Scientific Journal of Impact Factor (SJIF): 4.72
e-ISSN (O): 2348-4470
p-ISSN (P): 2348-6406

International Journal of Advance Engineering and Research Development

Volume 4, Issue 4, April -2017

Mechanical and Metallurgical Properties of Multipass Friction Stir Welded Joints of Aluminium 6061 Alloy

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Abstract — *Solid state joining process named Friction Stir Welding was developed in 1991 which has attracted considerable interest from the aerospace and automotive industries, since it is able to produce defect free joints particularly for light metals i.e. magnesium and aluminium. Aluminium alloy AL 6061 is medium strength architectural alloy, normally used in intricate extrusions. Due to difficulties in welding Aluminium using conventional welding processes, Friction Stir Welding has been used to weld aluminium alloy AL 6061. The effect of single pass and double pass was studied using combination of different parameters i.e. Square tool pin profile, tool rotational speed (1200 rpm), welding speed (45mm/min) and tool shoulder diameter 20 mm. The square pin (7×7 mm) profile was used to make a butt weld joint by using single pass, double pass (same side) and double pass (reversed side).Results was compared by studying the effect of number of passes on the tensile strength and micro hardness Test. After testing, the effect of single pass and double pass on friction stir welded aluminium alloy 6063 using square tool pin profile are concluded, it was observed that the maximum value of UTS i.e. 172.5 N/mm² was obtained at 1200 rpm tool rotational speed, 45 mm/min welding speed with square tool pin profile with double pass (same side) friction stir welding. The Vickers hardness value was maximum at stir zone i.e. 91 Hv with 1400 rpm tool rotational speed, 45 mm/min welding speed with square pin profile with double pass (same side)and(reversed side) as compared with the heat affected zone (HAZ) and thermo mechanically affected zone (TMAZ).*

Keywords- *single pass, double pass, friction stir welding, square tool pin profile.*

I. INTRODUCTION

1.1 Aluminium alloy

Aluminium alloys have played a critical role in modern industry. Aluminium is a relatively low cost, lightweight metal that can be heat treated to fairly high strength levels, and its ease of fabrication leads to low costs. It has a high strength-to-weight ratio and performs well from cryogenic temperatures to moderate temperatures. The disadvantages of high strength aluminium alloys include a low modulus of elasticity, rather low elevated temperature capability, and susceptibility to corrosion.

1.2 Aluminium 6061

Aluminium alloy 6061 is medium strength alloy commonly referred to as architectural alloy. It is normally used in intricate extrusions. It has good surface finish; high corrosion resistance is readily suited to welding and can be easily anodised. AL6061 is mostly used in extruded shapes for architecture, particularly window frames, door frames, roofs, and sign frames. It is typically produced with very smooth surfaces fit for anodizing. It has generally good mechanical properties and is heat treatable and weldable. It is similar to the British aluminium alloy HE9. T6 temper 6061 has an ultimate tensile strength of at least 28,000 psi (196 MPa) and yield strength of at least 23,000 psi (165 MPa). In thicknesses of 0.124-inch (3.1 mm) or less, it has elongation of 8% or more; in thicker sections, it has elongation of 10%.

The material used in the present work is aluminium alloy 6061. The chemical composition, mechanical properties and physical properties of aluminium alloy 6061 are present in Table 1.2.1, Table 1.2.2 and Table 1.2.3 respectively

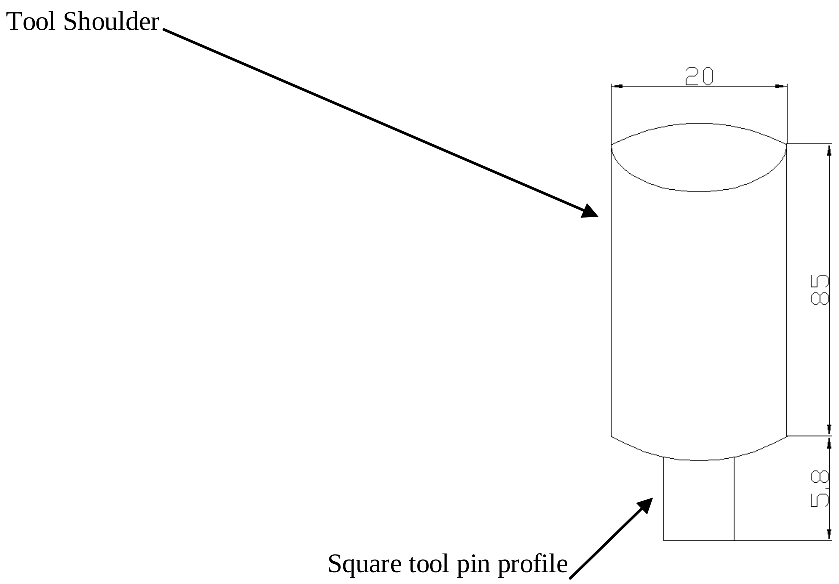
Table 1.2.1 Chemical composition of aluminium alloy6061

Al	Mg	Si	Fe	Cu	Mn	Zn	Cr	Ti	Ni
95.8-98.6	0.8-1.2	0.4-0.8	0.7 (Max)	0.15-0.4	0.15 (Max)	0.25 (Max)	0.04-0.35	0.0-0.15	0.01

Table 1.2.2 Mechanical properties of aluminium alloy6061

S. No.	Temper	T6
1	Proof Stress 0.2%	170MPa
2	Tensile Strength	215MPa
3	Shear Strength	152MPa
4	Elongation (%)	15
5	Hardness	83 HV

1.3. Tool configuration



1 Friction Stir Welding Tool Design

Machined Specifications are given in Figure 1.3.1. Configuration of the friction stir welding tool pin is square in shape. As given the figure the height of the shoulder is 85mm and the tool pin (probe) height is 5.8mm is used because the thickness of the base plate is 6mm. The shoulder and pin width is chosen on the basis of one third rule or closer to it that is why the shoulder diameter is 20 then the tool pin width is 7mm is used.

Table 1.3.1 the machining parameters of the Tool used.

S. No.	Description	Value
1	Diameter of Square Tool	21mm
2	Shoulder Dimensions of square tool	7×7mm
3	Length of Square Tool Shoulder	85mm
4	Length of Square Tool Pin	5.8mm

1.4 Friction Stir Welding

Friction stir welding is a solid state joining process in which a specially designed rotating tool, which is inserted into an adjoining edge of the sheets to be welded and the tool, is moved across the length of the joint. The tool produces the frictional heating and plastic deformation heating in the welding zone along the joining of the work piece length basis for welding. The friction stir welding is a solid state joining process means no melting of a material take place during the process. The main parameters in friction stir welding are tool shoulder diameter, welding speed, tool rotation speed, tool pin length, tool pin diameter. The various types of tool shapes are used in FSW like square, rectangular, hexagonal and triangular shapes, but by using square shaped tool we get a high strength weld. Friction welding can be used to produce butt, corner, lap, T, spot, filleted hem joints as well as hollow object such as tank and tubes or pipes, stock with different thickness, tapered section and parts with 3-dimenstionalcontours.

1.4.1. Working Principle

The schematic diagram for FSW is shown in Figure1.4.1.1. The non- consumable tool has a circular section except at the end where there is a threaded probe or more complicated flute, the junction between the cylindrical portion and the probe is known as the shoulder the probe penetrates the work piece whereas the shoulder rubs with the top surface. So the friction stir welding is working on the principle that when a rotating tool which has a pin and shoulder, the pin is inserted between the very small root gap of the two aluminium plates due to rotation of tool heat is produced because of friction. After the rolling friction of tool against the plates melting of the plates occur just before the melting of points of its material and the joining process starts. That is why this process is called solid state welding process.

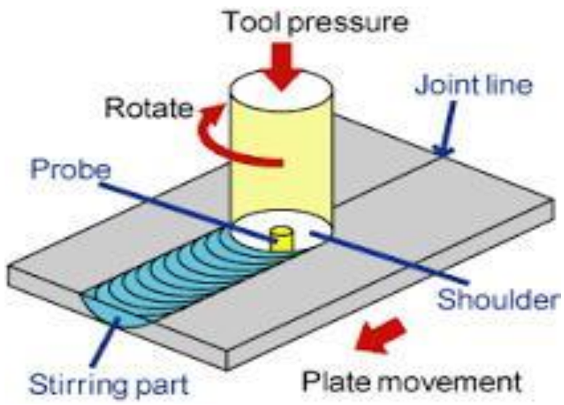


Figure1.4.1.1 Schematic diagram of FSW process

Figure1.4.1.1. A rotating tool is pressed against the surface of two abutting or overlapping plates. The side of the weld for which the rotating tool moves in the same direction as the traversing direction, is commonly known as the 'advancing side'; the other side, where tool rotation opposes the traversing direction, is known as the 'retreating side' An important feature of the tool is a probe (pin) which protrudes from the base of the tool (the shoulder), and is of a length only marginally less than the thickness of the plate. Frictional heat is generated, principally due to the high normal pressure and shearing action of the shoulder. Friction stir welding can be thought of as a process of constrained extrusion under the action of the tool. The frictional heating causes a softened zone of material to form around the probe. This softened material cannot escape as it is constrained by the tool shoulder. As the tool is traversed along the joint line, material is swept around the tool probe between the retreating side of the tool (where the local motion due to rotation opposes the forward motion) and the surrounding un-deformed material. The extruded material is deposited to form a solid phase joint behind the tool. Friction stir welding is therefore both a deformation and a thermal process, even though there is no bulk fusion. The maximum temperature reached is a matter of some debate. [13]

1.4.2. FSW Process Parameters

The research in the field of friction stir welding (FSW) a number of parameters are used by different researcher and they calculating the effect of parameters on FSW. The present study in which we used the different parameters to calculate the effect of these parameters for single pass and double pass using square tool pin profile. The present study aims to calculating the effect of the following parameters that is

(a) Number of passes– The second parameter that is used in the present study of work is the number of pass. In this study of work by varying the numbers of passes, different results are formed so type of pass is important to know that at which pass, a sound joint can form .In the present study we are using FSW with single pass, double pass (same side) and double pass (reverse).
(b) Tool traverse speed – The third parameter is the tool feed or we can say that a welding speed of a tool that is measured in mm/minute. By varying the welding speed of the tool a lot of changes arises like change in strength of the specimen, defects in the specimen and also Micro structural changes arises, so tool weld speed is a very important parameter and our aim is to get a that at what feed rate we get a high strength joint. in this present study of work we keep this parameter constant
(c) ***Tool shoulder*** – Tool shoulder is the fourth parameter. It is also very much important parameter because the bottom part of the shoulder is rubbing against on the top surface of the joining plates. It is also kept constant for the present study

II. METHODOLOGY

The next step is the experimentation in which come over those difficulties that are arises in the trial experimentation with the help of literature survey or what parameter set that will gave a perfect fiction stir welding and sound joint strength. Before starting, a vertical CNC milling machine as shown in Figure 2.1, V-450 vertical CNC milling machine is used in the present work. This machine is made for metal cutting operations. It operates under control of CNC (Computerized Numerical Control unit). It is used for milling, boring, drilling, tapping & 3Dcontouring for specific work under consideration.

V450 offers:

- High quality, heavy ribbed cast iron structures.
- Preloaded precision ball screws of C3 class for all 3 axes.

Figure 2.1. Vertical CNC Milling Machine.

Technical specifications:

Table 2.1 Technical specifications of vertical CNC milling machine

S.No	Features	Value
1	Power supply (Basic machine)	415 VAC (+/-10%),3 phase 50 Hz (+/-3%)
2	Compressed air supply	6 bar @ 10 cfm (for spindle air blow)
3	Positioning accuracy	+/- 0.006mm
4	Tool change time	2.0sec- Tool to Tool
5	Machine weight	5600kg
6	Spindle Motor	9 -11 KW
7	Tool declamp	Mechanical(Pneumatic)
8	Tool Selection	Random - shortest path
9	Work area	700x400 mm
10	Speed (rpm)	50-8000 (10000 – Optional)

The final Experimentation is done on vertical CNC milling machine in which a welding fixture is placed on a vertical milling machine Bed and clamped on a it. Tool is inserted in a tool holder.

The Table 2.2 shows a friction stir welding parameter used for final experimentation

To better understand see Figure 2.2 in which welding fixture and tool used for welding are shown and how the base metal is clamped firmly in fixture are shown

Table 2.2 Friction Stir Welding Parameter for Final experimentation

S. No.	**Parameter**	**Value/Description**
1	Rotational Speed	**1200 rpm clockwise**
2	Weld Speed	45mm/min
3	Weld Type	**Double Pass Butt Weld**
4	Tool pin Profile	Square (7mm)

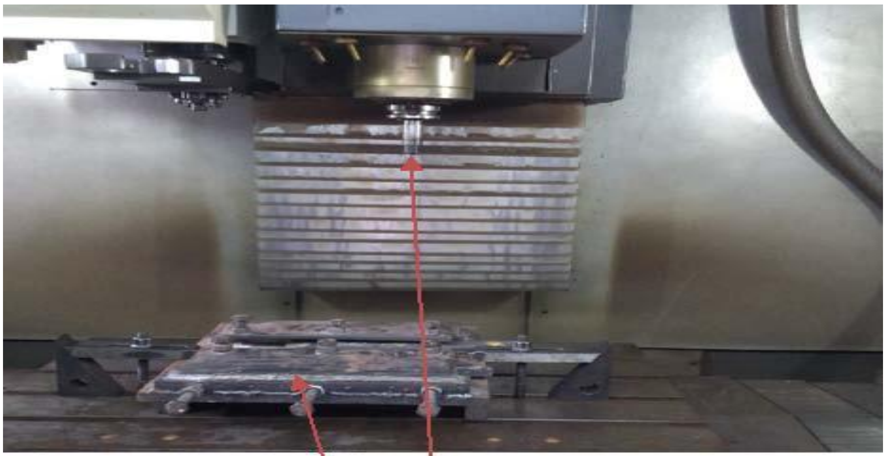


Figure 2.2 FSW Process

After this, friction stir welded high strength weld joint is formed, If it is compare with the specimen that is formed in trial experimentation, it has better result of similar Al alloy 6061 plates below. In which the welding speed is 45mm/min is used, Tool rotational speed 1200 rpm, square Tool pin profile having (7x7)mm, single pass butt weld.

Figure 2.3 Samples of FSW Produced In Final Experimentation

2.1 Experimentation

Place the welding fixture on a CNC vertical milling machine and then hold the fixture with the help clamping device. Two AL 6061 plates with dimensions 150×75×6mm (L×B×T) respectively were placed on Fixture in a manner that prevents the displacement of plates during welding and fix them along the travel line of welding tool. Tool was fixed firmly in the tool collect of respective dimension and rotated at required parameters.

Table 2.3 Parameters used for FSW of Three Specimens of Al alloy 6061

S No.	Specimens	Welding Speed (mm/min)	Tool Rotational speed	Tool pin profile	Tool Shoulder Diameter	Operation Type
1	S1	45	1200rpm	Square Tool	20mm	Single Pass
2	S2	45	1200rpm	Square Tool	20mm	Double Pass(same side)
3	S3	45	1200rpm	Square Tool	20mm	Double Pass(Rev side)

III. PRIOR APPROACH

Results of an extensive literature research in the field of Friction Stir welding and conventional welding with more emphasis on FSW for Aluminium are presented. Various other related comparative studies are also presented. This chapter presents the detail of work undertaken by different scientists and engineers in the field of welding aluminium by different methods of welding. The review includes theoretical as well as the experimental work undertaken from time to time for the development of better welding techniques for Aluminium.

After, study of fair amount of research papers it was noticed that a less amount of work has been done regarding the effect of tool pin profile and no. of passes (Direct and reverse pass) on the mechanical and metallurgical properties of Al alloy 6061. In friction stir welding different types of tool profile used .There is less research done for study the effect of number of passes on FSW aluminium 6061 alloy using square tool pin profiles. So to reduce the gaps in study in FSW we have to concentrate on the important parameters and do research on it properly.

IV. OUR APPROACH

Our approach for the research is to analyse the effect of number of passes (same side/ reverse side) on the friction stir welding of aluminum 6061 alloy using square tool pin profile. The main parameter of this research is number of passes of friction stir welding.

The research purposes to fulfill the following objective:-

1. To study the effect of single pass and double pass on the mechanical and metallurgical properties of friction stir welded joints of Al 6061 alloy using square tool pin profile.

TESTING

After welding is done different samples were taken for different types of testing. The testing setup basically consists of following three main elements:

1. Visual Inspection
2. Mechanical Testing (Tensile test)
3. Metallurgical testing (Micro hardness test)

1 Visual Inspection

The first step was the visual inspection. Several types of defects were revealed. In case of the joint FSW a surface-open tunnel was found as a result of insufficient downward pressure. Excessive lateral flash was also observed in most of the welds, resulting from the outflow of the plasticized material from underneath of the shoulder. For some of the welds no flaw or defect was detected on the weld. There are number of defects that are produced during FSW process. [3]

2 Mechanical Testing

It includes tensile test. For the present study of work, three plates are at different parameters as described in Table 2.3

4.2.1. Tensile Test

For tensile testing the specimens are prepared according to ASTM E8M-04 and its testing is done on Universal testing machine as shown in Figure 4.2

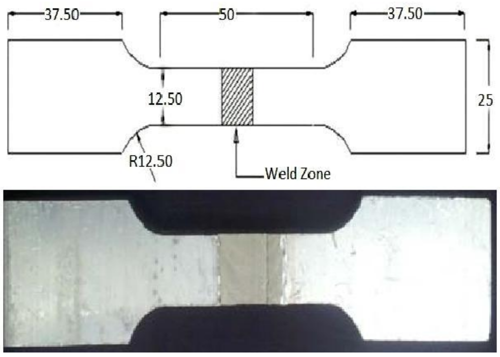


Figure 4.1 Tensile Test Specimens

In the present study the number of plates joined is three. From these welded plates, cut a four pieces of test specimen for tensile testing, three test specimens for impact testing and other two test specimens for metallurgical testing.

In the tensile testing following parameters are measured:

(1) 0.2 % proof stress: It is the maximum stress that is required to cause a permanent extension of to 0.2 % of gauge length.

(2) Ultimate Tensile strength: It is calculated by dividing the maximum load which a specimen is subjected during the test by the original area of cross-section of sample.

Figure 4.2 Tensile Testing on UTM

After tensile test is done on UTM machine, with the help of this test the ultimate tensile strength is calculated

3 Metallurgical Tests

It includes Micro hardness test

4.3.1 Micro Hardness Test

Results of hardness testing are given in table no. 4.2, 4.3, 4.4....4.7. The Figure 4.3.1.1 shows image of diamond indenter during micro hardness test.

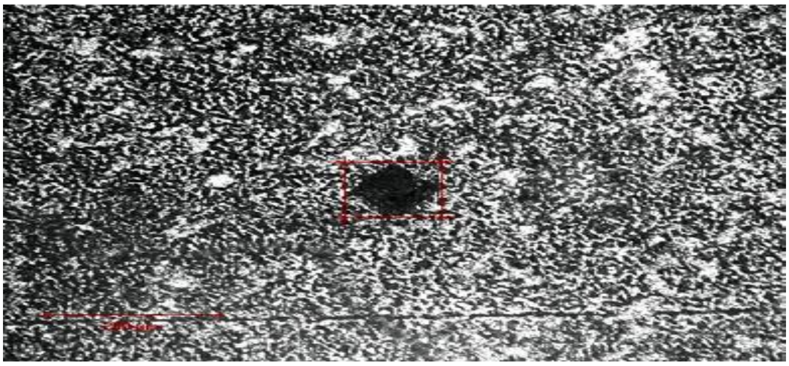


Figure 4..3.1.1 Image of Indenter during Test (300 gf for 10sec)

Hardness is measured at different locations using Vickers hardness testing machine. For hardness testing 300 gf loads was used for 10 seconds. Hardness points are taken in perpendicular direction from the weld at -2,-4,-6,-8,-10,-12, 0, 2, 4, 6, 8, 10,12mm respectively.

V. CONCLUSION

5.1 VISUAL INSPEECTION TEST

In Figure 5.1,The Tunnel defect at the bottom of the surface in the nugget zone arises due to (WillaimJ.Abregast et al) The insufficient material flow occur for Taper tool pin profile due to flow restriction during the FSW process for specimen S5. The insufficient material flow and heat generation with taper tool pin the flow of material is not vertical it is only horizontally flow from advancing side to retreating side due to this ,cavity is generated at the bottom part.

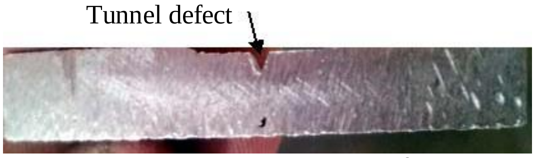


Figure 5.1 Tunnel Defect

Ribbon flash defect is due to insufficient downward force. Surface Lack of Fill defect is due to insufficient weld pitch.

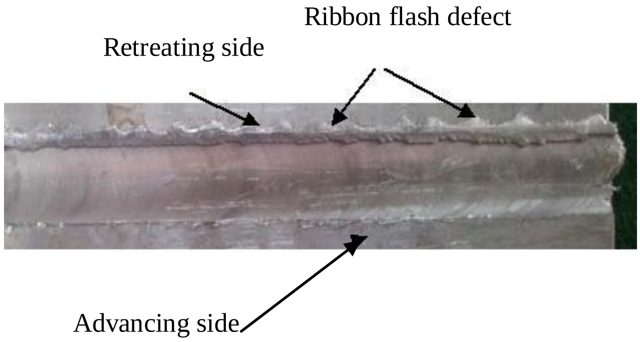


Figure 5.2 Ribbon Flash Defects

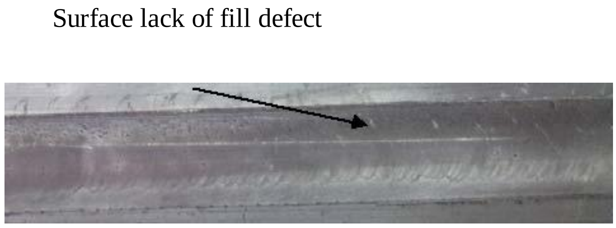


Figure 5.3 Surface Lack of Fill Defect

As shown above three Figures very less defects are produced in the present study.

5.2 TENSILE TESTING

Results of tensile testing are tabulated in Table 5.2.1

Table 5.2.1: Tensile Testing Results.

S No	Specimen No	Welding Speed(mm/min)	Tool Rotational Speed(RPM)	Tool Shoulder Diameter(mm)	Tool Pin Profile	Operation Type	Tensile Strength (MPa)
1	S1	45	1200	20	Square Tool (ST)	Single	165.7
2	S2	45	1200	20	Square Tool (ST)	Double(S)	172.5
3	S3	45	1200	20	Square Tool (ST)	Double(R)	168

5.2.1 EFFECT OF MULTIPLE PASSES ON MECHANICAL PROPERTIES.

5.2.1.1 Effect of single pass, double pass (same side) and double pass (reverse) on UTS

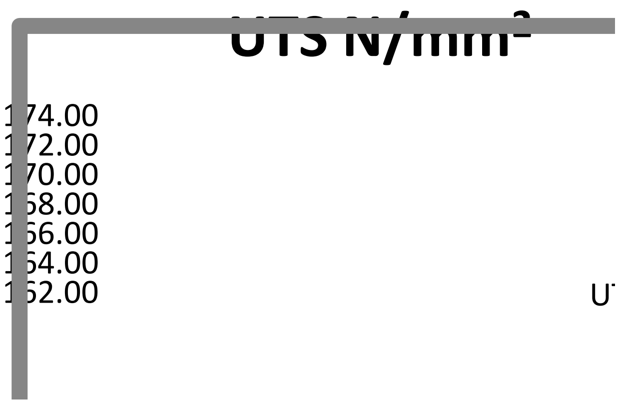


Figure 5.2.1.1.1 Ultimate tensile strength at constant 1200 r.p.m And Welding speed 45mm/min with Single Pass, Double Pass (same side)& double pass (reverse side)

From the Figure 5.2.1.1.1 it is concluded that the tensile strength increases with the double pass friction stir welding increases as compared to single pass friction stir welding. In case of single pass friction stir welding some defects are produced and the grains are not fine, but in case of double pass friction stir welding, defects produced with single pass are overcomed by double passing and also the grains are again refined and grain size decreases, become more fine as compared to single pass friction stir welding and hence the tensile strength increases in double pass friction stir welding as compared to single pass friction stir welding.

5.3. EFFECT OF FSW PROCESS PARAMETERS ON MICRO HARDNESS

The Vickers hardness profile of the welded specimens was measured at a distance 2.5mm from the top surface of the specimen thickness on a cross-section perpendicular to the welding direction using Vickers hardness tester with 300 gf load for 10 seconds. Hardness, points are taken at the nugget ,TMAZ,HAZ and base metal at perpendicular direction from the weld at 0,-2,-4,-6,-8,-10,-12,0,2,4,6,8,10,12 mm respectively. The Vickers hardness of the base metal was 83Hv.

Table 5.3.1 Hardness testing for square tool (single pass) for S1

Specimen/Distance from weld center	-12	-10	-8	-6	-4	-2	0	2	4	6	8	10	12
FS Welded	82	50	48.9	43	46	40.3	43	41	44	45.8	46	47.8	81

Table 5.3.2 Hardness testing for square tool (Double pass) for S2

Specimen/Distance from weld center	12	-10	-8	-6	-4	-2	0	2	4	6	8	10	12
FS Welded	87	55	48	46	45	40	43	43	45	49	45	47.8	87

Effect of Single pass and double pass on Micro hardness

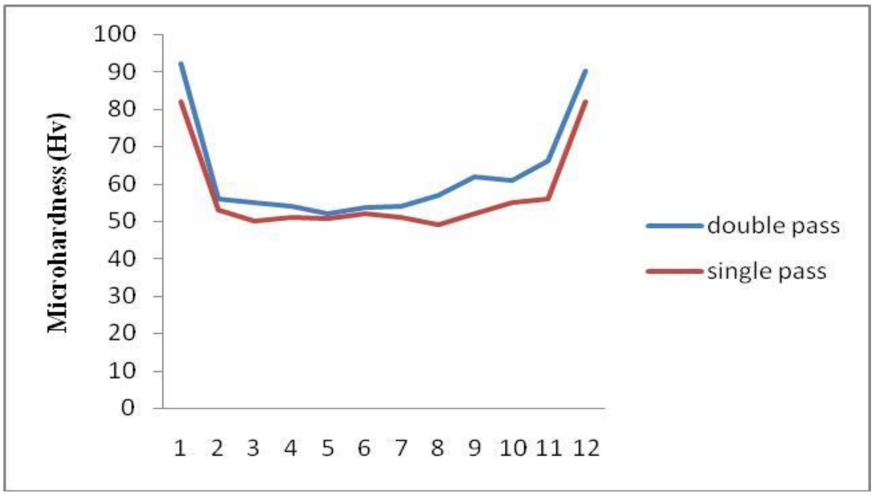


Figure 5.3.1 Effect of passes on Micro Hardness

From the Figure 5.3.1 it is concluded that the micro hardness value increases for the double pass friction stir welding as compared to single pass friction stir welding. According to (Shude ji et al.,2013) this is due to the material flow pattern in both the cases are different In case of single pass Friction stir welding, some tunnel defects are produced due to the material flow pattern due to heating. By the use of Double pass friction stir welding , the defects produced in single pass are removed because the grains are refined due to which the grains become more fine and grain size decreases and the micro hardness value increases with double pass friction stir processing.

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