 	**Cy; <GS> = 10.28 µm** 
Th; <GS> = 71.01 µm 	**Th; <GS> = 14.24 µm** 
Tr; <GS> = 76.47 µm 	**Tr; <GS> = 13.51 µm** 
S; <GS> = 66.73 µm 	**S; <GS> = 9.00 µm** 

Figure 5.7: OIM maps of welded joints at (a) HAZ (b) Interface.

Texture analysis:

Crystallographic texture (inverse pole figure) for base materials:

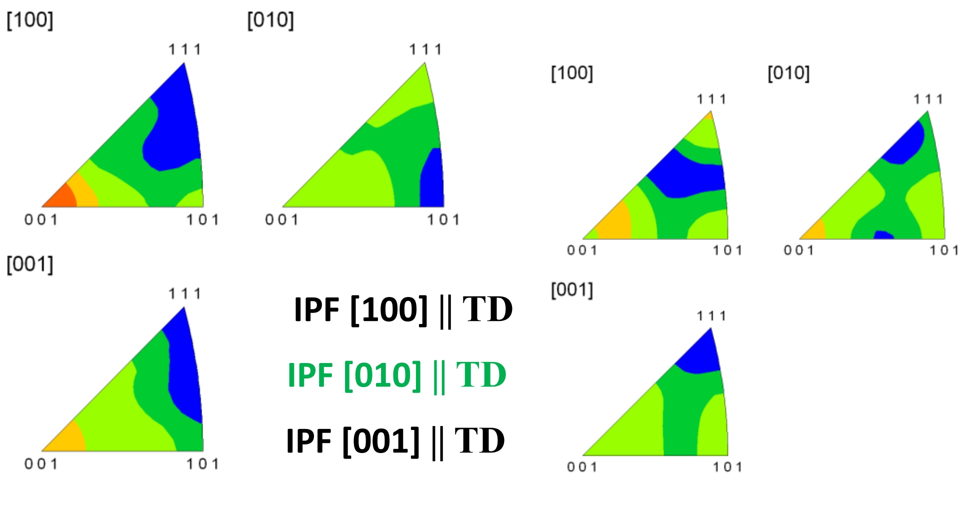


(a) AA 5083-IPF **(b) AA 6082-IPF**

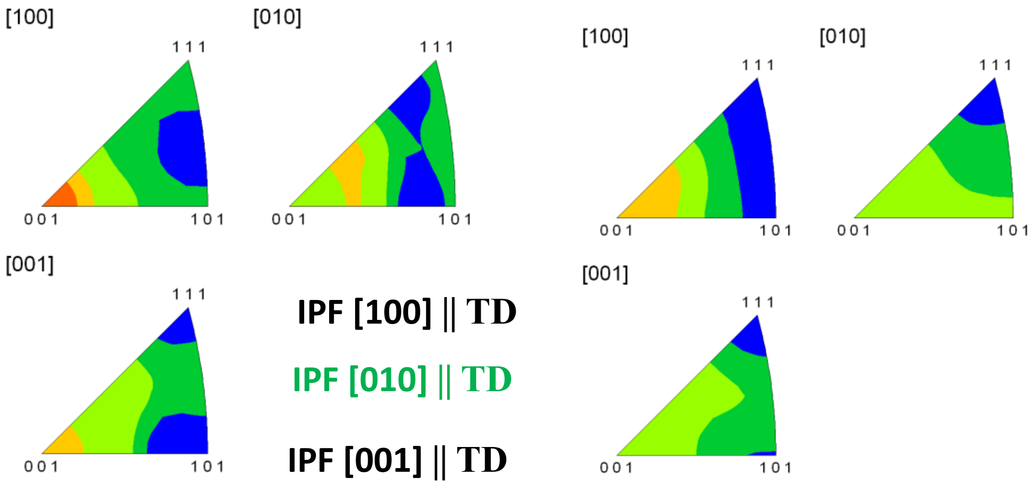
Figure 5.8: the inverse pole figures (IPF) of base materials on the plane perpendicular to the welding direction (TD- ND plane) (a) AA 5083 (b)AA 6082 with IPF color scale bar.

Inverse pole figure for all four different pin profiles:

Microstructural characterization is performed through Electron Backscattered Diffraction (EBSD) at the location of minimum hardness which falls in the HAZ of welded sample for all four different pin profiles. The inverse pole figures were evaluated by orientation image microscopy (OIM) and are shown in figure 5.9.



(a)Cylindrical **(b)Threaded**



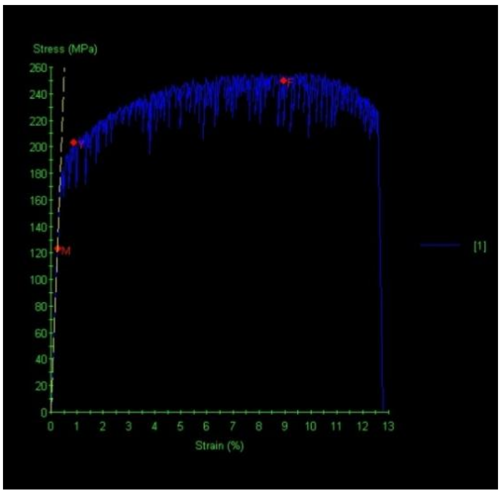
(c)Triangular (d)Square

Figure 5.9: the inverse pole figures (IPF) on the plane perpendicular to the welding direction (TD- ND plane) at the HAZ in the AA 6082 side for (a) Cylindrical (b)Threaded (c) Triangular (d)Square with same color scale bar as in figure 5.8.

Tensile Tests:

Base Material AA 5083 and AA 6082:

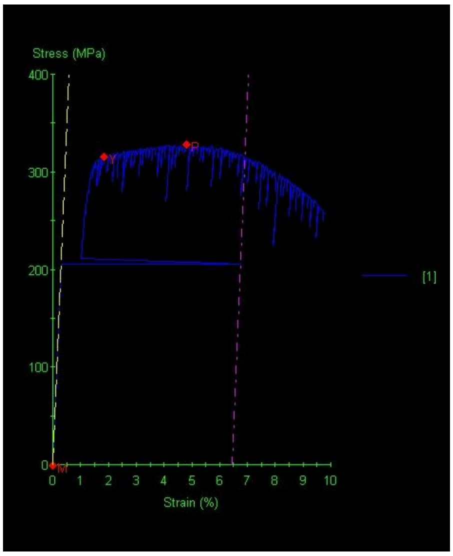
The various tensile values obtained from the base materials (AA 5083 and AA 6082) and given below in Figure 5.10.



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

(a) Base material 5083



Specimen Results: Base material AA 6082

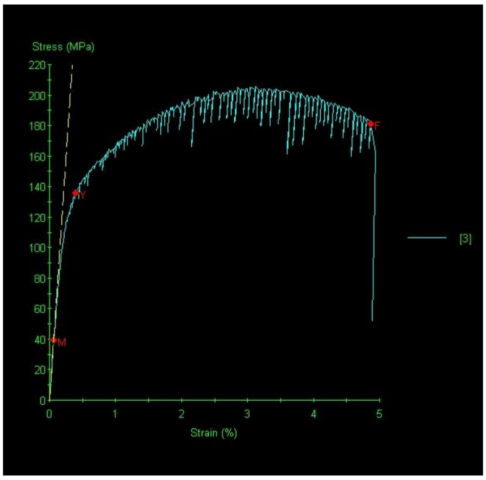
Name	Value	Units
Thickness	6.160	mm
Width	6.030	mm
Area	37.14480	mm^2
Modulus	69966.92535	MPa
Load At Offset Yield	7637.08057	N
Stress At Offset Yield	205.60295	MPa
Load At Yield	11718.66940	N
Stress At Yield	315.48614	MPa
Peak Load	12185.74969	N
Peak Stress	328.06072	MPa
Break Load	****	N
Break Stress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

(b)Base Material 6082

Figure 5.10: Tensile properties of base materials (a) AA 5083 (b) AA 6082

Tensile tests on different pin profiles specimens:

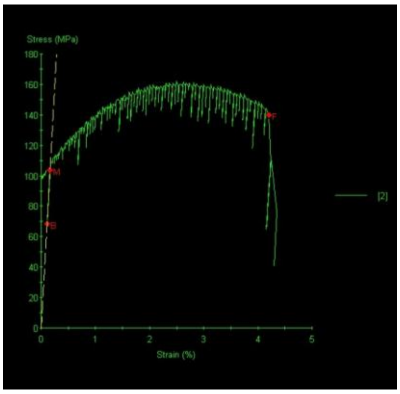
To check the strength of the welded joints, tensile tests on the four specimens are performed and are compared with the base materials. The tensile properties of the weld joints are shown in Figure 5.11 and their values are given in Table 3.



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

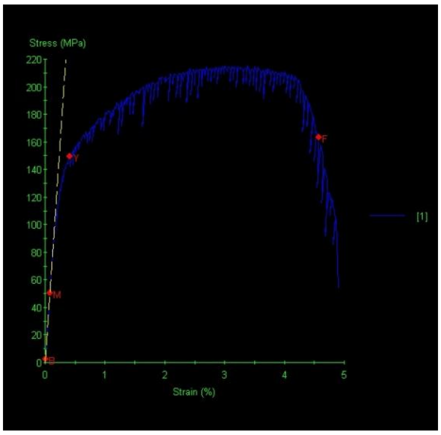
(a) Cylindrical pin



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

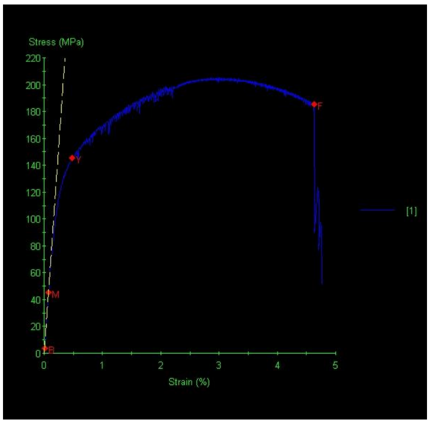
(b) Threaded pin



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

(c) Triangular Pin



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

(d) Square pin Profile

Figure 5.11: Tensile properties of four different pin profiles (a) Cylindrical (b) Threaded (c) Triangular and (d) Square

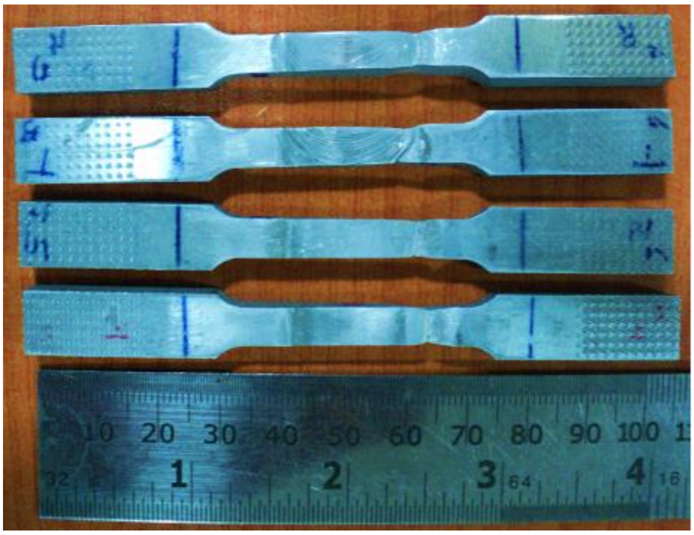


Figure 5.12: Fractured Samples after tensile test

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 5.12 shows fractured samples after tensile test.

Table 3: 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	206	136	4.86	9
Threaded	162	96	4.20	10
Triangular	215	150	4.57	7.5
Square	205	145	4.63	7

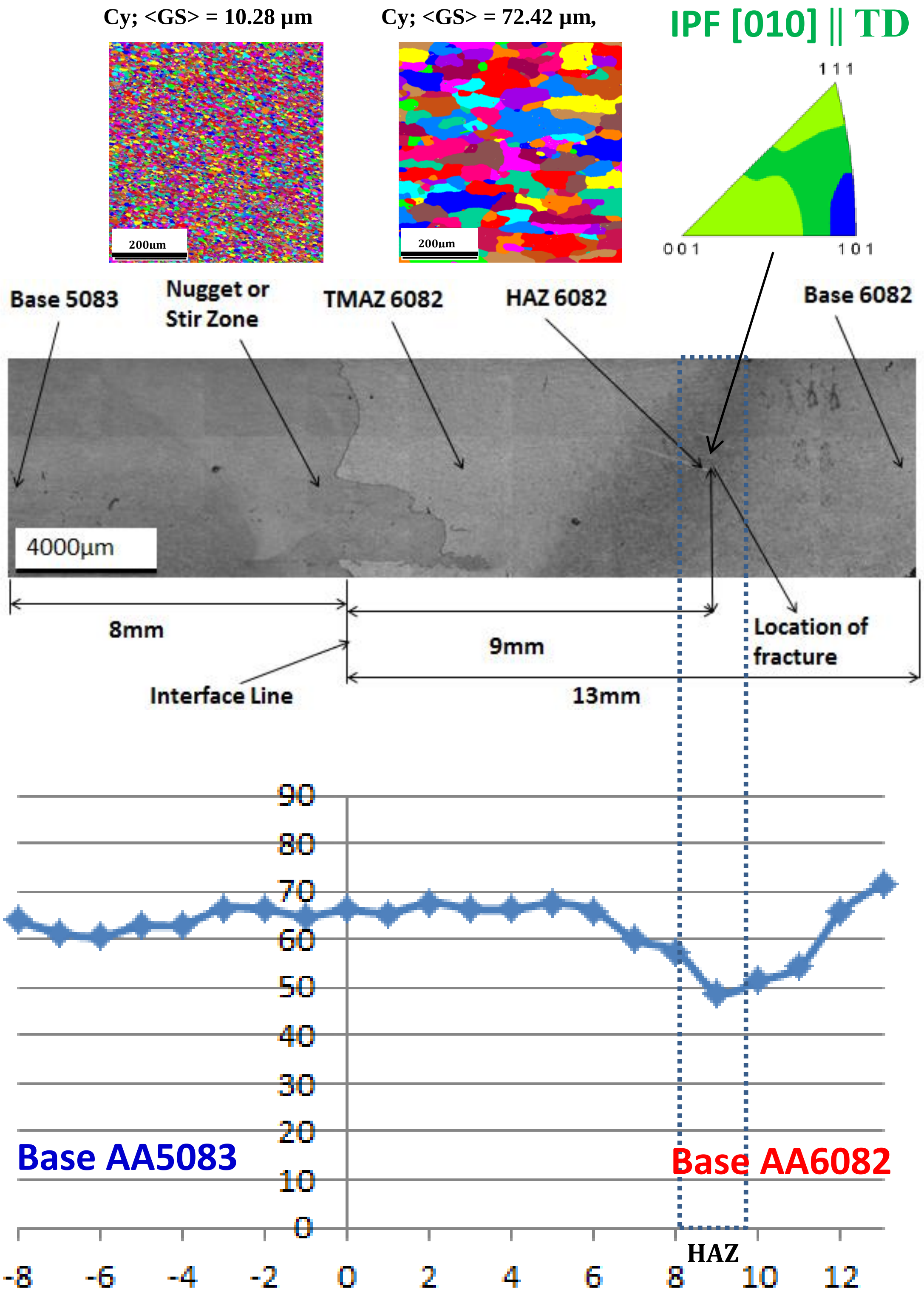
Chapter 6

Discussions

Optical micrographs with OIM images, inverse pole figure (IPF) and micro-hardness for all four different pin profiles:

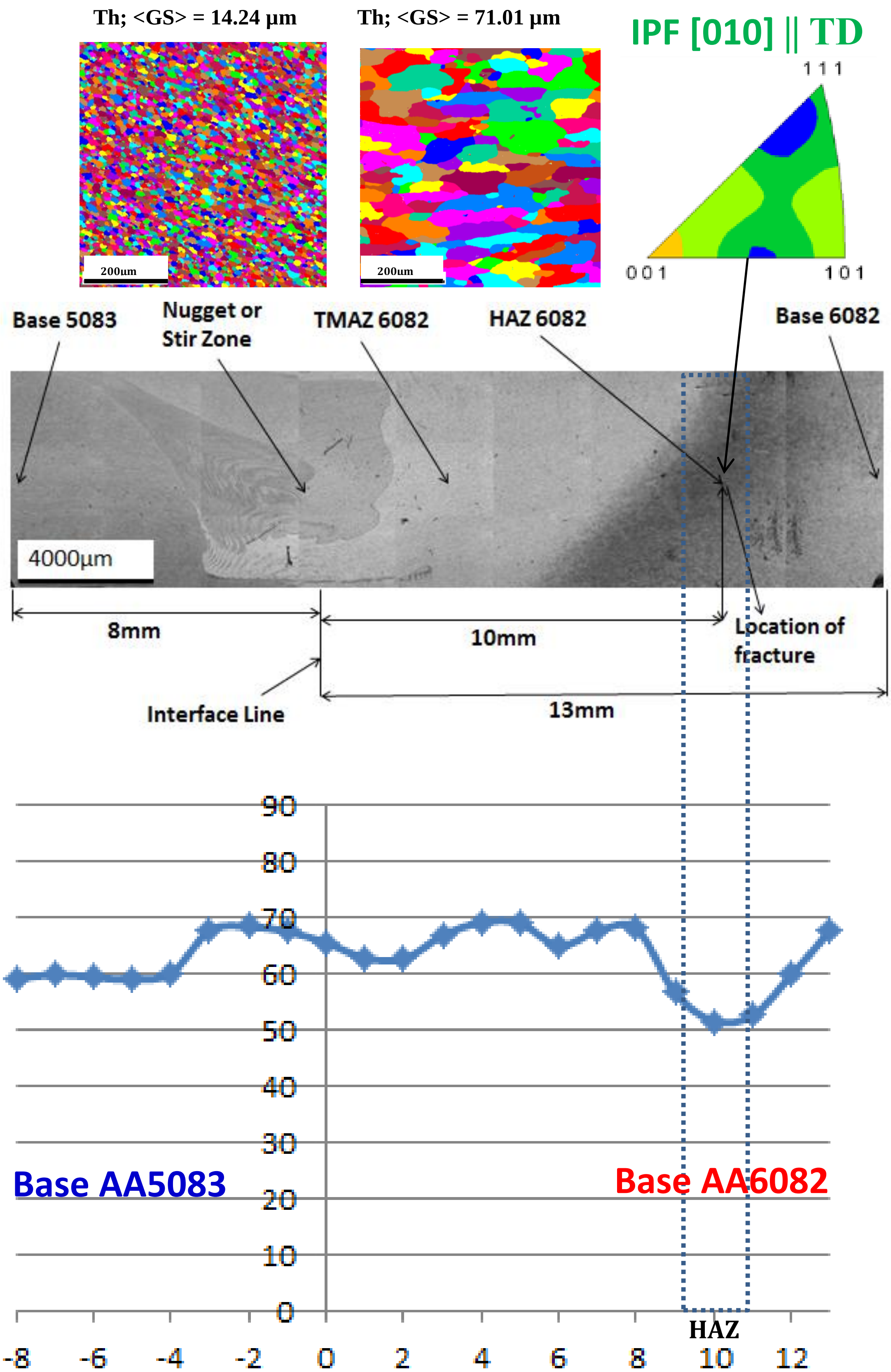
Optical micrographs from the transverse plane perpendicular to the welding direction of the four different pin profiles welded samples with the OIM images from the nugget zone and the heat affected zone (HAZ) in the AA 6082 side with mentioned average grain sizes and the inverse pole figures (IPF) parallel to the Tensile Direction at the HAZ in the AA 6082 side and Vickers micro hardness profiles are shown in Figure 6.1. Although there is not much grain size difference between the HAZ regions welded with different pin profiles in AA 6082 side and the base AA 6082 ,still there found variation of hardness (Figure 6.1) and which may be due to over-aging or dissolution of the initially present hardening precipitates (thermal effects) during friction welding. M.J. Peel et al. [20] reported this variation in hardness of AA 6082 due to the coarsening of existing β'' precipitates or transforming of them into softer β' precipitates during FSW. The behavior of hardness profile depends on two strengthening mechanisms; one is grain boundary strengthening and other is precipitation hardening. There noticed grain refinement with decreased grain size in the nugget zones in all the four specimens suggesting better joining strength according to Hell-Petch Equation. As we move towards the HAZ, hardness is going to decrease due to coarsening of precipitates or transforming of them into softer β precipitates and reached a minimum value in HAZ. 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 (Figure 5.5). 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. On comparing with their respective adjacent optical images the low hardness regions can be seen exactly falling over their heat affected zones (HAZ).Creating edges in the pins, their 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 [17]. Hence, the triangular and the square pin welded specimens are expecting to generate lower distance HAZ than the cylindrical and the threaded cylindrical welded specimens. Also, expected is the square pin welded specimen generating smallest grain size microstructure in the nugget zone (due to more number of sides and pulsating stirring action).

(a) Cylindrical Pin Profile:



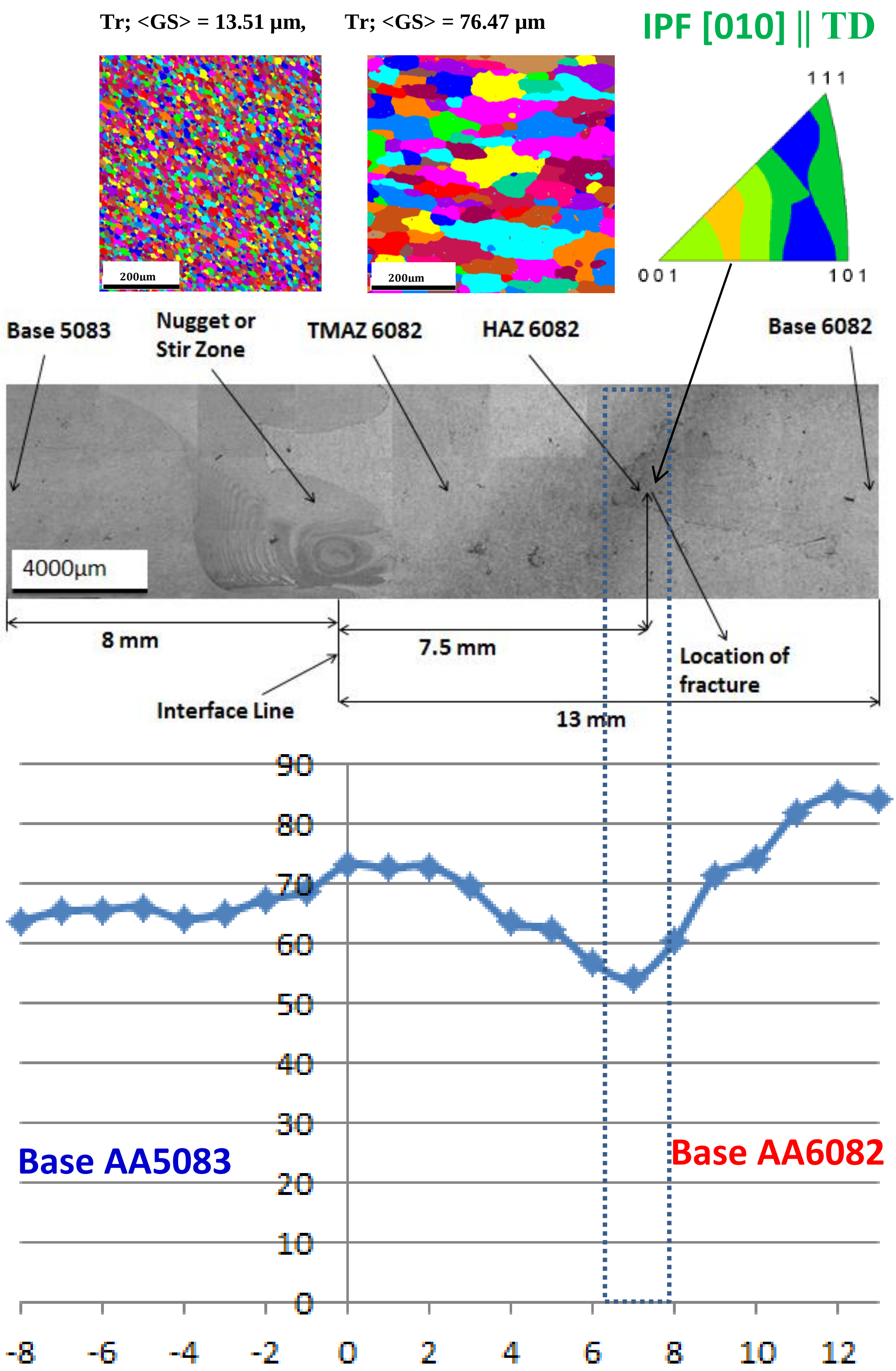
(a) Distance from interface or center line (mm)

(b) Threaded Pin Profile:



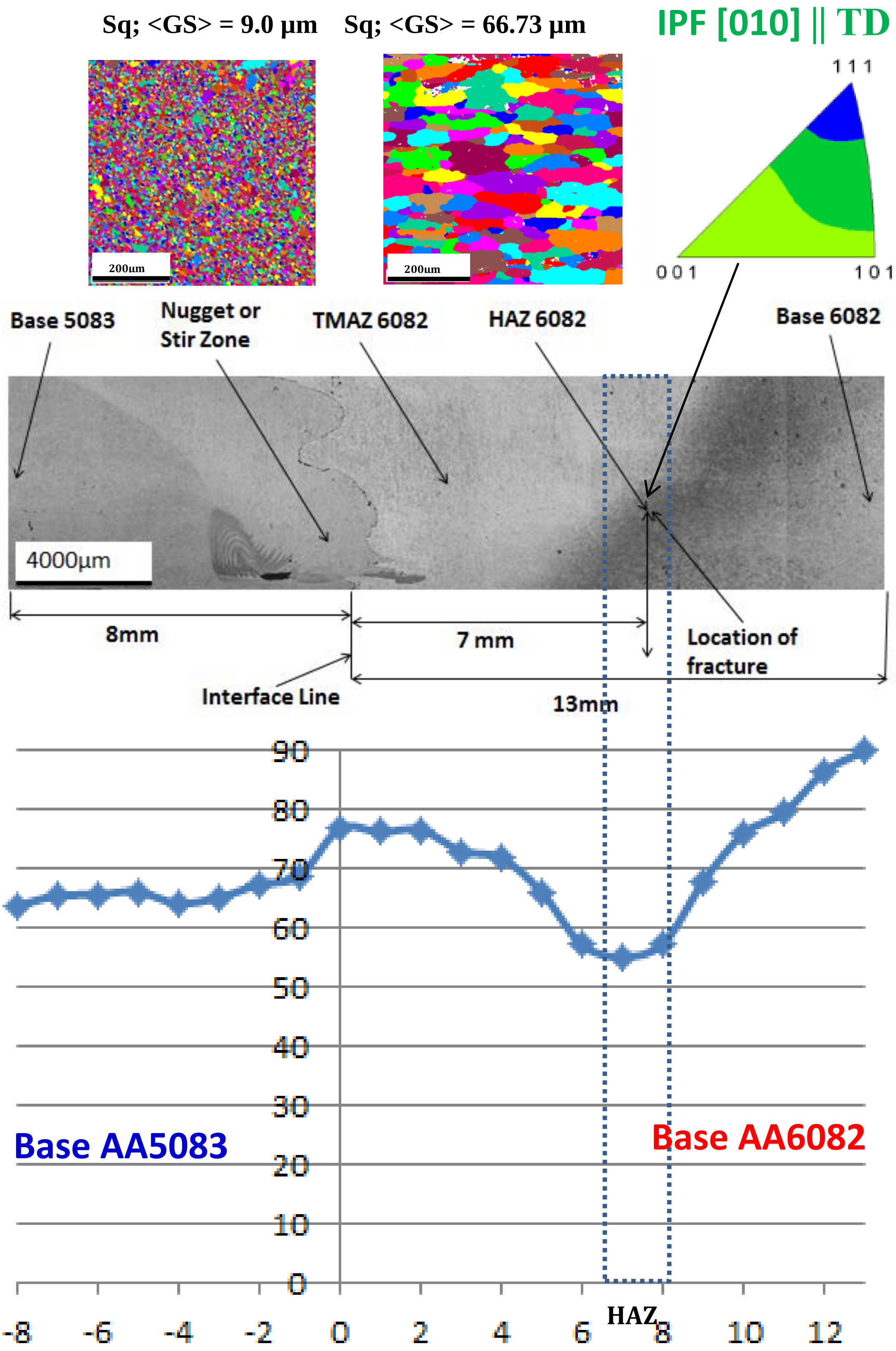
(b) Distance from interface or center line (mm)

(c) Triangular Pin Profiles:



(c) Distance from interface or center line (mm)

(d) **Square pin profiles:**



(d) Distance from interface or center line (mm)

Figure 6.1: Optical micrographs from the transverse plane perpendicular to the welding direction. Also, given are the OIM images from the nugget zone and the heat affected zone (HAZ) in the AA 6082 side with mentioned average grain sizes and the inverse pole figures (IPF) parallel to the Tensile Direction at the HAZ in the AA 6082 side and Vickers micro hardness profiles of the four different pin profiles welded samples. (a) Cylindrical (b) Threaded (c) Triangular (d) Square.

The highest ultimate tensile strength is obtained in the triangular pin welded specimen and the lowest strength is found in the cylindrical threaded pin welded specimen. The cylindrical and the square pin welded specimens generated almost similar strengths. Upon finding the location of fracture for these specimens, it was noted that the fracture did not occur at the weld joint but always few mm into the AA 6082 side. 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. Now, it can be clearly noticed that the fractured areas are indeed the heat affected zones (HAZ) of the four specimens containing lowest hardness values. But there is no significant variation noticed in the hardness values and the grain sizes from the HAZ of the four specimens that can explain the relatively lower tensile strength of the threaded cylindrical welded specimen. For that, the crystallographic textures (inverse pole figures||Tensile Direction, TD) in the fractured region (HAZ) of the four specimens were studied (given in Figure 6.1).

The IPF's of all the specimens are distinct but only the threaded cylindrical welded specimen showed a strong <001>||TD texture component. It is known that in aluminum alloys, being face centered cubic (FCC), the slip takes place in the {111} <011> slip systems. For cubic crystals the Taylor factor is the minimum for the <001> ||TD (tensile direction) and the maximum for the <111>||TD and the <110>||TD components [23]. The strength of the polycrystalline material decreases with low Taylor's factor. In the present case, the threaded pin profile specimen having the highest content of <001>||TD component provided lower mean value of Taylor factor and hence, attained lower tensile strength and fractured quickly at the HAZ. All the FSW specimens failed at the HAZ only and the way to improve their fracture strength is either completely stopping the generation of HAZ by rapid quenching during FSW itself or tailoring the texture and microstructure in the HAZ with edged pin profiles.

Chapter 7

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-EBSD 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 <001>||tensile direction texture component which rendered low Taylor factor and hence, poor strength.

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