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Effect of Weld Parameters on Mechanical Properties of Friction Stir Welded Aluminium Alloy6082-T6 and Soft Steel (Mild Steel)

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ABSTRACT

Friction Stir Welding is a solid state joining process where a tool with pin, which is non-consumable, is used to join the two facing workpieces without melting them. This technique was invented in 1991 by The Welding Institute, United Kingdom. Joining of Non-Ferrous and Ferrous materials like Aluminium to Steel finds its application in various industrial applications. Due to the large differences in melting temperature, physical and chemical properties makes it difficult to control weld and defects during welding. Formations of intermetallic compounds at the interface due to very low solubility of Fe in Al are detrimental to joint efficiency. The butt joint between Al 6082-T6 and Steel is formed by friction stir welding is carried out on a friction stir welder. Tensile tests and hardness test are conducted on the weld specimens to assess the change in mechanical and metallurgical behaviour. The fractured tensile specimens are subjected to fractography analysis in order to find out the origin of cracks and the fracture mechanism involved.

Key words: *Friction Stir Welding, Dissimilar Joining, Tensile Strength, Hardness, Aluminium Alloy, Stainless Steel, Fractography, Scanning Electron Microscope, Energy Dispersive Spectrograph, Intermetallic Compound.*

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1. INTRODUCTION

Metal welding processes are divided into groups namely: (1) fusion welding and (2) solid-state welding. In order to melt base metal fusion welding process makes use of high intensive localized heat source. In case of solid-state welding involves the combination of pressure and heat. Solid-state welding is performed below the melting temperature of base metal, where the metal turns into paste like state.

Friction stir welding is a solid state joining process which makes use of a tool to join two work-pieces into one. The contact between tool and work piece material result in heat production at the interface plasticizing the region near the tool. The stirring action of the tool blends the plasticized metal at the interface. As a result of the raised temperature the softened metal are joined by the downward force maintaining pressure and friction heat.

Welding process is achieved in three different phases that are (1) plunging and pre-heating, (2) transverse and (3) retraction of tool. The initial phase involves plunging of (rotating) tool pin into work piece slowly till the shoulder face comes in smooth contact with the work piece. Secondary stage involves the formation of weld joint by moving tool along the interface of the butted work piece with or without offsetting the tool till the desired weld length.

Final stage involves retraction of the tool to its initial position after reaching its destined point on the work piece along the weld length. The velocity vectors of transverse motion and rotational speeds are identical in advancing side, whereas are opposite in retreating side.

Based on the base material properties the process parameters are chosen. Plates are clamped onto a fixture rigidly arresting nine degrees of freedom. A backing bar is provided to thwart the faces of the butt joint being pulled apart.

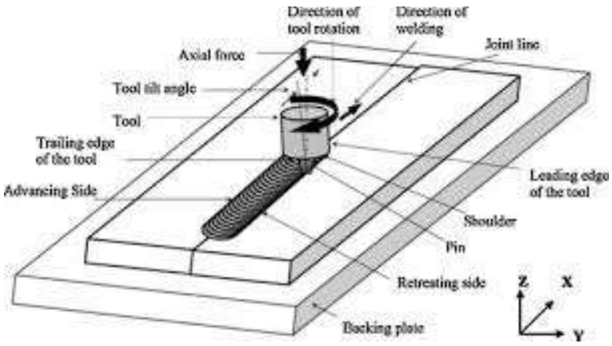

Figure 1.1: Friction Stir Welding Process

1.1 Key Process Parameters:

Tool Rotation and Traverse Speed

Tool Rotation and Traverse speed are the two essential parameters that determine the weld quality and material flow. Rotation of tool is either in clockwise or anti-clockwise direction. Traverse speed is the rate at which the tool traverses along the weld line. Efficient welding cycle is accomplished by selecting precise input values. Rigorous stir mixing of metal is observed in the case of high rotational speeds and low traverse speeds ensuing hot weld. The material which surrounds the tool must be hot enough to assist effective plastic flow. Whilst tool rotating extrudes the plasticized material and forges at the same time traversing from front to back of the pin to form solid-state weld joint.

Plunge Depth and Dwell Time

Plunge depth is the depth up to which the tool pin is sunken into work piece, the surface of the shoulder is lowered below the work piece surface facilitates the necessary rise in pressure ensuring adequate forging of material. Dwell time is the time spent at the same position by the tool to initiate pre-heating of work material.

Tool Tilt and Tool Offset

The tool is designated by a small tilt angle. Tilting the spindle towards the dragging direction maintains proper flow following local backward extrusion.Tool offset is the length of way in of the pin perimeter into the joint line positioned on the same plane.

Like this many more process parameters are their which may be considered such as Tool Material, Tool and Pin Profile, preheating, placing of work-pieces in fixture (advancing or retreating side) etc…

1.2 Microstructure Classification of Stir Weld:

Microstructure in and around weld region is influenced by its interaction with surrounding environment, rotation and transverse of the tool affecting temperature distribution and material flow resulting an asymmetry process. It can be classified into following zones.

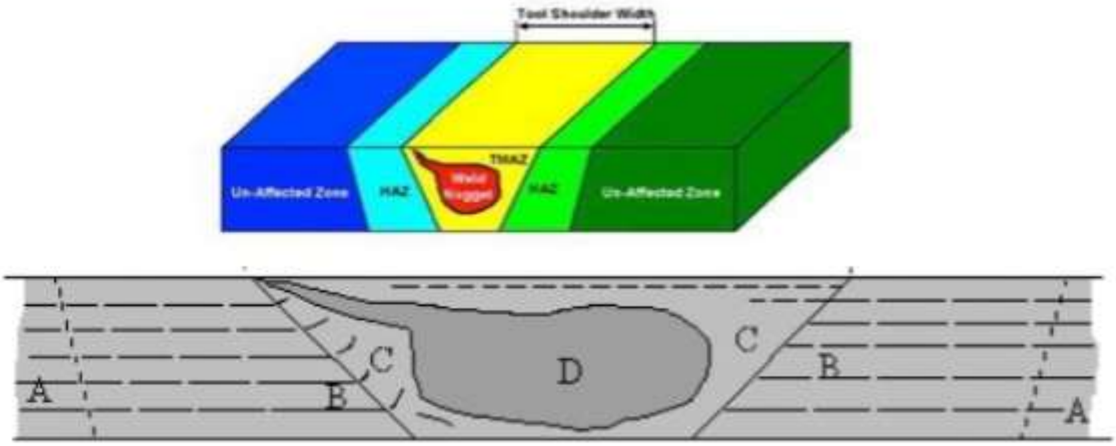

Figure1.2: Microstructure classification of FSW

- A: Base Metal (BM).
- B: Heat affected zone (HAZ).
- C: Thermo-mechanically affected zone (TMAZ).
- D: Nugget zone (NZ) or Dynamically Recrystallized Zone.

Base metal zone is the region which doesn't undergo any grain deformation heat produced during process doesn't affect or alter the zone structure.

Nugget zone corresponds to the actual tool pin position, includes intense plastic deformation consists mainly the recrystallined grains. Concentric onion rings are formed on the surface of this zone.

Thermo-mechanically affected zone is found on the either side of the nugget. In this zone plastic deformation and heat conduction are not as much as compared to nugget, but changes in hardness and microstructure can be observed.

Heat affected zone doesn't engage any plastic deformation, microstructure are faintly altered by heat conduction.

2. WORK IDENTIFICATION:

Issues related to transportation sector such as environmental, fuel efficiency and energy have strong influence on selecting appropriate material. Iron based alloys and aluminium based alloys are the most desirable materials which are well-known for their sustainability and feasibility.

Introduction of light weight material such as aluminium alloys in steel structures promote significant weight reduction under recycling standards. A joint has to fulfil basic criterions of durability, being economical, good impact and corrosion resistance properties.

The bond strength of the weld joint is pretty weak resultant of dispersion of precipitates at the time of solidification, steel has nearly zero solubility in aluminium resulting in heterogeneous brittle and excessive Al-rich Fe_xAl_yintermetallic phase.

The flaws such as distortion, cracks and cavity formation are unfavourable to mechanical strength. Controlling the size and extent of the Al/Fe intermetallic layer is decisive and challenging.

There is a positive growing inclination towards the use of Al/Fe joints in industries like shipbuilding, military vehicles and transportation industries.

3. EXPERIMENTAL DETAILS

To carry out the experiment Milling Machine is used, the machine specification is given below.

Table 3.1. Specification of Milling Machine

Make	BFW
Model	UF – 1
Table clamping area	1000×230 mm
No. of T- slots	3
Width of T- slots	14 mm
Centre distance	45 mm
No. of speeds	45 – 2000 RPM
Power of Main motor	3 hp
Motor speed	1500 rpm

Figure 3.1:Fixture to hold the Workpieces

Table 3.2. Workpiece Material

No	Material	Specifications
1	Sheet metal Al 6082-T6	100mm (length) × 50mm (width) × 4mm (thick)
2	Commercial Mild Steel	100mm (length) × 50mm (width)× 4mm (thick)

Table 3.ChemiComposition of AluminiumAlloy 6082-T6

Chemical Element	Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr	Al
% Present	0.7-1.3	0.0-0.5	0.0-0.1	0.4-1.0	0.6-1.2	0.0-0.2	0.0-0.1	0.0-0.25	Balance

Table 3.4. Chemical Composition of Mild Steel

Chemical Element	C	Fe	Mn	P	S
% Present	0.14 - 0.20 %	98.81 - 99.26 %	0.60 - 0.90 %	≤ 0.040 %	≤ 0.050 %

Table 3.5.Tool Material and Specifications

Tool Material	Carbide
Pin Profile	Cylindrical Tapered
Tool Shoulder Diameter	20 mm
Tool Pin Top Diameter	5 mm
Tool Pin Bottom Diameter	3 mm
Tool Pin Length	3.4 mm
Tool Shoulder Length	30 mm

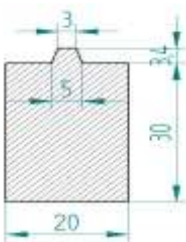

Figure 3.2: Carbide Tool

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Initial Experimental Setup:

The end milled work pieces are clamped rigidly on the fixture plate arresting the all possible movements of the work pieces. Clamping devices are used to clamp work pieces rigidly to the base plate, asbestos sheet is placed between fixture plate and table of the machine, so that the heat generated during operation should not transfer to machine table. Aluminium plate is fixed on the retreating side thus, steel plate on the advancing side. Tool is installed into tool holder firmly; tool is made to rotate in clockwise direction.

TRAIL No.1

Table 3.6.Process Parameters of Trail No.1

Process Variables	Parameters
Rotation Direction	Positive
Transverse Speed	16 mm/min
Plunge Depth	3.8 mm
Rotational Speed	710 rpm
Tool Offset	-1 mm

Figure 3.3: Surface View of the Weld Specimen

In this trail, sound weld between Mild Steel and Aluminium 6082-T6 couldn’t be achieved. The tool wore out after traversing for certain distance along the joint line due to induced thermal shocks.From the visual examination, it’s evident to say cause of failure is due to tool offset resulting in insufficient heat generation and unsteady weld state leaving behind cavities along the weld line.

Figure 3.4:Worn Out Tool Pin

TRAIL No.2

Table 3.7. Process Parameters of Trail No.2

Process Variables	Parameters
Rotation Direction	Positive
Transverse Speed	20 mm/min
Plunge Depth	3.80 mm
Rotational Speed	1400 rpm
Tool Offset	-1.5 mm

Figure 3.5: Surface View of the Weld Specimen

The weld obtained in this trail has fewer defects compared to previous weld. The tool offset input value was increased from -1mm to -1.5,Traverse speed was increased from 16 mm/min to 20 mm/min.

TRAIL No.3

Table 3.8. Process Parameters of Trail No.3

Process Variables	Parameters
Rotation Direction	Positive
Transverse Speed	20 mm/min
Plunge Depth	3.8 mm
Rotational Speed	1000 rpm
Tool Offset	-2 mm

Figure 3.6: Surface View of the Weld Specimen

Visual inspection of the joint formed reveal the input tool offset value may perhaps be the reason for inefficient stirring of material from steel side towards aluminium for necessary joint formation at high rotational speed.

TRAIL No.4

Table 3.9. Process Parameters of Trail No.4

Process Variables	Parameters
Rotation Direction	Positive
Transverse Speed	16 mm/min
Plunge Depth	3.80 mm
Rotational Speed	710 rpm
Tool Offset	-1.5 mm

Figure 3.7:Surface View of the Weld Specimen

Welding of Mild Steel and Aluminium 6082-T6 plates turned out to be a failure in this trail. The inappropriate material flow affected the weld joint leaving behind huge voids. The process was aborted within a few distance of tool traverse.

TRAIL No.5

Table 3.10. Process Parameters of Trail No.5

Process Variables	Parameters
Rotation Direction	Positive
Transverse Speed	16 mm/min
Plunge Depth	3.80 mm
Rotational Speed	1000 rpm
Tool Offset	-1.5 mm

Figure 3.8: Surface View of the Weld Specimen

The weld obtained was defective in nature; the kissing bond defect was evident in this trail resultant of insufficient fusion between the two materials.

TRAIL No.6

Table 3.11. Process Parameters of Trail No.6

Process Variables	Parameters
Rotation Direction	Positive
Transverse Speed	20 mm/min
Plunge Depth	3.80 mm
Rotational Speed	710 rpm
Tool Offset	-1.5 mm

Figure 3.9:Surface View of the Weld Specimen

At lower speeds, the tool pin couldn’t keep itself steady along the weld line after certain distance of transverse. The tool pin worn out due the mechanical resistance from the work piece.

Figure 3.10: Worn Out Tool Pin

TRAIL No.7

Table 3.12. Process Parameters of Trail No.7

Process Variables	Parameters
Rotation Direction	Positive
Transverse Speed	25 mm/min
Plunge Depth	3.80 mm
Rotational Speed	1000 rpm
Tool Offset	-1.5 mm

Figure 3.11:Surface View of the Weld Specimen

The weld joint produced in this trial is satisfactory compared to the previous trail.

TRAIL No.8

Table 3.13. Process Parameters of Trail No.8

Process Variables	Parameters
Rotation Direction	Positive
Transverse Speed	16 mm/min
Plunge Depth	3.80 mm
Rotational Speed	1400 rpm
Tool Offset	-1.5 mm

Figure 3.12:Surface View of the Weld Specimen

The weld joint accomplished in this trail has least defects compared to all other trails performed.

4. MECHANICAL TESTS

The welded specimens were visually examined to carry out the further testing to determine their mechanical properties .Weld specimens of the $2^{nd}$and the 8^{th} trail were only suitable to carry out. The left over impression made by tool shoulder and other marks were machined off. The welded Samples are cut along the joint in transverse direction to the weld. Universal tensile test and microhardness tests are carried out to determine the mechanical behaviour of the joint. Later, the tensile tested specimens are subjected to fractography analysis conducted using Scanning Electron Microscope (SEM) equipped with (Electron Backscatter Diffraction) EBSD and (Energy Dispersive X-ray Spectroscopy) EDS system.

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4.1 Tensile Test

Considering the tensile test, the specimens are flattened with gauge section machined along transverse direction of the weld by Electrical Discharge Machining (EDM). The tensile tests are carried out on Universal Testing Machine of 25kN load capacity equipped with 24-bit data acquisition system. The uniaxial test specimen are prepared as per ASTM standard (E8/E 8M-08).

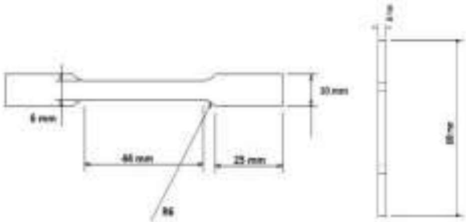

Figure 4.1: Standard Tensile Specimen Dimensioning and Tolerance as per ASTM E8/E 8M-08

The tensile tested fracture specimens are subjected for fractography examination in order to find out fracture behaviour and its source of origin.

4.2Microhardness Test

The microhardness is measured across the specimen at different microstructural regions: base metal (BM), thermo-mechanically affected zone (TMAZ), heat affected zone (HAZ) and nugget zone (NZ) to study the metallurgical changes caused by the FSW tool. The microhardness measurements are made across the specimen under a low-load Vickers hardness tester integrated with optical microscope (OM) of high magnification lens produces a live high resolution images of the specimen for defining indentation positions. The Vickers hardness tests are carried out as per to ASTM E 384 standards for every interval of 2 mm for a distance of 10 mm from the interface line horizontally along both sides by an indentation load of 200grams for dwell time of 10sec.

5.RESULTS AND DISCUSSION

5.1 Tensile Properties

Figure 5.1:Tensile Tested Fracture Specimens

Visual inspection of the tested tensile specimen revealed the fracture took place at the centre of the weld joint (nugget zone).

5.2 Stress-Strain Curves

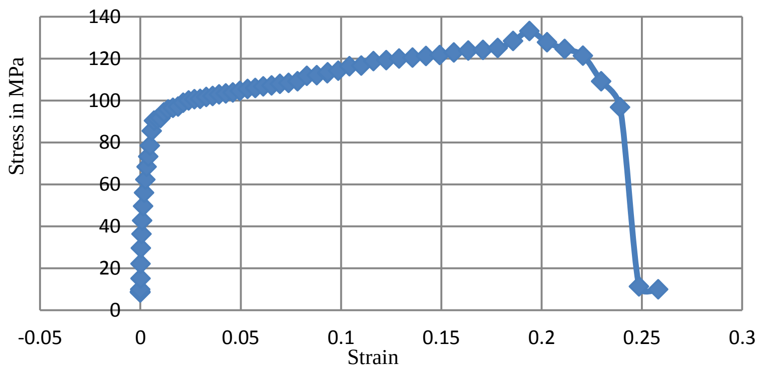

Figure 5.2: Stress-Strain Behaviour of Trail No.2 Tensile Specimen

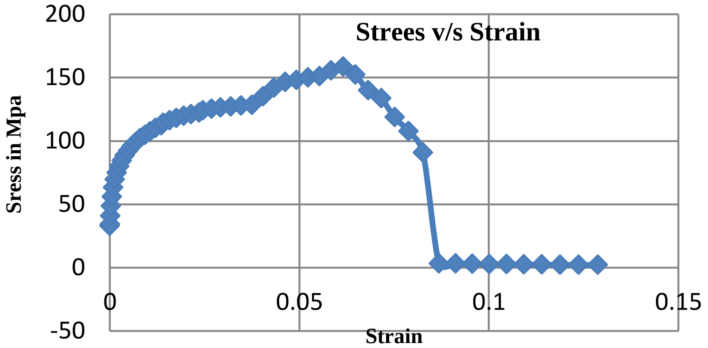

Figure 5.3: Stress-Strain Behaviour of Trail No.8 Tensile Specimen

The formation of brittle intermetallic compounds at the interface due to heterogeneous distribution of aluminium in steel matrix vice versa shows ductile to brittle transition fracture characteristics. Joint interface is a critical factor influencing joint efficiency.

6. CALCULATION

Ultimate Tensile Strength of the Tensile Specimen:

a) Trail No.2 Tensile Specimen

$$\text{UTS} = \frac{2129.99}{16} = 133.124 \text{ MPa.}$$

b) Trail No.8 Tensile Specimen

$$\text{UTS} = \frac{2615.47}{16.5} = 158.513 \text{ MPa.}$$

Tensile strength of the final trail weld joint is better among all trials and nearer to that of the Aluminium alloy (220Mpa).

7. FRACTOGRAPHY ANALYSIS

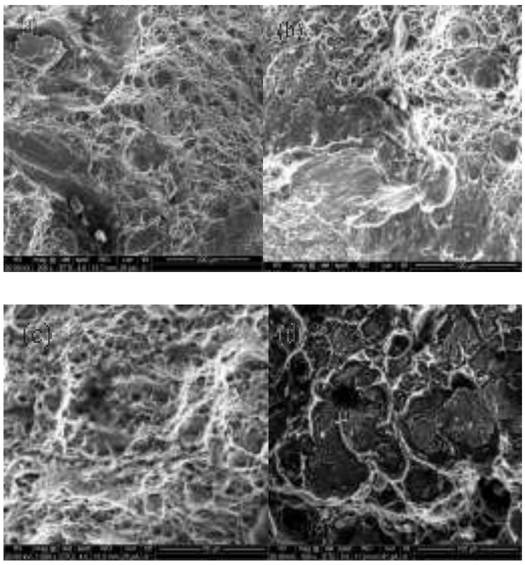

Figure 7.1: SEM-EBSD Characterised Micrographs of Fractured Tensile Specimens: (a) Intermetallic Compounds surrounding Equiaxed Grains in Stir zone; (b-d) Equiaxed Dimples away from Nugget;

The grains in and around nugget region undergo a sturdy deformation by the movement of tool shoulder during its traverse along the weld line. From the EBSD findings its reaveled there is a significant indication of sub-grain devlopment during deformation.

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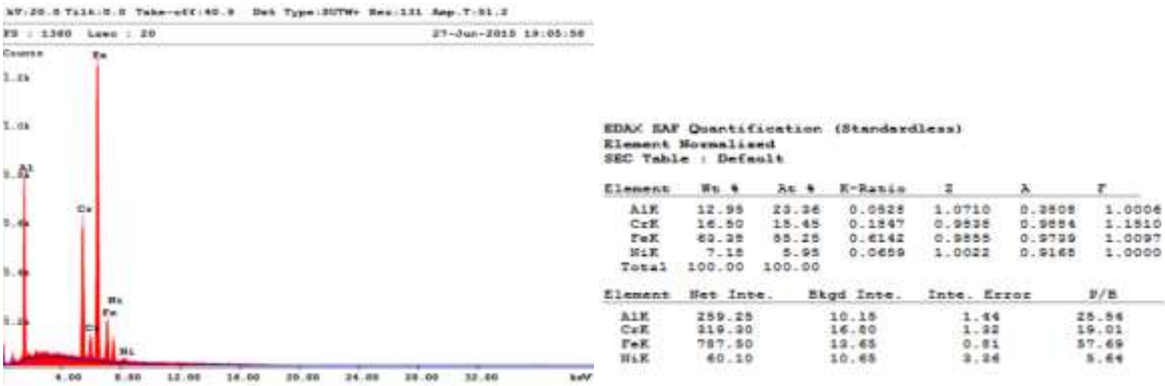
Frictional heat along with strain build up leading to nucleation and development of new grains(hetrogenous dynamic recrystallization).

Chemical composition mapping carried out through EDS examination substantiates the source of cracks are associated with the inclusions and the intermetallic compounds surrounding around equiaxed grains at the interface [Figure 7.1 (a) and Figure 7.2].Presence of equiaxed dimples away from the inferface is evident of ductile behavior in and around the heat affected zone [Figure 7.1 (b-d).Certain amount of steel fragments were strewn in the alluminium alloy matrix.

The intermetallic compounds indeed act as strees concentrators upon load. Controlling the amount of intermetallics compounds and inclusions iscritical for transition from ductile to brittle behaviour.



EDAX ZAF Quantification (Standardless)
Element Normalized
SEC Table : Default

Element	Wt %	At %	K-Ratio	Z	A	F
AlK	12.95	23.36	0.0528	1.0710	0.3808	1.0006
CrK	16.50	15.45	0.1847	0.9538	0.9854	1.1510
FeK	63.38	55.25	0.6142	0.9555	0.9739	1.0097
NiK	7.18	5.95	0.0659	1.0022	0.9165	1.0000
Total	100.00	100.00				

Element	Net Inte.	Bkgd Inte.	Inte. Error	P/B
AlK	259.25	10.15	1.44	25.54
CrK	319.30	16.80	1.32	19.01
FeK	787.50	13.65	0.81	57.69
NiK	60.10	10.65	3.24	5.64

Figure 7.2: Chemical Composition Mapping of a Crack Associated with Intermetallic Compound

8. MICROHARDNESS ASSESSMENT

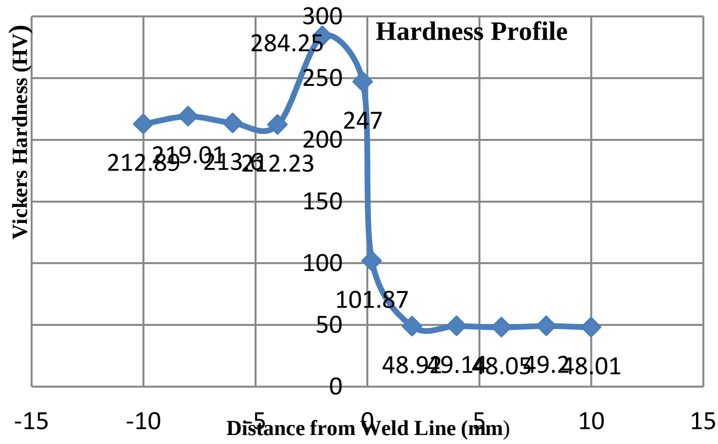


Figure 8.1: Vickers Microhardness Distribution Profile along the Weld Cross section Trail No.2

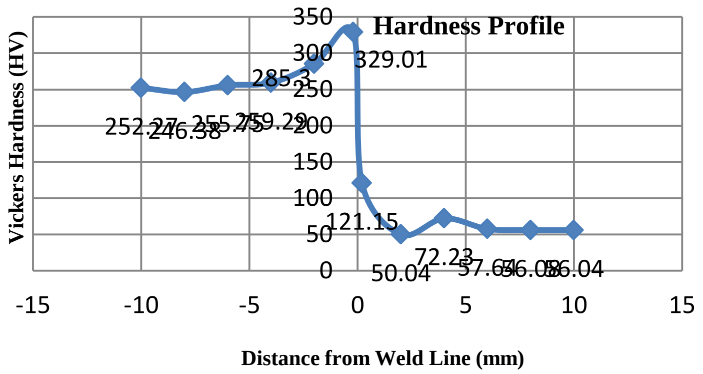


Figure 8.2: Vickers Microhardness Distribution Profile along the Weld Cross section Trail No.8

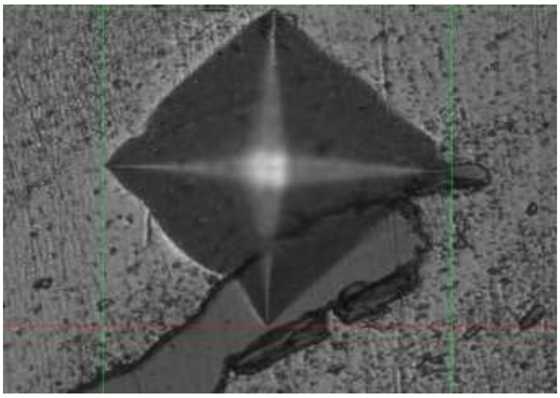


Figure 8.3: Microhardness Indenter Microscopic Image

Noteworthy variation in hardness value is found at nugget zone. This is ascribed to the heterogeneous nucleation. The peak of hardness measured at the interface is associated to the presence of intermetallic compounds and inclusions.

An increase in hardness can be associated with the fine grain structure formed in base steel near nugget zone but decreases in direction away from nugget zone due to the coarse grain structure, but no evidence of increase or decrease in hardness is observed in base aluminium near or in away direction away from the nugget zone except at steel inclusions in aluminium matrix [Figure 8.3].The plastic deformation increases the mechanical strength.

CONCLUSIONS:

The following conclusions are drawn from the present study:-

a) The process variables such as Rotational Speed, Traverse Speed and Tool Offset are the critical parameters to be optimized in order to accomplish sound weld.

b) The intermetallic compounds formed at the interface determine the strength of the weld joint and the mode of fracture.The fracture took place at nugget region due to heterogeneous nucleation.

c) The Microhardness measured at the interface was obviously more than that of base metal due to finer grain refinement on the either side of the weld joint line.Failure analysis showed the cracks originated from the dispersed inclusions.

d) The maximum UTS attained was up to 72% of the base metal Aluminium alloy.

e) Weld with least defects can be achieved by following process parameters :

T

Table 3.14. Process Parameters which gives least defects

Process Variables	Parameters
Rotation Direction	Positive
Transverse Speed	16 mm/min
Plunge Depth	3.80 mm
Rotational Speed	1400 rpm
Tool Offset	-1.5 mm

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