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Research Article

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Effects of Friction Stir Welding on Hardness and Microstructure of AA6061-T651 Aluminium Alloy

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Abstract Friction stir welding (FSW) of AA6061-T651 aluminium alloy is carried out successfully to investigate the effects of welding parameters on microstructure and hardness of the joint. Being a solid state welding process; friction stir welding possess a number of advantages i.e. low distortion, absence of melt related defects and high joint strength. The process parameters involved in the present study are rotational speed and welding speed. The material chosen for friction stir welding is 6mm thick plates of AA6061-T651 aluminium alloy. The FSW is accomplished using a simple cylindrical pin tool made of high carbon high chromium (HCHCr) tool steel. The effects of process parameters (rotational speed, welding speed) on microhardness and metallurgical properties of friction stir welded AA6061-T651 aluminum alloy joints are investigated. The microstructures of the base alloy, heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ) and weld nugget are characterized by optical microscopy. Hardness of these welded zones is measured by Vickers microhardness tester. The microstructures of the friction stir welded specimens show that the process has resulted in significant grain refinement in the weld nugget region. The micro hardness results reveal that there is a reduction of 42.96 % in the hardness of the weld nugget region as compared to the base alloy.

Keywords Friction stir welding, AA6061-T651, Micro-hardness, Micro-structure

1. Introduction

Friction Stir Welding (FSW) is a fairly recent welding technique, invented by The Welding Institute (TWI), Cambridge, UK. This technique utilizes a non-consumable rotating welding tool to generate frictional heat and deformation at the welding location, thereby affecting the formation of a joint, while the material is in the solid state. The principal advantages of FSW, being a solid-state process, are low distortion, absence of melt-related defects and high joint strength, even in those alloys that are considered non-weldable by conventional techniques (e.g., 2xxx and 7xxx series aluminum alloys). Furthermore, Friction Stir welded joints are characterized by the absence of filler-induced problems / defects, since the technique requires no filler [1]. The basic concept of FSW is remarkably simple. A non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of the sheets or plates to be joined and subsequently traversed along the joint line.

In FSW a rotating pin emerging from a cylindrical shoulder is plunged between two pieces of shoot and mound forward along the joint line. The material is heated by friction between the rotating shoulder and the work piece surface and simultaneously stirred by the profiled pin leaving a solid phase bond between the two pieces to be joined. Special preparations of the weld seam and filler wire are not required. In contrast to conventional welding technologies, the FSW process takes place in the solid phase below the melting point of the metals to be joined [2]. The interference between the welding tool and the metal to be welded generates plastically deformed zone through the associated stirring action. At the same time, the thermo-mechanical plasticized zone is produced by friction between the tool shoulder and the top plate surface and by contact of the material with the tool edges, inducing plastic deformation. The probe is slightly shorter than the thickness of the work piece [3-4].

The localized heating softens material around the pin and, combined with the tool rotation and the translation, leads to movement of material from the front to the back of the pin, thus filling the hole in the tool wake as the tool moves forward. The tool shoulder restricts metal flow to a level equivalent to the shoulder position that is approximately to the initial work piece top surface [5].

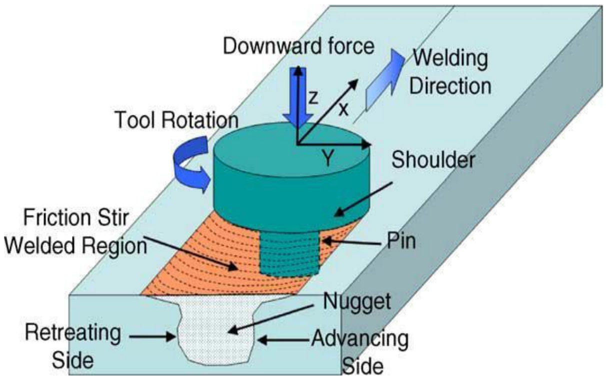


Figure 1: Schematic diagram of friction stir welding [5]

2. Experimentation

2.1. Workpiece Material for FSW

The work piece material AA6061-T651 in the form of rolled sheet of size 1200 mm x 300 mm x 6 mm has been purchased from M/s Mahender Prakash Ram Prakash, chawri bazaar, Delhi (India). The workpieces were then cut into small pieces of size 100 mm x 50 mm x 6 mm using press cutting machine as shown in figure 2. The chemical composition of AA6061-T651 aluminium alloy is given in table 1.

Figure 2: Test specimens of aluminium alloy AA6061

Table 1: Chemical composition of AA6061-T651 aluminium alloy

Cu	**Mg**	**Si**	**Fe**	**Ni**	**Mn**	**Zn**	**Pb**	**Sn**	**Ti**	**Cr**	**Va**	**Al**
0.211	1.180	0.810	0.321	0.013	0.068	0.169	0.010	0.003	0.061	0.046	<0.01	97.09

2.2. FSW Machine Setup

Friction stir welding is a versatile process which can be easily accomplished using a conventional vertical milling machine. In this research study, the HMT-FN2V conventional vertical milling machine available at M/s LARK ENGINEERING CO. (India) PRIVATE LIMITED, YAMUNANAGAR is modified to accomplish the friction stir welding. A dedicated fixture is developed to hold the work pieces in the appropriate position. The complete setup is shown in figure 3.

2.3. Fabrication of Friction Stir Welding Tool

Tool geometry, tool size and tool material are important aspects of friction stir welding. Tool should have higher melting point and higher hardness than the work piece material. The tool used in this study as shown in figure 4 is fabricated from 25 mm diameter round bar of High Carbon High Chromium tool steel.

Figure 3: Vertical milling machine HMT-FN2V *Figure 4: Fabricated FSW Tool*

3. Investigation of Microhardness and Metallurgical Properties

3.1. Production of Friction Stir Welded Specimens of Aluminium Alloy AA6061-T651

The specimens to be joined using friction stir welding are held on a dedicated fixture in order to prevent the displacement during the welding. At the weld line, at a distance of 10 mm from the extreme edge; a hole of diameter 6 mm is drilled. The purpose of this hole is to provide an easy path to the tool to plunge into the work-piece material. The fixture with the workpieces is then clamped tightly on the table of the converted vertical milling machine.

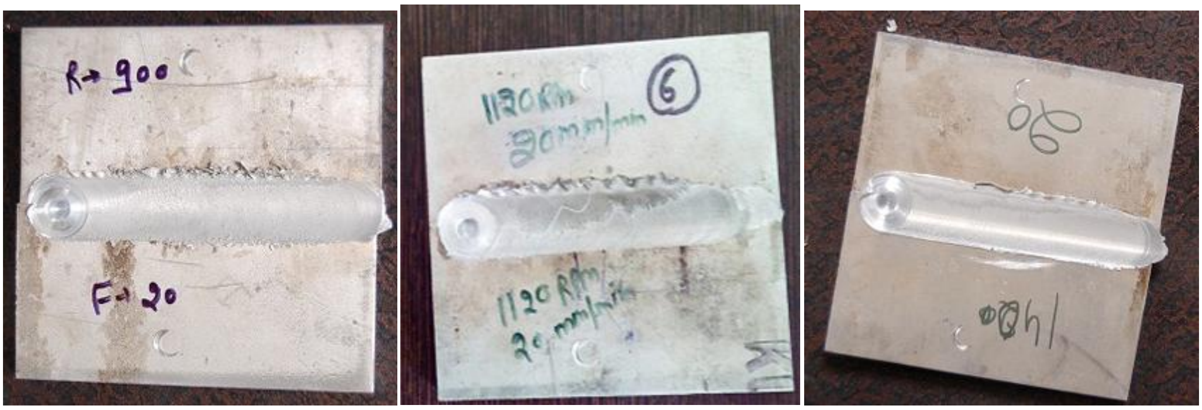


Figure 5: Friction stir welded AA6061-T651 alloy specimens

Table 2: FSW Process Parameters

Experiment No.	Speed (rpm)	Translation Speed (mm/min)
1	900	20
2	900	25
3	900	30
4	1120	20
5	1120	25
6	1120	30
7	1400	20
8	1400	25
9	1400	30

The friction stir welding tool is then mounted on the collet of the machine spindle and the spindle is rotated at desired rotational speed. The rotating tool pin is forced into the work-piece till the shoulder touches the upper surface of the workpiece. The length of the pin is kept slightly shorter than the thickness of the work pieces; therefore, the tool could be prevented to penetrate through the workpieces into the base plate. A dwell time of 40 seconds has been given to the tool after the plunge so that, sufficient frictional heat could be generated. The tool is then moved forward in the direction of weld line at desired welding speed. After the welding is accomplished, the tool is pulled out of the workpiece 10 mm before reaching the extreme edge of the workpiece. The specimens welded using different process parameters are shown in figure 5. The welding parameters were optimally chosen through Taguchi's L9 array. The two factors and three level design of experiments was adopted. Various welding parameters used in this study are given in the table 2.

3.2. Microstructural Testing

The microstructural testing of the base alloy and as welded specimens is done at U.I.E.T., MDU, Rohtak using optical microscopy. Dewinter make inverted optical microscope as shown in figure 6 with a zooming range of 50-400 µm has been used to study the microstructural evolution. The specimens for microstructural testing have been prepared using ASM 9 standards. The procedure for metallographic specimen preparation is as follow:

- The specimen was first ground on 60 grit emery paper, so that scratches were produced roughly at right angle to those initially existing on the specimen and produced through preliminary grinding.
- Grinding was then continued on the 80 grit emery paper, again turning the specimen through 90^o and grinding until the previous scratch marks were removed.
- The process is repeated with 120, 150, 220, 320, 400, 600 and 800 grit emery papers.
- In the next step, specimens were thoroughly polished on a rotating polishing wheel using Alumina powder.
- After fine polishing the specimens were etched with Keller's reagent (5 ml HNO_3).
- Specimens were then placed on the microscope to test the microstructures.

Figure 6: Optical Microscope

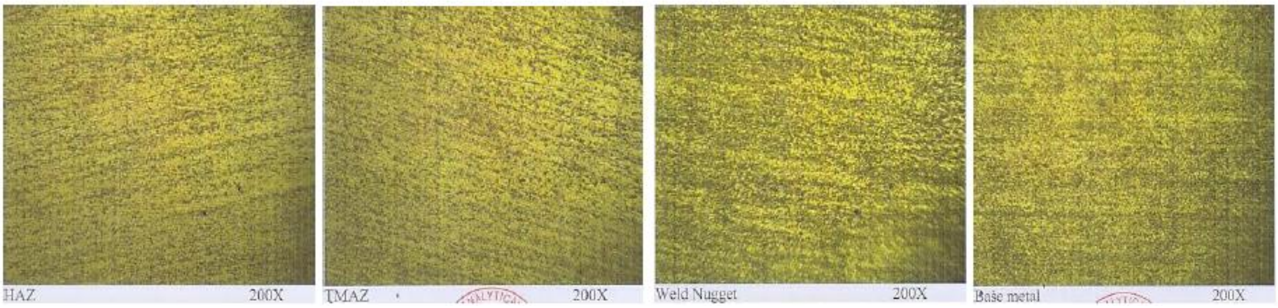
3.3. Microhardness Testing

Microhardness of base alloy AA6061-T651 and of as welded specimens is evaluated using FIE make Vickers Hardness Tester at U.I.E.T., Maharshi Dayanand University, Rohtak. The test load applied was 100gf with a dwell time of 10 seconds. The microhardness of all welded specimens was tested in different zones on the both sides of the weld at transverse plane i.e. in the base metal zone, Heat affected zone (HAZ), Thermomechanically affected zone (TMAZ) and in the weld nugget zone.

4. Results

4.1. Metallurgical Test Results

The metallographic tests using optical microscope at 200X zoom has been carried out to investigate the micro structural evolution during FSW of AA6061-T651 aluminium alloy. The micrographs of weld nuggets produced using various combinations of FSW parameters are shown in Figure 7 (a) to 7 (h).


HAZ
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TMAZ
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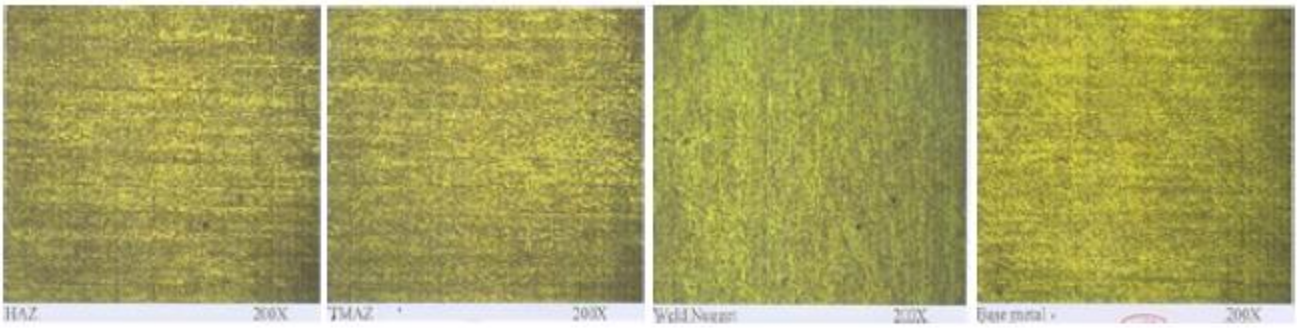
Weld Nugget
200X
Base metal
200X

a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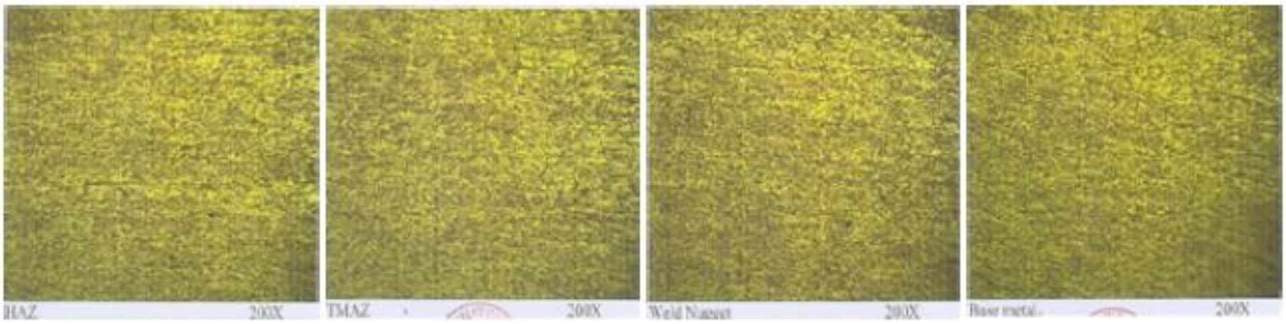
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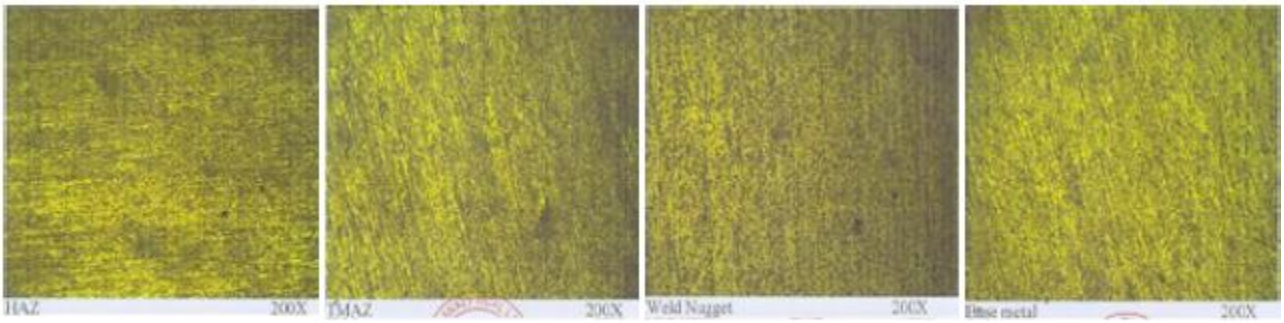
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TMAZ
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Weld Nugget
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Base metal
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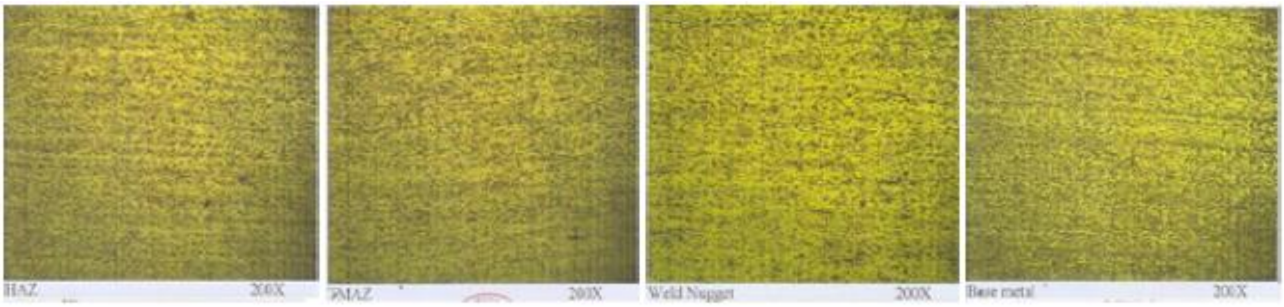
d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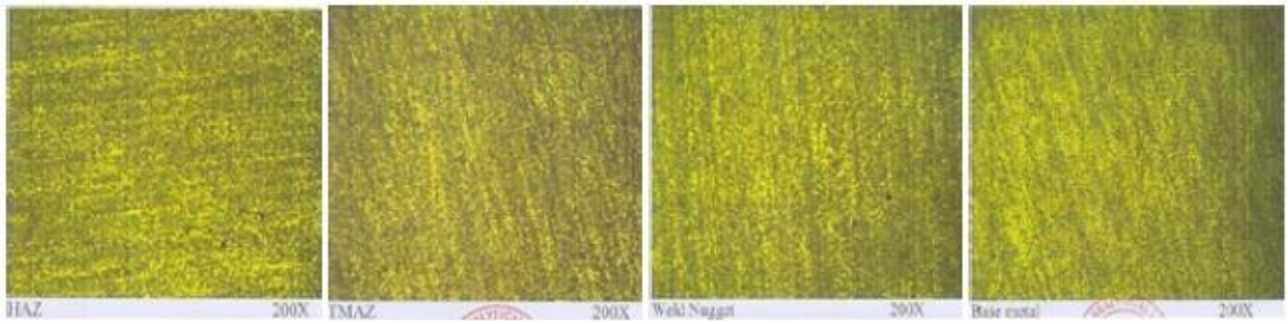

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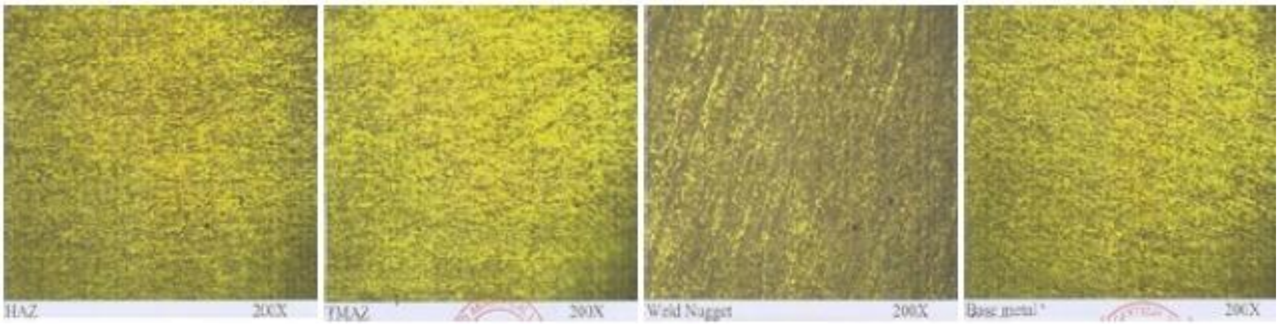

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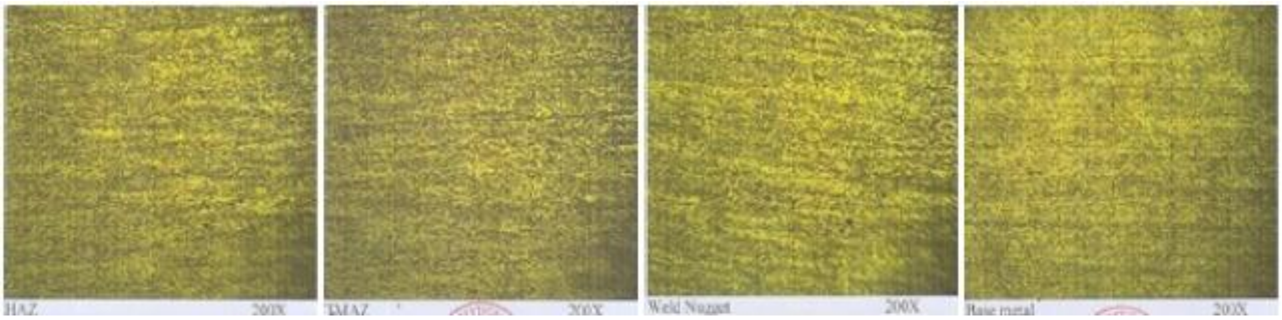

h

Figure 7: Microstructure of (a) specimen 1 (900 rpm and 20 mm/min) (b) specimen 2 (900 rpm and 25 mm/min) (c) specimen 3 (900 rpm and 30 mm/min) (d) specimen 4 (1120 rpm and 20 mm/min) (e) specimen 5 (1120 rpm and 25 mm/min) (f) specimen 6 (1120 rpm and 30 mm/min) (g) specimen 7 (1400 rpm and 20 mm/min) (h) specimen 8 (1400 rpm and 25 mm/min) (i) specimen 8 (1400 rpm and 30 mm/min)

4.2.1. Base Alloy

The microstructure of base alloy shows that the base alloy contains longer elongated fine grains. The average grain size is investigated to be 15-20 µm.

4.2.2. Heat Affected Zone (HAZ)

The microstructure of heat affected zones of all as welded specimens are investigated and the results show that the heat affected zone (HAZ) consists of grains having approximately the same size as that of base metal. This is because of the fact that the HAZ is only exposed to the welding heat but not the deformation and re-crystallization [5-7]. The average grain size in the HAZ has been observed to be 15 µm.

4.2.3. Thermo Mechanical Affected Zone (TMAZ)

Thermomechanically affected zone (TMAZ) is the transition zone between the base metal and the weld nugget, characterized by a highly deformed structure [6]. The microstructure in this zone consists of finer grains than that in the HAZ. The average grain size in the TMAZ is observed to be 10-15 µm, except in the specimen no. 7 and 8 where the average grain size is found to be 10 µm. This is due to high deformation and re-crystallization produce by high rotational speed of 1400 rpm.

4.2.4. Weld Nugget

Microstructure of weld nugget consists of finest, equiaxed and recrystallized grains of average size of 5-10 μm. The same results have also been mentioned in the previous studies [6], where the grain structure of the order of 4-5 μm has been observed. These very fine recrystallized grains present in the weld nugget zone are due to the high deformation and high temperature during the process. The grains in the weld nugget are much smaller and equiaxed when compared to the elongated base metal microstructure [8].

5. Microhardness Testing Results

The results of microhardness testing are shown in table 4. The microhardness of all as welded specimens was tested at various locations on both sides of the weld and also at the weld center. The results as shown in figure 8; reveal that the hardness values on advancing side of weld differ from that on retreating side [4]. There is not much difference in the hardness values of base alloy and the HAZ of both sides of all as welded specimens. The nugget zone or weld nugget experiences the lowest values of micro hardness for all welded specimens [9]. The weld nugget zone of all specimens is found to be softer than the base alloy [2, 8-9]. The average hardness value of the base alloy of all specimens is found to be 90.44 Hv and the average hardness of the weld nugget of all as welded specimens is 51.60 Hv. This shows that there is an average reduction of 42.96 % in the hardness of the base alloy. The thermomechanically affected zone on the both sides of the weld experiences intermediate hardness *i.e.* the hardness value in TMAZ lies between the hardness values of HAZ and weld nugget for all the specimens.

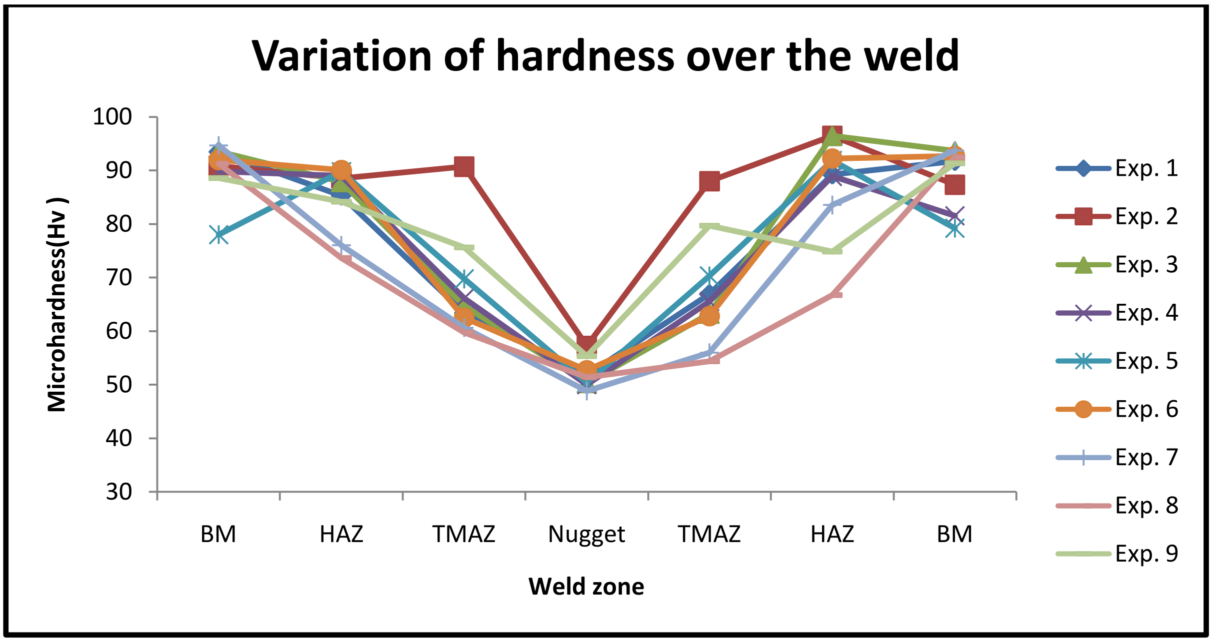

Figure 8: Microhardness of all as welded specimens

Table 3: Microhardness test results

Experiment No.	Base Metal	Advancing Side HAZ	Advancing Side TMAZ	Nugget	Retreating Side HAZ	Retreating Side TMAZ	Base Metal
1	93.45	85.32	63.37	51.83	66.93	89.25	91.77
2	90.87	88.53	90.70	57.25	88.01	96.45	87.32
3	93.51	87.84	64.71	50.33	63.29	96.48	93.65
4	89.85	89.01	66.16	50.02	65.56	88.91	81.54
5	78.02	89.75	69.76	50.40	70.30	91.88	79.23
6	91.97	90.10	62.49	52.72	62.80	92.22	92.68
7	94.67	76.07	60.67	48.85	55.99	83.55	93.71
8	91.24	73.67	59.75	51.42	54.38	66.72	92.46
9	88.56	84.19	75.63	55.32	79.66	74.83	91.32

6. Conclusion

Friction stir welding has proved its capability to join various metals and alloys especially aluminium based alloys. The paper explores and presents the investigation of effect of welding parameters on microhardness and metallurgical properties of friction stir welded AA6061-T651 aluminium alloy. The relationship among microhardness, microstructure and process parameters are also presented.

Following conclusions are derived from the present experimental work:

- The friction stir welding has proved to be the suitable process for joining AA6061-T651aluminium alloy and defect free joints were obtained using various combinations of process parameters.
- High Carbon High Chromium (HCHCr) tool steel has been used to accomplish the friction stir welding. HCHCr has proved to be an efficient tool material for the successful accomplishment of FSW AA6061-T651 aluminium alloy.
- The microstructure of the friction stir welded specimens show that the process has resulted in significant grain refinement in the weld nugget region.
- The microhardness results reveal that there is a reduction of 42.95 % in the hardness of the weld nugget region as compare to the base alloy. The maximum hardness of the nugget zone is obtained at a rotational speed of 710 rpm and a welding speed of 20 mm/min.

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