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Experimental Investigation of Mechanical Properties of Friction Stir Welded Butt Joint of Aluminium Alloy AA6061

Dr. T. Nancharaiah

Professor & Head, Deaprtment of Mechanical Engineering, Bapatla Engineering College, Bapatla-522102, A.P., INDIA

ABSTRACT

Friction Stir Welding (FSW) is solid state welding process. This process is widely used in now a day because it produces sound welds and does not have common problems such as solidification and liquefaction cracking associated with fusion welding techniques. Using Taguchi design of experiments, at different levels of identical process parameters, orthogonal array is selected based on the orthogonal array the test specimens are to be prepared using FSW process. The present work aims to determine the feasibility to weld aluminium alloy AA6061 by FSW process and study the effect of process parameters on the mechanical properties of welded joint. By using MINITAB17 analyzed the results and plotted the S/N ratio and mean graphs. Special welding fixture fixed on conventional milling machine has been conducted to attempt this welding. Finally, the mechanical properties of welded joints were investigated using destructive testing.

Key words: Friction stir welding, tensile strength, hardness, signal to noise ratio.

1. INTRODUCTION

Modern welding technology started just before the end of the 19th century with the development of methods for generating high temperature localized zones. Welding generally requires a heat source to produce a high temperature zone to melt the material; there are different methods and standards adopted to melt the material, though it is possible to weld two metal pieces without much increase in temperature. There are different and standards adopted for increase in temperature there is a still continuous search for new and improved methods of welding. Friction-stir welding was invented and experimentally proven by Wayne Thomas and a team of his colleagues at the TWI Welding Institute U.K in December 1991.TWI holds a patent for the process .In FSW a cylindrical-shouldered tool with a profiled threaded/unthreaded probe (nib) is rotated at a constant speed and fed at a constant traverse rate into the joint line between two pieces.

1.1 Introduction to FSW

Friction stir welding (FSW) was invented and patented in 1991 at TW1 in Cambridge (UK) and has been developed to a stage where it is applied in series production. Currently 53 organizations hold non-exclusive licenses to use the process. Most of them are industrial companies, and several of them exploit the process in commercial production. They have filed more than 285 patent applications related to FSW.

The work pieces of Aluminium Alloy have to be clamped onto a backing bar and secured against the vertical, longitudinal and lateral forces, which will try to lift them and push them apart (fixture)

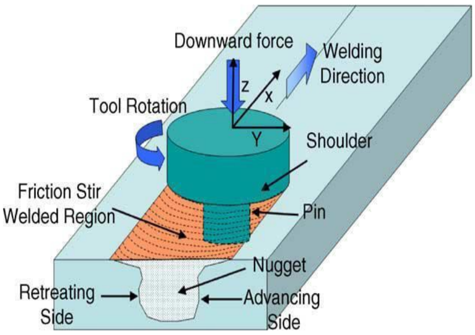


Fig 1: Schematic diagram of Friction Stir welding with a rotating tool

The salient features of the process which operates by generating frictional heat between a rotating tools (of harder material than the work piece being welded), to plasticize the abutting weld region. Commonly the tool is shaped with a large diameter of 20 mm shoulder and a small diameter its varying 3 mm, specially profiled, probe that makes contact first as it is plunged into the joint region. The components to be welded are secured to prevent the butted joint faces from being forced apart as the probe passes through and along the seam. The depth of penetration is controlled by the length of the probe below the shoulder of the tool.

The initial plunging friction contact heats the adjacent metal around the probe as well as a small region of material underneath the probe, but once in contact with the top surface of substrate the shoulder contributes significant additional heat to the weld region. In addition, the contacting shoulder, which can be profiled to provide improved coupling, prevents highly plasticized material from being expelled from the welding region.

Once the rotating tool is in position the thermally softened and heat affected region take up a shape corresponding to that of the overall tool geometry. The heat-affected region is much wider at the top surface (in contact with the shoulder).

The combined frictional heat from the probe and the shoulder creates a highly plasticized 'third-body' condition around the immersed probe and the adjacent contacting surface of the work piece top. This highly plasticized material provides for some hydrostatic effect as the rotating tool moves along the joint, which helps the plasticized material to flow around the tool. The plasticized weld material then coalesces behind the tool as the tool moves away.

Friction stir welding can be regarded as an autogenously keyhole joining technique, where consolidated welds are solid-phase in nature and do not show fusion welding defects. No consumable filler material or edge preparation is normally necessary. The distortion is significantly less than that caused by arc fusion welding techniques.

1.2 Micro structure classification of FS welds

The first attempt at classifying microstructures was made by P L Thread gill (Bulletin, March 1997). The system divides the weld zone into distinct regions as follows:

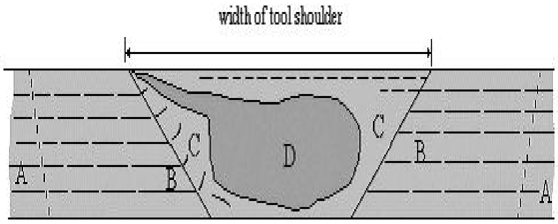


Fig.2: Microstructure of Friction Stir Welded joint

A. Unaffected material
B. Heat-affected zone (HAZ)
C. Thermo-mechanically affected zone (TMAZ)
D. Weld nugget (Part of thermo-mechanically affected zone)

a. **Unaffected material or parent metal**: This is material remote from the weld, which has not been deformed, and which although it may have experienced a thermal cycle from the weld is not affected by the heat in terms of microstructure or mechanical properties.
b. **Heat affected zone (HAZ):** In this region, which clearly will lie closer to the weld centre, the material has experienced a thermal cycle which has modified the microstructure and/or the mechanical properties. However, there is no plastic deformation occurring in this area.
c. **Thermally-mechanically affected zone (TMAZ):** TMAZ occurs on the either side of the stir zone. In this region the strain and temperature are lower and the effect of welding on the microstructure is correspondingly smaller. Unlike the stir zone the microstructure is recognisably that of the parent material, albeit significantly deformed and rotated. Although term TMAZ technically refers to the entire deformed region it is often used to describe any region not already covered by the terms stir zone and flow arm.
d. **Weld Nugget**: The recrystallized area in the TMAZ in aluminium alloys has traditionally been called the nugget. The microstructure here is determined by rubbing by the rear face of the shoulder, and the material may have cooled below its maximum. It is suggested that this area is treated as a separate sub-zone of the TMAZ.

1.3 Parameters

a. **Tool :** The rotating device between the machine spindle and the work piece is referred to as the tool. The part which creates stirring action is referred to as the pin. The part of the tool, which is pressed on to the surface of the work piece during welding is referred to as shoulder.

b. **Leading Edge and Trailing Edge:** In a non-cylindrical tool the terms leading edge (front face of the shoulder during welding) and trailing edge(rear face of the shoulder during welding) are used, whereas in cylindrical profiled tools there is clearly no edge and so the terms „leading face and trailing face may be preferred. Pin leading face‟ is the front face of the pin during welding. Similarly, Pin trailing face is the rear face of the pin during welding.

c. **Advancing side and Retreating side:** The side of the weld where the direction is same as the direction of rotation of shoulder is called the Advancing Side(AS) and where the direction is opposite to direction of rotation of shoulder is called the Retreating Side (RS). The total area of the tool on the work piece surface is described as the tool shoulder foot print.

d. **Forces:** Due to the force applied downward and due to the force with which the two plates to be joined are kept in contact at the time of process are Important in FSW process. The force applied parallel to the axis of the rotation of the tool (Z-direction) is the down force. The force applied parallel to the welding direction (X-direction) is the traversing force.

e. **Welding speed and Rotational speed:** The term welding speed is referred to travelling speed or traversing speed, which is the rate of travel of tool along line of joint. Tool Rotational Speed is the speed at which the friction stir welding tool rotates

1.4 Friction Stir Welding –Applications

The shipbuilding and marine industries are two of the first industry sectors which have adopted the process for commercial applications. The process is suitable for Panels for decks, sides, bulkheads and floors, Aluminium extrusions, Hulls and superstructures, Helicopter landing platforms, Offshore accommodation, Marine and transport structures, Masts and booms e.g. for sailing boats and Refrigeration plant.

2. LITERATURE REVIEW

Many researchers were carried out their research work on FSW of aluminium alloys, aluminium joint properties are studied. Qasim M Doos et al. (2012) determined the feasibility to weld two pieces of aluminium pipe by FSW process and study the effect of mechanical properties of welding joint. Xun Liu,et al(2014) et al. indicate that the weld nugget can be considered as aluminium matrix composite, which is enhanced by dispersed sheared-off steel fragments encompassed by a thin intermetallic layer or simply intermetallic particles. Effects of process parameters on the joint microstructure evolution were analysed based on mechanical welding force and temperature that have been measured during the welding process. B. Ravi sankar, P. Umamaheswarrao (2014), studied the influence of various operating parameters on the mechanical properties of the friction stir welded joint on AA6061 alloy. Zhihua Song et al. (2014) et al. conducted experiment on effect of probe offset distance on the interfacial microstructure and mechanical properties of butt joint. They stated that when the probe offset distance is not sufficient, two alloys cannot be completely joined together. Kovacevic (2003) studied the friction stir welding (FSW) is a relatively new welding process that may have significant advantages compared to the fusion processes. Chen et al. (2008) focused on Al–Si alloy and pure titanium were lap joined using friction stir welding technology. Microstructure and tensile properties of joints were examined.

From the literature survey, the researchers worked on FSW where considered mainly AA6061 series alloys and the properties were studied. Hence, it is proposed to work on FSW considering aluminium alloys series and the materials properties are to be compared.

3. EXPERIMENTAL SETUP

A conventional vertical 3 axis milling machine was used for friction stir processing (FSW) of AA6061. The machine could achieve the maximum speed of 2000 rpm . The AA6061 plate dimensions of 100mm (L) 65mm (W) 8mm (T) were used in present study. The AA6061 plates were clamped rigidly on backup plate to produce butt joint using the FSW technique as shown in fig .3.1. The experiments are conducted on the AA6061. Before the friction stir welding, the weld surface of the base material was cleaned. The FSW tool is then placed in to the bit. The sample plunged with downward ward feed rate in to the sample then moves linearly through rotating tip along butt line with certain feed rates are 11mm/min and 18 mm/min. When the central point of the tool reaches the given welding length of 65mm, the linear movements stops and the tip is lifted out of the sample with a certain upward feed. AA6061 butt joint was made using H13tool under controllable process parameters like rotational speeds of 1340,2000 rpm and tool tilt angles of 0,2 degree. Based on this a total of 4 experiments were carried out.

Fig 3: Conventional milling machine with work piece and tool

3.1 Flow chart:
The experimental setup of friction stir welding at various stages are shown as flow chart in the below fig (4).

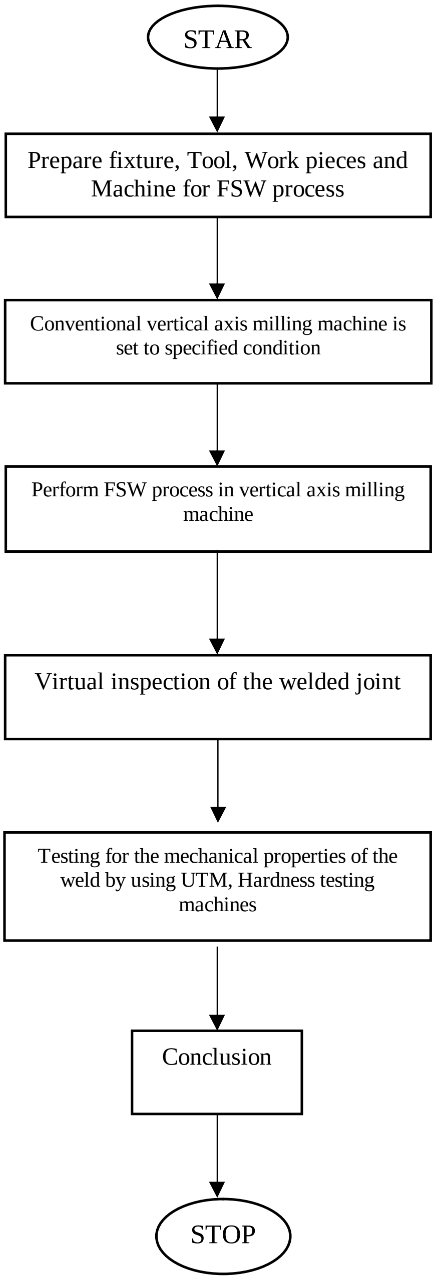


Fig 4: Flow chart for experimentation

3.2 Base material:

The present work, AA6061 aluminum alloy was selected as base material of 8mm thick. The base material plates were prepared with the dimensions of 100x65x8mm whose properties are listed in below tables.

Properties of AA6061:

Properties of aluminum alloy AA6061 were listed below.

Table 3.1: Composition of AA6061

Elements	Aluminum	Silicon	Iron	Copper	Magnesium	Other elements
Weight %	95.8-98.6	0.40-0.8	0.7	0.15-0.4	0.8-1.2	2.15

Table 3.2: Physical properties of AA6061

Physical property	Density (g/cm^3)	Melting point(C)	Modulus of elasticity (Gpa)	Poisson's ratio
Base metal(AA6061)	2.7	585	68.9	0.33

Table 3.3: Mechanical properties of AA6061

Mechanical property	Yield stress(Mpa)	Ultimate tensile strength (Mpa)	Hardness number(BHN)	Elongation (%)
Base metal(AA6061)	55	120	30-33	25-30

3.3 Tool selection

- Cylindrical with threaded shape tool is selected.
- Threads are used to transfer material from bottom of shoulder to the bottom of the pin.

Tool specifications

Fig 5: Cylindrical tool with threaded pin

Table 3.4 Tool specifications

Specifications	Values
Tool material	High speed steel
Shoulder diameter	16mm
Pin diameter	M8x1mm
Pin length	7.4mm
Tool length	100mm

Table 3.5 Number of experiments obtained by taguchi orthogonal array

S.no	Feed(mm/min)	Speed(rpm)	Tilt (degree)
1	2000	11	0
2	2000	18	2
3	1340	11	2
4	1340	18	0

3.4 Evaluation of mechanical properties

Tensile test

a) Clamp the test piece in a suitable gripping device in such a way that the force is applied as axially as possible. Attach the extensometer to the test piece.

b) Apply a tensile force on the test piece so as to strain the test piece in a non- decreasing manner, without shock or vibration. Maintain the speed of testing within the limits specified.

Record the force and the corresponding extension.

c) Calculate the tensile strength (Rm) by dividing the maximum force (Fm) by the original Cross-sectional area (So) of the test piece. Rm=Fm/So

Fig 6: Specimens for tensile testing

Fig 7: Specimens after tensile test

Hardness test

Hardness is the resistance to plastic deformation (e.g., a local dent or scratch). Thus, it is a measure of plastic deformation, as is the tensile strength, so they are well correlated. Historically, it was measured on an empirically scale, determined by the ability of a material to scratch another, diamond being the hardest and talc the softer. Now we use standard tests, where a ball or point is pressed into a material and the size of the dent is measured. There are a few different hardness tests: Rockwell, Brinell, Vickers, etc. They are popular because they are easy and non-destructive (except for the small dent).

4. RESULTS AND DISCUSSION

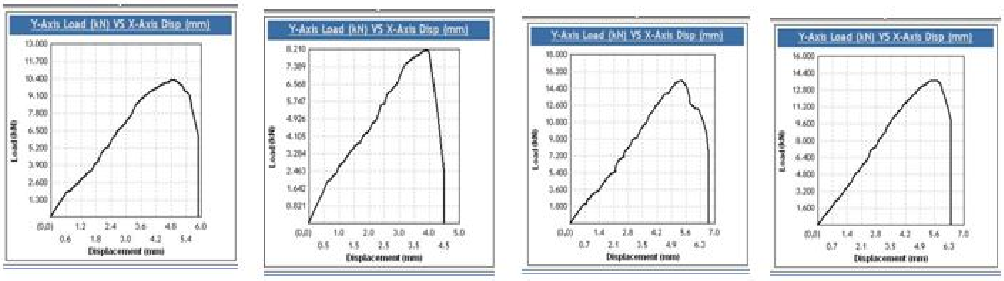
The experimented details of friction stir welding process for AA6061 material have been discussed in previous chapter. From the experimental results, it is found that the joints are fabricated using different rotational speeds, welding speed, tilt angles and ensure axial force and tool diameter as constant.

Table 4.0 Process Parameters and their levels

Sl No.	Process Parameter	Level 1	Level 2
1	Speed (rpm)	2000	1340
2	Feed (mm/min)	11	18
3	Tilt (degree)	0	2

Table 4.1: Table showing results of tensile test and hardness.

S.No	Speed (rpm)	Feed (mm/ min)	Tilt (degree)	Ultimate tensile strength (N/mm^2)	Yield strength (N/mm^2)	Percentage of elongation (%)	Brinell's hardness number
1	2000	11	0	76.0020	68.682	5.780	64.53
2	2000	18	2	57.591	37.264	3.160	59.73
3	1340	11	2	110.523	109.65	7.300	60.07
4	1340	18	0	96.813	63.604	6.040	74.20



Load vs displacement curve (sample1)

Load vs displacement curve (sample2)

Load vs displacement curve (sample3)

Load vs displacement curve (sample4)

Fig 8: Load vs Displacement curves for samples 1, 2, 3 &4

Table 4.2 Values of S/N ratio and mean of Ultimate tensile strength

s.no	Speed(rpm)	Feed(mm/min)	Tilt (degree)	Ultimate tensile strength (N/mm^2)	S/N ratio	Mean
1	2000	11	0	76.02	37.6186	76.02
2	2000	18	2	57.591	35.2071	57.591
3	1340	11	2	110.523	40.8691	110.523
4	1340	18	0	96.813	39.7187	96.813

Table 4.3 Response table for S/N ratio of Ultimate tensile strength

Level	Speed(rpm)	Feed(mm/min)	Tilt(degree)
1	40.29	39.24	38.67
2	36.41	37.46	38.04
Delta	3.88	1.78	0.63
Rank	1	2	3

Table 4.4 Response table for mean values of Ultimate tensile strength

Level	Speed(rpm)	Feed(mm/min)	Tilt(degree)
1	103.67	93.27	86.42
2	66.81	77.2	84.06
Delta	36.86	16.07	2.36
Rank	1	2	3

Fig 9 Main effects plot for means of Ultimate tensile strength

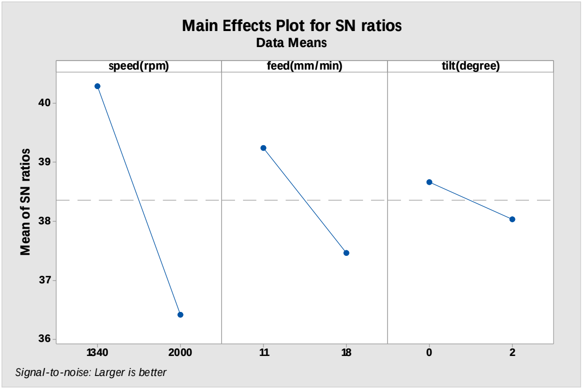


Fig 10 Main effects plot for S/N ratios of Ultimate tensile strength

Table 4.5 Values of S/N ratio and mean of Yield strength

s.no	Speed(rpm)	Feed(mm/min)	Tilt (degree)	Yield strength(N/mm^2)	S/N ratio	Mean
1	2000	11	0	68.682	36.7369	68.682
2	2000	18	2	37.264	31.4258	37.264
3	1340	11	2	109.653	40.8004	109.653
4	1340	18	0	63.604	36.0697	63.604

Table 4.6 Response table for S/N ratio of Yield strength

Level	Speed(rpm)	Feed(mm/min)	Tilt(degree)
1	38.44	38.77	36.4
2	34.08	33.75	36.11
Delta	4.35	5.02	0.29
Rank	2	1	3

Table 4.7 Response table for mean values of Yield strength

Level	Speed(rpm)	Feed(mm/min)	Tilt(degree)
1	86.63	89.17	66.14
2	52.97	50.43	73.46
Delta	33.66	38.73	7.32
Rank	2	1	3

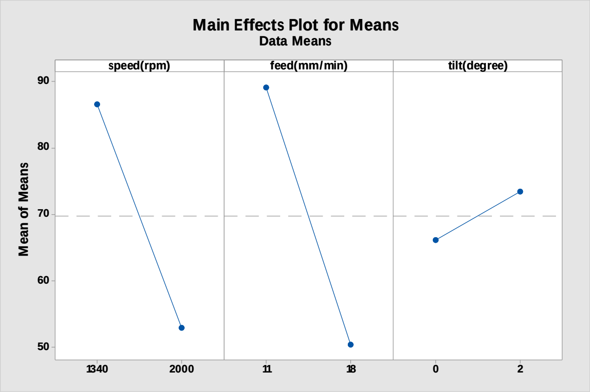


Fig 11 Main effects plot for means of Yield strength

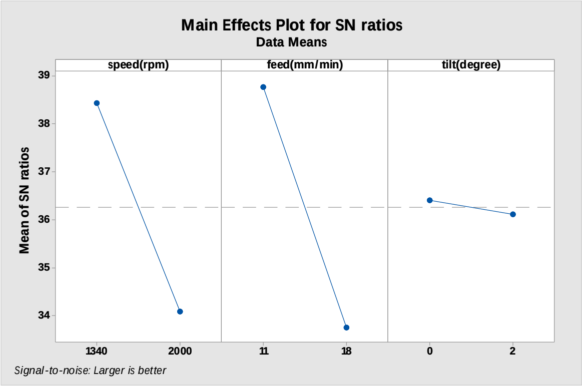


Fig 12 Main effects plot for S/N ratios of Yield strength

Table 4.8 Values of S/N ratio and mean of Percentage of elongation

s.no	Speed(rpm)	Feed(mm/min)	Tilt (degree)	Percentage of elongation (%)	S/N ratio	Mean
1	2000	11	0	5.78	-15.2386	5.78
2	2000	18	2	3.16	-9.9937	3.16
3	1340	11	2	7.3	-17.2665	7.3
4	1340	18	0	6.04	-15.6207	6.04

Table 4.9 Response table for S/N ratio of Percentage of elongation

Level	Speed(rpm)	Feed(mm/min)	Tilt(degree)
1	-16.44	-16.25	-15.43
2	-12.62	-12.81	-13.63
Delta	3.83	3.45	1.8
Rank	1	2	3

Table 4.10 Response table for mean values of Percentage of elongation

Level	Speed(rpm)	Feed(mm/min)	Tilt(degree)
1	6.67	6.54	5.91
2	4.47	4.6	5.23
Delta	2.2	1.94	0.68
Rank	1	2	3

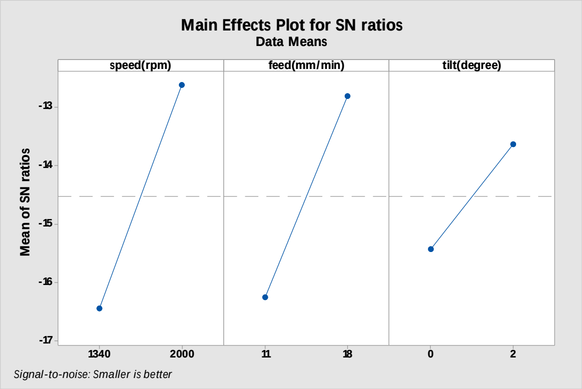


Fig 13 Main effects plot for means of Percentage of elongation

Fig 14 Main effects plot for S/N ratios of Percentage of elongation

Table 4.11 Values of S/N ratio and mean of Brinell hardness number

S.no	Speed(rpm)	Feed (mm/min)	Tilt (degree)	Brinell hardness number(BHN)	S/N ratio	Mean
1	2000	11	0	64.53	36.1952	64.53
2	2000	18	2	59.73	35.5239	59.73
3	1340	11	2	60.07	35.5732	60.07
4	1340	18	0	74.2	37.4081	74.2

Table 4.12 Response table for S/N ratio of Brinell hardness number

Level	Speed(rpm)	Feed(mm/min)	Tilt(degree)
1	36.49	35.88	36.80
2	35.86	36.47	35.55
Delta	0.63	0.58	1.25
Rank	2	3	1

Table 4.13 Response table for mean values of Brinell hardness number

Level	Speed(rpm)	Feed(mm/min)	Tilt(degree)
1	67.14	62.3	69.37
2	62.13	66.97	59.9
Delta	5.01	4.67	9.47
Rank	2	3	1

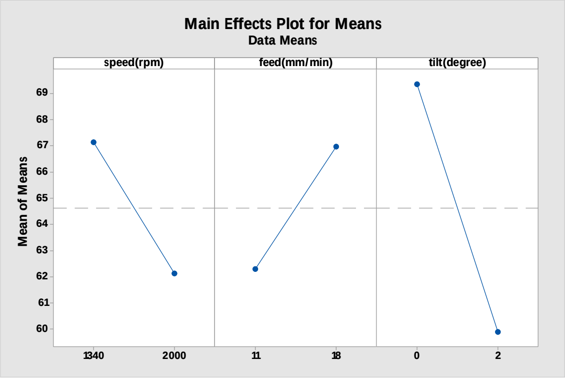


Fig 15 Main effects plot for means of Brinell hardness number

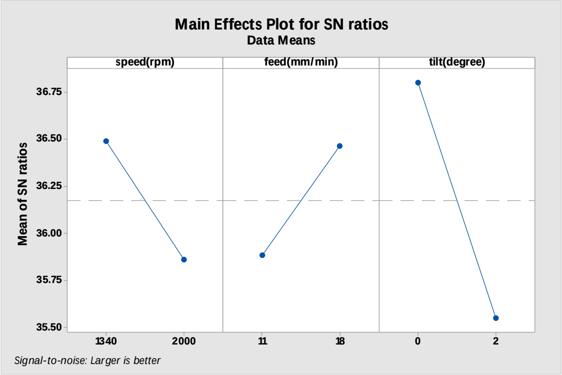


Fig 16 Main effects plot for S/N ratios of Brinell hardness number

5.CONCLUSION

In this work, aluminium alloy of AA6061 can be weld successfully by using friction stir welding process. Also we studied that the effect of process parameters on the mechanical properties of welded joint. The experimental results were analyzed using MINITAB17 and conclude the following:

(1) Lower speed, feed and zero drill can give high ultimate tensile strength.
(2) Lower speed and tilt and higher speed gives higher hardness value.

Also it can be concluded that the effect of rotational speed of tool is more on ultimate tensile strength and tilt angle effect is more on hardness.

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