ISSN: 2277-9655
Scientific Journal Impact Factor: 3.449
(ISRA), Impact Factor: 1.852

IJESRT
INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY

Feasibility of Underwater Friction Stir Welding and Its Optimization Using Taguchi Method

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Abstract

In this paper we are approaching to the feasibility of underwater friction stir welding of aluminum alloy which widely has the various applications where strength to density ratio plays a crucial role such as in marine, aircraft and automobile industries. The problems associated with joining of parts through conventional welding method is overcome by use of friction stir welding process yet the friction stir welding encloses the problems such as rapid tool wear especially during plunging period of tool, softening of the weld nugget formed due to decreased rate of cooling hence formation of precipitates takes more time which causes the mechanical properties such as strength, hardness etc are reduced and dissimilar base materials with considerable difference in their melting points are still a challenge to be welded by the present process . To overcome the above difficulties of the modified form of process of friction stir welding is used hence the whole process is performed under water i.e Underwater friction stir welding is used now a days.

Keywords: Underwater fiction stir welding, Milling machine, Vicker's Hardness, Tesile test.

Introduction

Friction stir welding (FSW), as a solid state joining process, has been successfully utilized to weld various precipitate hardened aluminum alloys [1]. However, it has been demonstrated that FSW tends to create a softening region in the joints due to the dissolution or growth of the strengthening precipitates during the welding, thus leading to a degradation of mechanical properties of the joints[4]. The softening region consists of the weld nugget zone (WNZ), the thermal mechanically affected zone (TMAZ), and the heat-affected zone (HAZ). Generally, the HAZ is the weakest location of the joints since it experiences the greatest coarsening and transformation of meta-stable precipitates but does not achieve the sufficient temperature for re precipitation [8]. Accordingly, improving the mechanical properties of the HAZ is crucial to the optimization of the whole joint performances. In order to weaken the negative effect of thermal cycles on the HAZ and improve the mechanical properties of the joints, external liquid cooling has been applied during FSW in several investigations. Benavides et al. [12] developed FSW experiment of 2024 aluminum alloy using liquid nitrogen cooling to decrease the initial temperature of plates to be welded from 30 to 30 LC. It was found that the hardness of the HAZ was remarkably improved, but void defect was formed in the WNZ and the hardness-microstructure relation-ship was not clarified.

Fratini et al. [13] and the present authors [14] considered water as the cooling liquid to exert an in-process heat treatment on welding samples during FSW. Likewise, a notable hardness improvement was observed in the HAZ. However, the micro structural evolution dominantly causing the hardness improvement was still not illuminated. In this article, a 2219-T6 aluminum alloy was friction stir welded under two kinds of circumstances. One is in air, and the other is under water. The purpose of the present study is to clarify the intrinsic reason for the hardness improvement in the HAZ from the aspects of microstructures and welding thermal cycles when external liquid cooling is applied during FSW.

This thesis presents the relation between the welding speed, tool profile and angle of tool inclination that how it effects the weld quality of the specimen .the weld quality is analysis against three parameters that are through microstructure analysis, tensile strength test and Vickers hardness. Further the optimized parameter is obtained through Taguchi optimization technique for which software Mini Tab 16 is used.

Literature review

The friction stir welding (FSW), a new solid-state welding process invented by The Welding Institute (TWI) in 1991, has been widely used in the area of space, aircraft and marine industries[1] .In this process a tool is rotated and traversed along a square butt weld joint similar to milling technique. The frictionally heated material around the tool pin is plastically deformed and extruded to the back of the pin where it joins and forms the weld. FSW offers several advantages over conventional fusion welding processes, due to its low heat input and absence of melting and solidification process. The most important benefits of FSW are its ability to weld the materials that were thought of difficult to be welded, such as aluminum alloys. FSW is a solid state joining process and gives better material properties, fewer weld defects lower residual stresses and improved dimensional stability[2]. Minton *et al.*[3] demonstrated the use of a common milling machine with a less optimal tool for FSW of aluminum alloys. Ericsson *et al.*[4] studied the influence of welding speed on fatigue strength of aluminum alloy 6082 welded by FSW and predicted that weld speed in the tested range has no influence on fatigue properties of the friction stir weld. The influence of stirrer geometry on bonding and mechanical properties of A1018 alloy metals was studied by Mustafa Boz *et al.*[5] and it was found that a 0.85 mm screw pitched stirrer had given the best bonding and mechanical properties. Yan-hua Zhao *et al.*[6] studied the influence of stirrer geometry on bonding and mechanical properties of aluminum alloy 2014, and reported that joint welded by taper screw thread pin had the best tensile properties. Scialpi *et al.*[7] studied the effect of tool shoulder geometry on mechanical and microstructural properties of friction stir welded 6082-T6 alloy. Results showed that there was no considerable change in transverse tensile strength of the weld due to shoulder geometry. Santella *et al.*[8] illustrated the potential of friction stir processing (FSP), to improve the mechanical properties of cast aluminum alloys A356 and A319. They suggested that FSP is a viable alternative to the hot isostatic pressing of the casting. Ceschini *et al*.[9] studied the effect of friction stir welding on microstructure, tensile and fatigue properties of AA7005/10 vol. % Al_2O_3 composite, and reported that the tensile test had evidenced a FSW joint efficiency of 80% compared to ultimate tensile strength. Abbasi Gharacheh *et al.*[10] carried out a study on friction stir welding of magnesium alloy, and concluded that the ratio of rotational speed/traverse speed (mm/v) is an important parameter which affects the tensile properties of material.. Reynolds[12] studied the material flow behaviour of material 2195 and identified various zones such as weld nugget, thermo-mechanically affected zone and heat affected zone in the weldment. S Yazdanian et al. [13] scrutinized the effect of pin length, welding speed and rotation rate on the weld strength using AA 6060 as work piece for FSW. The major factor in determining the weld strength is the rotation speed of the tool. Higher rotation rate made the joint weak and vice versa. Effect of rotation speed on heat generation and material flow was also enlightened. It was found that higher rotation rate may result in larger interface lifting and hence higher degree of hooking, reducing the effective weight bearing area.

Operational Principal of Friction Stir Welding

FSW produces high quality welds that can be fabricated with absence of solidification cracking, porosity, oxidation and other defects typical of traditional fusion welding techniques [Chao et al., 2003]. FSW has the capacity to develop welds of materials and alloys that were difficult to weld using traditional welding methods [Deqing et al., 2004]. It is used to join dissimilar aluminium alloys, having different mechanical properties, without weld zone defects, even under a wide range of welding conditions [Lee et al., 2003].

One particular benefit of FSW is the formation of the weld joint created by the solidification of the plasticized parent materials rather than using a filler material. The filler material normally produces welds with inferior properties to those made up of only the parent material. The FSW process also produces welds with narrower heat-affected zones than those produced by fusion welding techniques [Deqing et al., 2004].

Figure 1 illustrates the basic setup typical of the FSW process. The rotating FSW tool pin is plunged into the interface at one end of the material, and halted until there is adequate frictional energy to plasticize the material around the tool shoulder before the tool transverses the material interface. As the tool is moved along the welding joint, it leaves the plasticized material to be cooled, thus solidly bonding the interface [Colegrove et al., 2003].

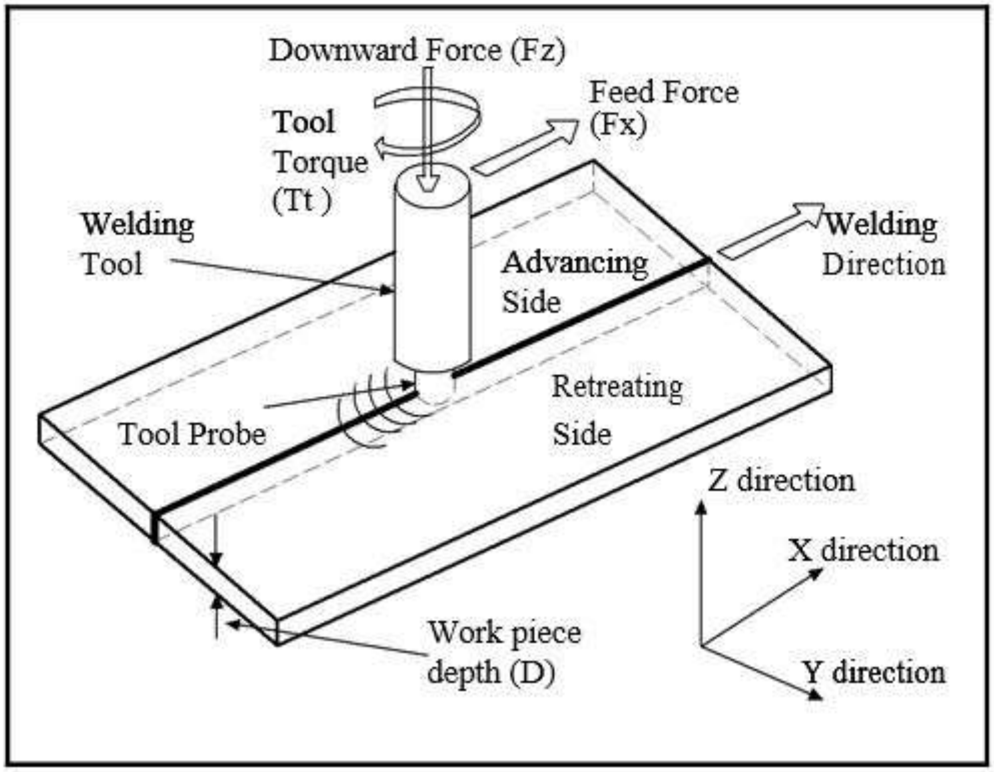

Fig 1 A basic FSW process setup for making butt joints.

The tool probe or pin profile tends to control the mixture of the material for a satisfactory weld. The shoulder of the welding tool compresses the surface of the work-piece and contains the plasticized material within the weld region. It also forms the main source of heat during the welding process.

Experiment Setup

FSW research platform used for research activities at NIET. A conventional CM milling machine forms the basis of the adapted milling machine for FSW process. The welding machine has a table size of 100 by 700 mm. The 5.5kW and 1.5kW 3-phase squirrel cage induction motors are used for the spindle and bed feed respectively

Fig 2:- FSW research platform at NIET.

Siemens Micro master 440 Inverters provide the interfaces between each motor and the computer. The computer controlled electromagnetic clutches and brakes are used to control the bed feed movement. The welding head is able to move in the up-down direction, while the table can be moved in the forward-backward and sideways directions. One of the machine's limiting factors is that the machine can only move one axis at a time.

Support and Clamping Structure Used For Underwater FSW

The basic structure used for the clamping arrangement for holding the specimen during the welding process. This type of setup is typical of a FSW machine designed to perform linear butt joints. The welding tools and backing plates, used to weld aluminum alloys, are normally made up of carbon-steel.

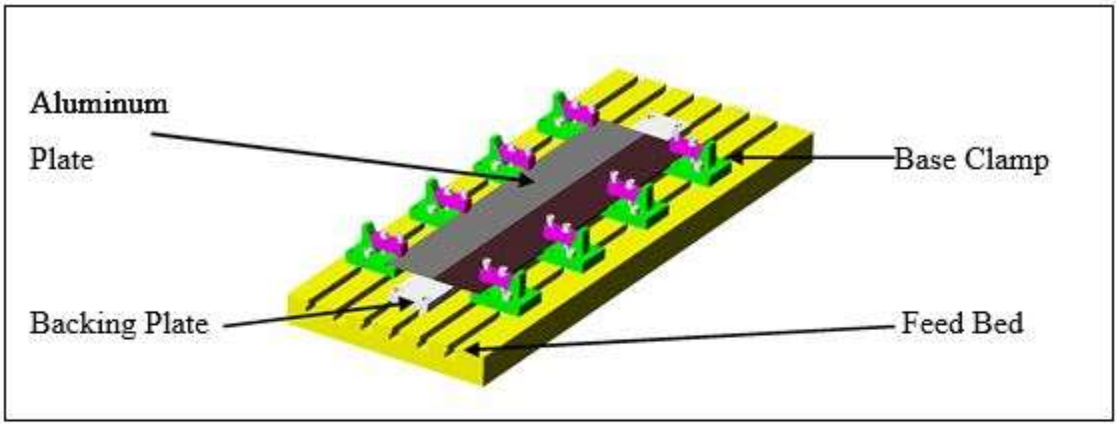

Fig 3: The clamping arrangement for FSW process .

The work-piece is normally laid horizontally onto a steel backing plate and the welding direction is made to be perpendicular to the rolled direction of the aluminum plates The pin length of the welding tool is determined by the thickness of the welded plates. The tool pin is designed to be slightly shorter than the thickness, to avoid contact with the backing plate surface and bringing debris into the weld.

The base clamps are used to rigidly hold the work-piece along its sides; thereby preventing the lateral movement of the work-piece during the welding process. They are also used to prevent the plasticized material from extruding through the interface to the underside of the joint .

Welding Tool Properties

As both the welding tool pin and shoulder contribute to the generation of energy input to the weld, one of the main issues is how their combinations affect the quality of the produced weld. the experiments are conducted to determine the relationship between the dimensions of the welding tool and the quality of the produced weld . Both the tool shoulder and pin are made up of stainless steel are used as per the dimensions given below. The pin diameter is made to be smaller than the diameter of the tool shoulder, about one-third of the shoulder's diameter for the production of good quality welds.

The tool profile also plays a crucial role in producing the quality joint. Thus, the tool with hexagonal, square and triangular profile are used in the experiment process and effects are analyzed the tools with different profile are shown in the figure.

Fig 4 : The Tool Profile Used

Under water FSW Plate Material

The various similar and dissimilar materials can be easily welded using Friction Stir Welding Process. For the analysis of Underwater FSW process feasibility and its optimization the base material plates of aluminum 6061 alloy are used which are butt welded .the plates are shown in Fig 5 and its composition details are given in Table 1

Figure 5: The Base Material Plates Welded

Table 1: The composition of Aluminum Plates Used.

S.No.	Fe	Si	Mg	Mn	Cr	Zn	Ti	Cu	Al
1.	0.27	0.72	0.90	0.30	0.03	0.07	0.02	0.95	Bala.

Various FSW Process Parameters

The tool feed rate and welding speed form the main parameters of the FSW process. The feed rate affects the micro hardness of the weld and decreases as the feed rate is increased. The hardness strength of the welds has a strong dependency on the tool welding speed. The correlation is discussed after the experimentation is performed and analysis carried out. The experimental domains for the welding parameters, welding conditions and process variables.

Table 2: various FSW welding parameters.

S. NO.	Welding parameters
1	Welding speed
2	Tool rotation speed
3	Tool material
4	Tool offset angle
5	Tool profile

The welding of the aluminum 6021 alloy is carried out by varying the 3 parameters that are tool rotation speed, tool offset angle and tool profile. The levels of input for welding are given as follows:

Parameters	Level 1	Level 2	Level 3
Tool Rotation Speed	1200	1300	1400
Tool offset Angle	2	3	4
Tool Profile	Triangular(T)	Hexagonal(H)	Square (S)

The experimental data analysis is done through the test and verification of the welding of aluminum plates welded through the underwater FSW welding set up which is discussed earlier in previous chapter. Thus, in this chapter the weld quality is discussed as obtained by the process. The micrographs are analyzed is done to observe the changes in microstructure occurs due to welding. And further the Hardness tests are carried out to observe the strength of the welds.

Micro-structural Test Results:

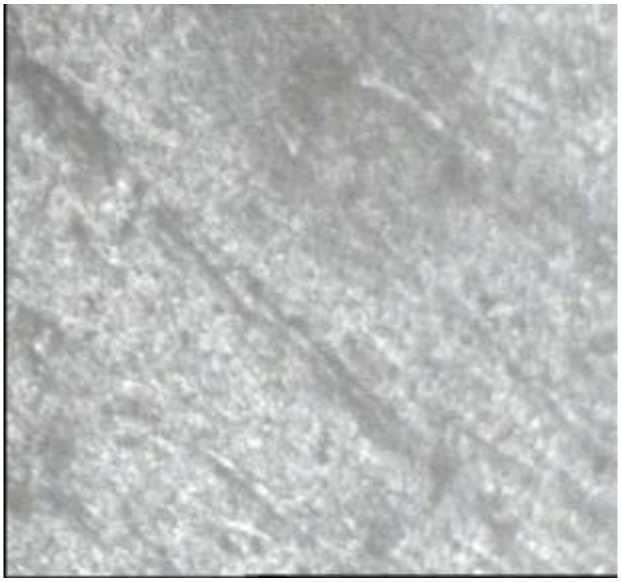

Figure 6- Micrograph Of Weld

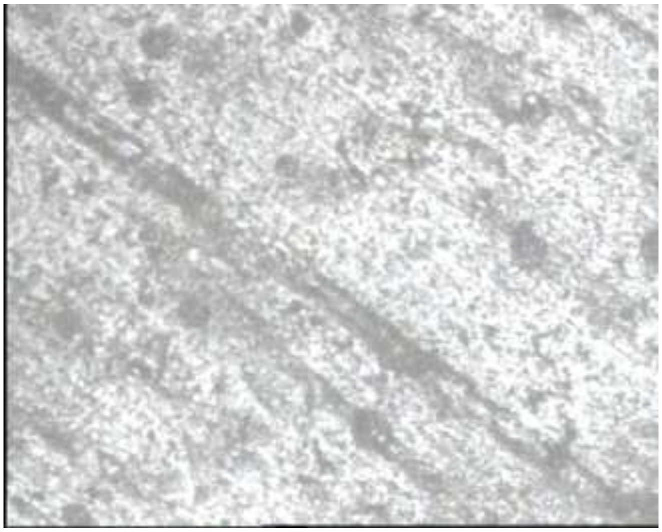

Figure: 7 micrograph of weld 2

Microstructure analysis reveals that the joint is clearly visible. Very small amount of porosity is observed No cracks was observed No voids was observed. No unwanted element is present at the joint.

Tensile Test Result:

Exp.no.	Rotational speed	Angle	Profile	Strength	Elongation.
1	1200	2	T	310	5.570
2	1200	3	H	350	8.446
3	1200	4	S	360	9.867
4	1300	2	H	390	10.034
5	1300	3	S	420	13.636
6	1300	4	T	400	12.336
7	1400	2	S	295	5.140
8	1400	3	T	285	5.461
9	1400	4	H	320	7.210
Average :				347.78	8.633

Vicker's Hardness Test Result:

Exp.no.	Rotational Speed	Angle	Profile	Hardness
1	1200	2	T	90.996
2	1200	3	H	105.473
3	1200	4	S	108.406
4	1300	2	H	113.267

5	1300	3	S	126.000
6	1300	4	T	120.208
7	1400	2	S	85.970
8	1400	3	T	87.221
9	1400	4	H	95.123
Average				95.32

Difference of the result in the FSW and UFSW

	FSW	**UFSW**
Tensile Strength (Mpa)	267.57	347.68
Elongation (%)	6.286	9.65
Hardness (HB)	79.85	95.32

Thus, it is observed that the mechanical properties of the joint produced by the underwater friction stir welding process exhibits greater mechanical properties than joint produced by the normal friction stir welding process . hence the underwater welding process is preferred over friction stir welding .

Taguchi Analysis: Elongation versus welding speed, angle, profile:

Exp.no.	tool rotation	angle	Profile	elong.	SNRA1	MEAN1
1	1200	2	T	5.570	14.9171	5.570
2	1200	3	H	8.446	18.5330	8.446
3	1200	4	S	9.867	19.8837	9.867
4	1300	2	H	10.034	20.0295	10.034
5	1300	3	S	13.636	22.6937	13.636
6	1300	4	T	12.336	21.8235	12.336
7	1400	2	S	5.140	14.2193	5.140
8	1400	3	T	5.461	14.7454	5.461
9	1400	4	H	7.210	17.1587	7.210
	Net average			8.633	18.2226	

Linear Model Analysis: SN ratios versus welding speed, angle, profile:

Estimated Model Coefficients for SN ratios

Term	**Coef**	**SE Coef**	**T**	**P**
Constant	18.2227	0.01871	973.882	0.000
Welding 1200	-0.4447	0.02646	-16.806	0.004
Welding 1300	3.2929	0.02646	124.440	0.000
Angle 2	-1.8340	0.02646	-69.309	0.000
Angle 3	0.4347	0.02646	16.429	0.004
Profile t	-1.0606	0.02646	-40.082	0.001
profile s	0.3511	0.02646	13.267	0.006

S = 0.05613   R-Sq = 100.0%   R-Sq(adj) = 100.0%

Analysis of Variance for SN ratios

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**	**%PC**
tool rotation	2	57.4596	57.4596	28.7298	9117.58	0.000	72.50
angle	2	16.5323	16.5323	8.2662	2623.32	0.000	20.86
profile	2	5.2552	5.2552	2.6276	833.88	0.001	6.63

Residual Error	2	0.0063	0.0063	0.0032			
Total	8	79.2534					

Linear Model Analysis: Means versus welding speed, angle and profile:

Estimated Model Coefficients for Means:

Term	**Coef**	**SE Coef**	**T**	**P**
Constant	8.63333	0.1015	85.068	0.000
welding 1200	-0.67233	0.1435	-4.684	0.043
welding 1300	3.36867	0.1435	23.471	0.002
angle 2	-1.71867	0.1435	-11.975	0.007
angle 3	0.54767	0.1435	3.816	0.062
profile t	-0.84433	0.1435	-5.883	0.028
profile s	-0.07000	0.1435	-0.488	0.674

S = 0.3045   R-Sq = 99.8%   R-Sq(adj) = 99.0%

Analysis of Variance for Means

Source	DF	Seq SS	Adj SS	Adj MS	F	P	%PC
tool rotation	2	57.2105	57.2105	28.6052	308.59	0.003	75.34
angle	2	13.8750	13.8750	6.9375	74.84	0.013	18.27
profile	2	4.6614	4.6614	2.3307	25.14	0.038	6.13
Residual Error	2	0.1854	0.1854	0.0927			
Total	8	75.9323					

Response Table for Signal to Noise Ratios
Larger is better

Level	Tool rotation	angle	Profile
1	17.78	16.39	17.16
2	21.52	18.66	18.57
3	15.37	19.62	18.93
Delta	6.14	3.23	1.77
Rank	1	2	3

Response Table for Means
Larger is better

Level	Tool rotation	angle	profile
1	7.961	6.915	7.789
2	12.002	9.181	8.563
3	5.937	9.804	9.548
Delta	6.065	2.890	1.759
Rank	1	2	3

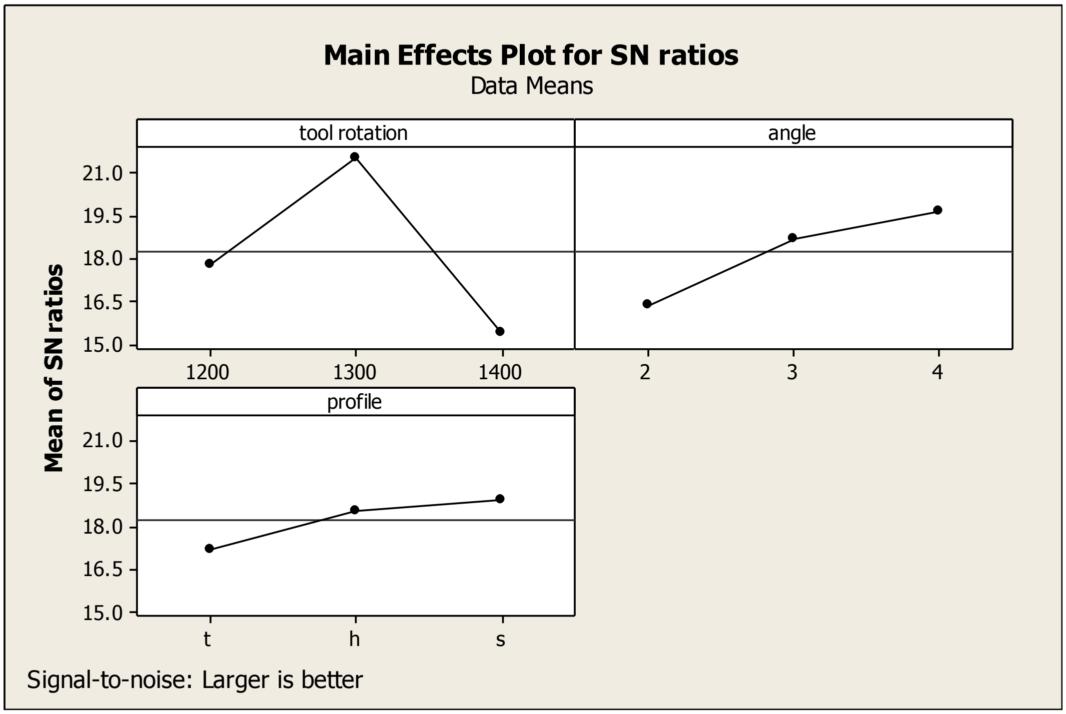

Figure: 8 Plot for SN ratio to show main effect of Input Parameters on elongation.

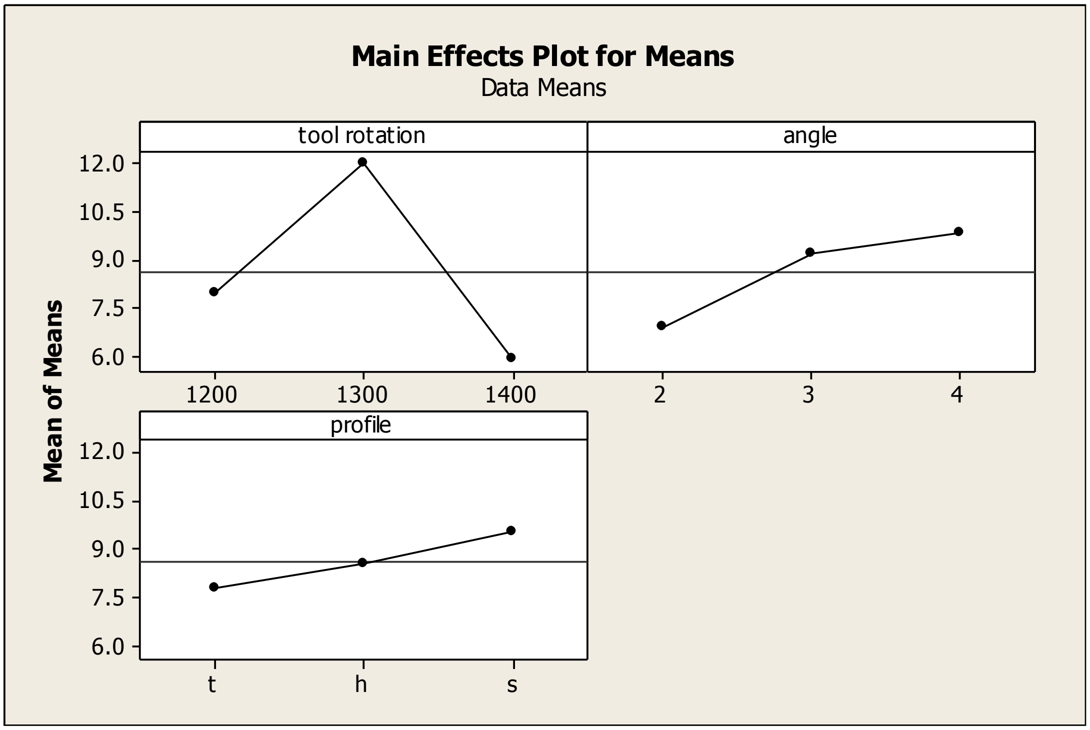

Figure: 9 Plot for Means to show main effect of Input Parameters on elongation.

	Predicted Mean Value	Experimental Value	Confidence Interval
Tensile Strength (MPa)	352.25	347.68	$342.65< \mu_{TS} < 398.64$
Elongation (%)	9.852	9.254	$9.124< \mu_{EL} < 10.78$
Hardness (HB)	97.65	95.32	$94.65< \mu_{H} < 98.85$

Conclusion

The following conclusions can be:

1. Fabrication of welded joint has been successfully achieved.
2. Microstructure analysis reveals that proper joining takes place and very small amount of porosity is observed.
3. No voids and cracks are observed at the joint in microstructure analysis.
4. XRD analysis indicates that their was no unwanted compound which become hindrance during machining. These compounds improves the mechanical properties of the joint.
5. It was observed that the mechanical properties in UFSW is approximately 20% increased than the FSW.
6. The optimum condition for tensile strength, percentage elongation and hardness are as follows :
   Tool rotation speed 1300rpm.
   Tool offset angle 4^0

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