Int. J. Nonlinear Anal. Appl. 13 (2022) No. 1, 1011–1022
ISSN: 2008-6822 (electronic)
http://dx.doi.org/10.22075/ijnaa.2021.24678.2795

Optimization of FSW process parameters for welding dissimilar 6061 and 7075 Al alloys using Taguchi design approach

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(Communicated by Madjid Eshaghi Gordji)

Abstract

Friction stir welding (FSW) produce a strong metallurgical joint with the application of severe deformations and frictional heating in the metals and alloys by using a non-consumable rotating tool consisting of pin and tool shoulder. During welding, the plastic deformations of base metals vary for the varying mechanical properties such as tensile strength (TS), impact strength (IS), and hardness (HV) which in turn varies the welding conditions and parameters. Therefore, selection of optimal weld parameters plays an important role in enhancing the quality of weld joint. In this article, friction stir butt welds made of 6061 and 7075 Al alloys are performed with various welding parameters such as rotational speed of tool, angle of tilt, and axial force using tool has taper pin profile. Experiments are carried out on twenty-seven joints that are made on 6061 and 7075 Al Alloy plates of 6.50 mm thick of same nature and tested for its tensile, impact and HV properties.

Keywords: Friction stir welding, 6061 and 7075 Al alloys, Taguchi design approach.

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Received: May 2021 *Accepted:* October 2021

1. Introduction

FSW is a new class of joining technique being employed for a broad kind of similar and dissimilar metals and alloys. It is an approach of fabrication (i.e., solid state thermo-mechanical), where the temperature of welding comparatively below the base metal melting point [8, 3, 14]. In the process of FSW, friction heat will be produced by a non-expendable rotating tool (comprising of a pin, and shoulder) that is engrossed into the edge of butting. This frictional heat produced at the interface of work piece and tool topically softens the work piece and appropriates the tool to move with a forward motion of the joint. Rotation and translation of tool induce the material flow of work piece from front to back of the pin, which results in welded joint [11]. The hardening of the weld cracking issue does not originate in FSW process due to that the generated heat does not accomplish its melting point. In the same manner, procedure of solid-state welding surmounts other kind of problems in unified aluminum alloys welding like sequestration, porosity, formation of un annealed inter-metallic, and cracking of heat affected area liquation [10], which made the process of FSW as an efficacious approach of welding for grouping a broad kind of metals and alloys those are similar and dissimilar in various field of applications such as automobile, aerospace, and industrial. Recent years, the potentiality of making effective welded joints with alloys or metals which are not similar has acquired a panoptic interest in the field of research because of possible significance in engineering and issues related with traditional welding procedures. However, the control variation of FSW process parameters has substantial impact on the quality of welded joint. It is quite difficult to the process engineer to control these process parameters of FSW due to the conflict nature of these input process parameters with the characteristics of welding quality. In addition, it is also significant to choose these control variables in FSW process for each new component of welding to incur an effectual welded joint as per the specifications of design. Since the components of frictional stir welded dissimilar aluminum alloys find a wide variety of applications in aircraft, automotive and industrial structures whereby possible multi-material configurations involve among others the alloys [1]. J. F. Guo et al. [6] studied the variations in mechanical properties of friction stir welded AA6061-AA7075 alloys by varying the welding speeds and axial load and placing both the materials on advancing and retreating sides. They reported that placing the AA6061 on advancing side accelerates the metal mixing and leads to possible enhancement of the mechanical properties. Noor et al. [7] investigated the tunneling and kissing bond defects during friction stir welding of AA5083-H116 and AA6063-T6 alloys. They found that offsetting the tool towards the stronger material, and insufficient tool plunge are the promising reasons for these defects which significantly deteriorate the TS of the weld joint. Landry et al [5] stated that increasing the weld velocities caused to higher grain refinement in the nugget region despite of positioning of metals the fracture surface was located at minimum HV area during welding AA7020-T651 with AA6060-T6. Azizieh et al. [2] studied the effect of pin profile, rotational speed, and welding speed during welding AA1100 with AZ31 by placing the metals on both advancing and retreating sides and found that the higher rotational speeds result in higher HV. Mastanaiah et al. [12] found that the lower rotational speed and high welding speed result in defect formation during welding AA2219 and AA5083 alloys. The investigations in the literature conclude that the process parameters like tool rotational speed, translational speed, tilt angle, position of the alloys, tool pin profile, tool off-set, shoulder to pin diameter ratio significantly influence the mechanical properties of the friction stir welded dissimilar alloys.

Besides this, many attempts have been made to improve the performance of FSW for welding dissimilar aluminum alloys based on modeling and optimization of the process performance. Rajakumar et al. [13] employed FSW with response surface methodology which derived the optimized welding specifications to achieve utmost strength for six distinct aluminum alloy grades. In addition, optimal process parameters of FSW also estimated form the known properties of base material by demonstrating the empirical associations between the mechanical attributes of base metal of aluminium alloy. Koilraj et al. [9] optimized the process parameters for joining AA2219 and AA5083 based on Taguchi's approach under the consideration of pin geometry, rotational speed, welding speed and shoulder to pin diameter ratio as process parameters. They derived the optimum parameters for a sound weld based on TS and micro HV. Venkateswarlu et al. [15] derived the optimal weld characteristics for welding AA 2219 to AA 7039 aluminum alloys using response surface methodology. Several researchers attempted to optimize the process parameters of FSW using gray relational analysis (GRA) [4], where the authors employed taguchi-based GRA approach for multi-objective optimization of process parameters of FSW with aluminum alloy and AM20 magnesium alloy, respectively. Traditionally, selection of the weld parameters is done based on the skill of the engineer or machine operator and the parameter tables provided by the machine manufacturer. However, such criterion does not guarantee the desired weld quality characteristics. This article proposes an innovative optimized approach to influence the optimal specifications of FSW process on welding of dissimilar 6061 and 7075 Al alloys. Rotational speed of tool, tilt angle, and axial force are assumed as input process control variables which had substantial impact on the weld joint mechanical attributes and TS, IS, and HV are considered as the performance measures of FSW process. In addition, taguchi approach is utilized to optimize the experimental results in terms of S/N ratios for three response parameters.

2. Materials and Methods

This section describes the methods and materials used to perform the experimental investigation of FSW process. Aluminum alloy of grade 6061 and 7075 which is a haste solidifying alloy of aluminum (comprises magnesium and silicon as major alloying components) is utilized as a base metal with the 6.5mm thickness of rolled plates for producing welded joints with solitary pass. Additionally, it provides good ability of welding due to its beneficial properties of mechanical.

Table 1: Chemical composition of alloys

Material	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
AA6061-T6	0.62	0.45	0.20	0.08	1.05	0.09	0.03	0.07	Balance
AA7075-T6	0.05	0.14	1.4	0.03	2.4	0.19	5.8	0.07	Balance

Table 2: Mechanical properties of alloys

Base Metal	TS (MPa)	Yield Strength (MPa)	% Elongation	HV
AA6061-T6	315.0	287.0	12.0	107
AA7075-T6	575.0	530.0	13.0	175

FSW employs a non-expendable rotating tool made of tungsten carbide to build the joint, where the tool comprises of body, pin or probe, shank, and shoulder. The necessitated joints are fabricated using the TAL Vertimech V-350 Vertical Machining Center which has furnished with eminent precision and weighty loading series linear guide directs on three axes.

2.1. Methodology

Here three input process parameters such as rotational speed of tool (N), axial force (F), and angle of tilt (T) have been chosen for the experimental investigation which led to heat input and later determine FSW joints of aluminum. The values of input process parameters and their levels are listed in table 3 and taguchi with L27 array design is utilized for experiment optimization.

Table 3: The values of input process parameters with their corresponding levels

Name of parameter	Level 1	Level 2	Level 3
Rotational speed (Rpm)	700	900	1100
Axial force (KN)	1.5	2	2.5
Tilt angle (^{0})	1	2	3

3. Experimental Results

This section describes the experimental setup and the results obtained using FSW process of Al 6061 and 7075 alloys to assert the mechanical attributes of FSW like IS, TS, and HV equated after the process of welding done by vertical CNC machine which utilizes the vertical milling machine with automatic feed. Accordingly, rotational speed of tool and the angle of tilt have been set, and several experiments are investigated with taper threaded tool profile.

3.1. Process

Figure 1 shows the process of tool inserting and the stir zone after FSW process. The plate's dimensions are assumed as 100×50×6.5mm and shearing process is applied to cut them into the required size. Both the plates are clinched to the bed of machine and the depth of plunge is rendered with a center bit at the connecting place of the plates. The hole has been made for the tool to travel across the plates to be friction stir welded. Tool shoulder is utilized employ the pressure on the plates which results in passing of the tool on the two plate's intersection after the production of hole. Due to the automatic feed, the tool has been moved on another side of the weld. After the insertion of tool, the friction is developed after some time and the material gets heated up to the condition of red-hot, which is also cited as indentation time (usually 5-8 sec). Finally, the plates are said to be friction stir welded after the tool reaches another side.

3.2. Analysis of the joint

Tensile specimens as shown in figure 2 are prepared to required dimensions as per ASTM E8M-04 standards. Tensile test has been carried out in Universal Testing Machine and the obtained results are presented in table 4. Figure 3 discloses the specimens utilized for impact test. IS of the material can be found by using impact testing machine. Charpy test is one of the methods to find out IS of the material and results are presented in table 4.

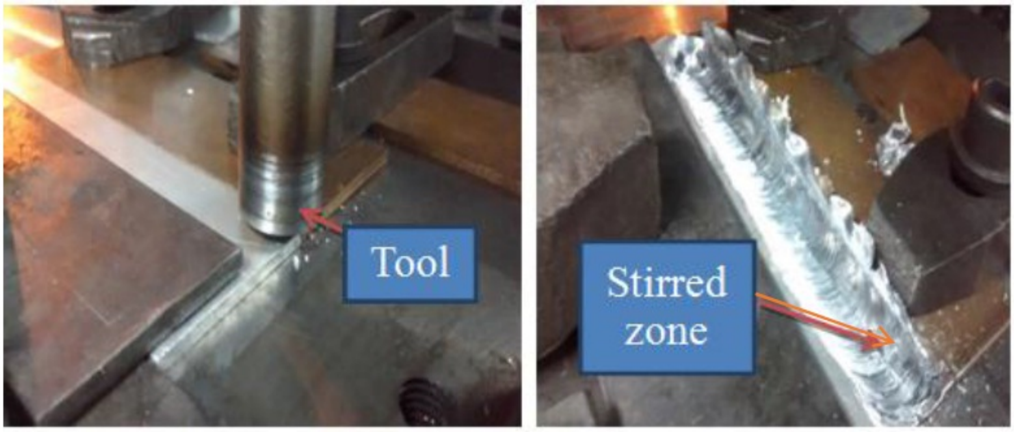

Figure 1: Tool inserted and the stir zone after FSW process.

Table 4: Obtained experimental results of output responses with various input process parameters

Tool rotational speed (N) in rpm	Tilt angle (^{0})	Axial force (F) in KN	TS in MPa	IS in KN/mm^2	HV
700	1	1.5	116.67	1.00215	27
700	1	2	125.91	1.20121	31
700	1	2.5	137.38	1.72175	30
700	2	1.5	127.74	1.0814	32
700	2	2	136.17	1.2211	33
700	2	2.5	150.36	1.6915	32
700	3	1.5	134.25	0.7941	30
700	3	2	145.43	0.9495	31
700	3	2.5	156.26	1.3412	30
900	1	1.5	139.13	0.9967	33
900	1	2	145.15	1.4308	32
900	1	2.5	156.17	1.6104	31
900	2	1.5	136.25	1.1074	34
900	2	2	150.13	1.4652	30
900	2	2.5	161.12	1.7645	34
900	3	1.5	139.56	0.9612	30
900	3	2	153.12	1.3454	33
900	3	2.5	160.93	1.6085	34
1100	1	1.5	133.45	0.8965	31
1100	1	2	144.61	1.2034	33
1100	1	2.5	152.42	1.4924	35
1100	2	1.5	140.12	0.9912	32
1100	2	2	153.71	1.3214	34
1100	2	2.5	165.34	1.5923	35
1100	3	1.5	148.24	0.9242	33
1100	3	2	156.96	1.1561	36
1100	3	2.5	168.34	1.5237	37

Figure 2: Specimens after tensile testing.

Figure 3: Specimens for impact test.

A Rockwell HV tester machine used for the HV measurement. Figure 4 presents the HV test image. In general, the surface being examined needs a metallographic finish and it was achieved with the help of emery paper of 100, 220, 400, 600 and 1000 grit sizes. On each sample, the load used on the Rockwell HV tester was 200 grammes at 20 seconds dwell time. Each welded specimen has been evaluated, and results are presented in table 4.

4. Results and discussion

4.1. Taguchi method

Taguchi method also stated as robust method of design pioneered by Dr. Taguchi. This approach immensely enhances the productivity of design and efficacious to greater extent due to its easier

Figure 4: HV test.

design of experiments and structural approach to render best quality at low cost. It works with the functions of input and produces optimal predicted outcomes as compared to experimentally obtained results. The optimal results are formed with ratio of S/N and means of response with the impact of input process parameters. Here, the criteria of larger is better has been applied. The first two steps in taguchi method are to plot the interaction and S/N ratio for TS as shown in figure 5 and figure 6. The final step is to verify the improvement in responses by conducting experiments using optimal conditions. The confirmation test result for TS is shown in table 5. Similarly, the plots of interaction and S/N ratio for IS and HV are disclosed in figure 7, figure 8, figure 9, and figure 10, respectively. Table 6 and Table 7 are listed with the experimental and predicted values of IS and HV for confirmation test results.

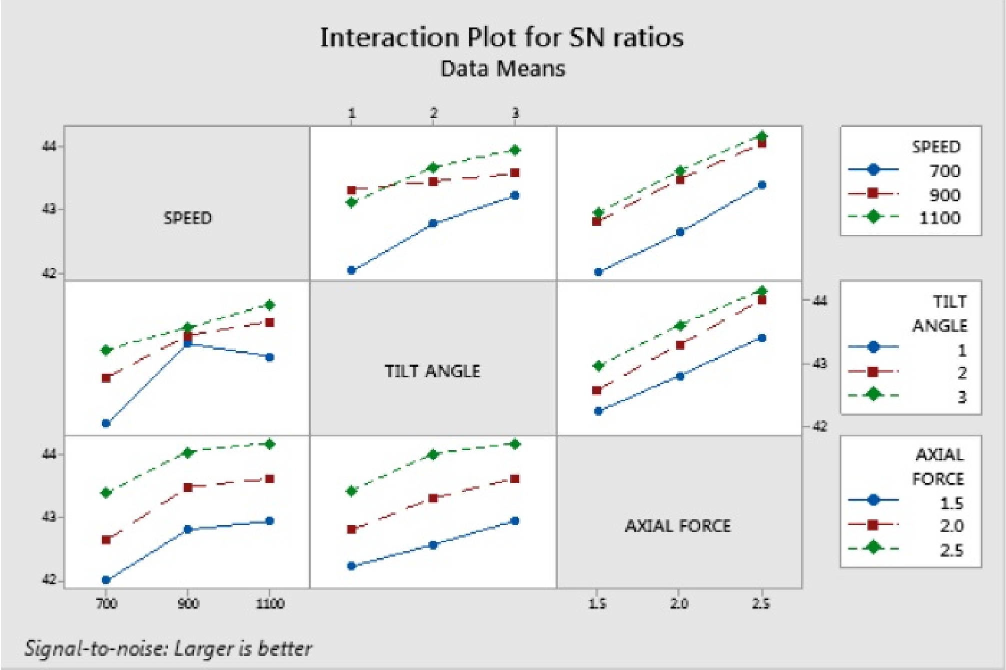

Figure 5: Interaction plot for TS.

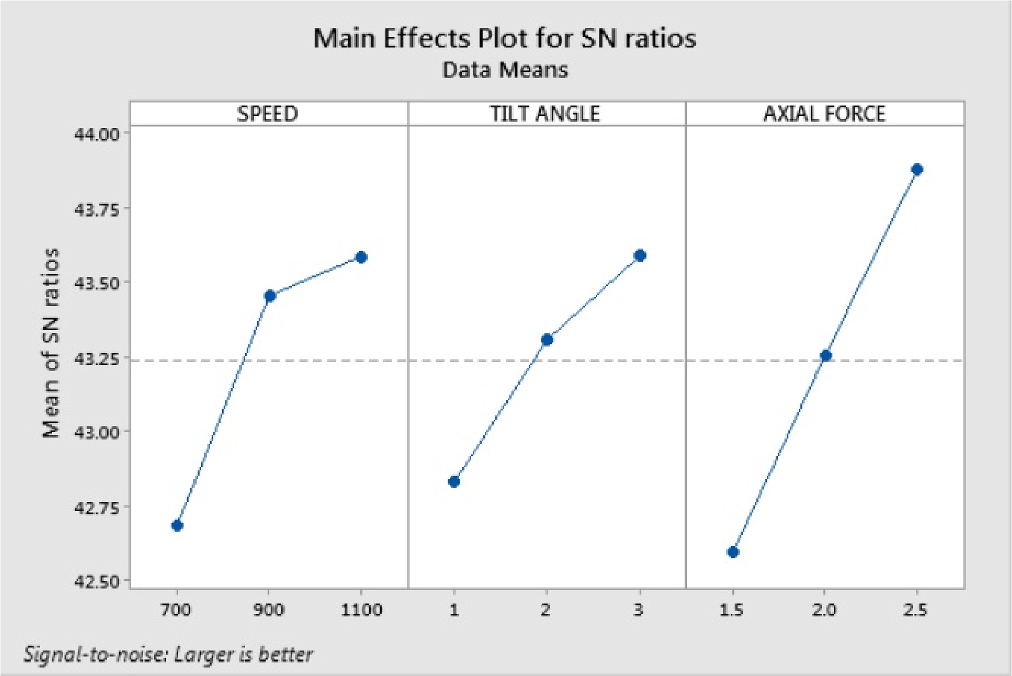

Figure 6: S/N ratio plot for TS.

Table 5: Confirmation test results for TS using experimental and taguchi method

	Optimal TS parameters	
	Experimental values	Predicted values
Setting level	Speed-1100Rpm, Tilt angle-3^0, Axial force-2.5 KN	Speed-1100Rpm, Tilt angle-3^0, Axial force-2.5 KN
TS (Mpa)	168.34	167.43

Table 6: Confirmation test results of IS using experimental and taguchi method

	Optimal IS parameters	
	Experimental values	Predicted values
Setting level	Speed-900Rpm, Tilt angle-2^0, Axial force-2.5 KN	Speed-900Rpm, Tilt angle-2^0, Axial force-2.5 KN
IS (Mpa)	1.7645	1.7510

Figure 7: Interaction plot for IS.

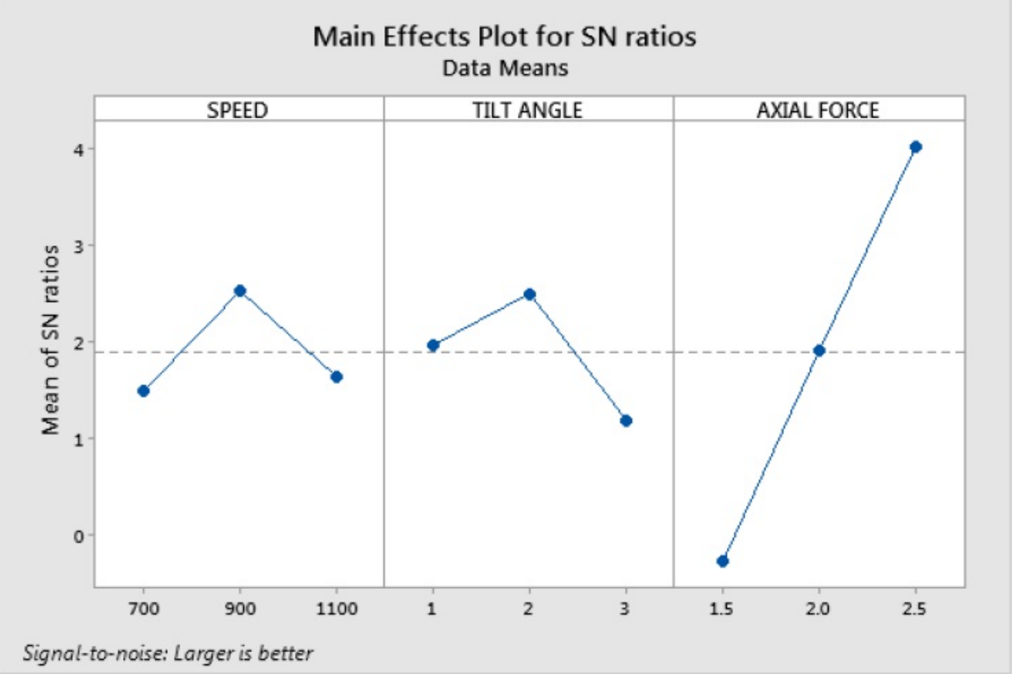

Figure 8: S/N ratio plot for IS.

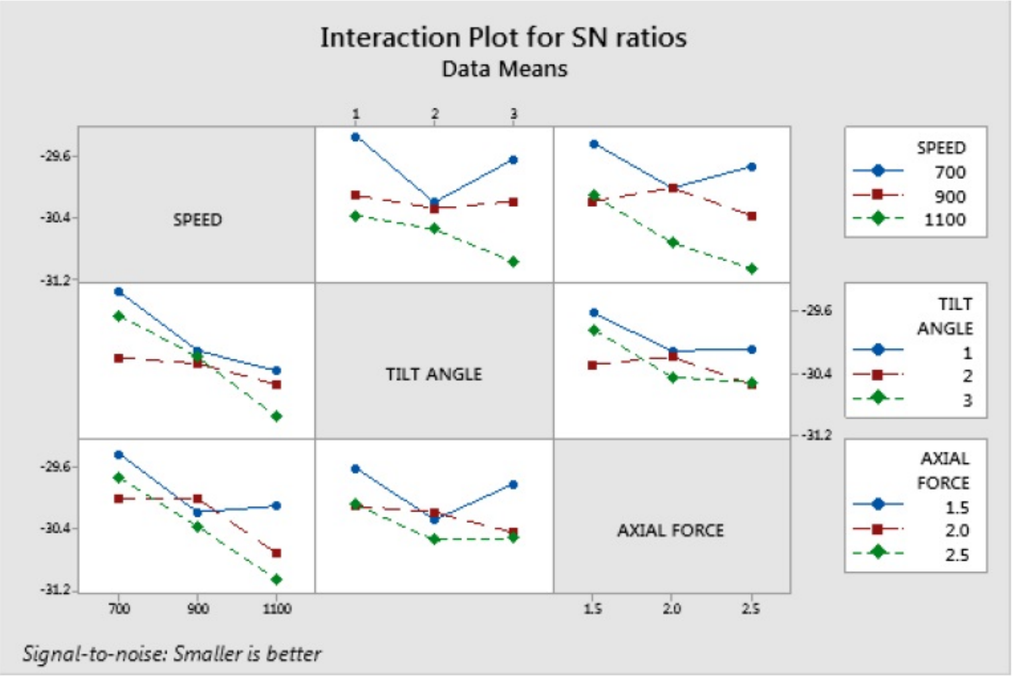

Figure 9: Interaction plot for HV.

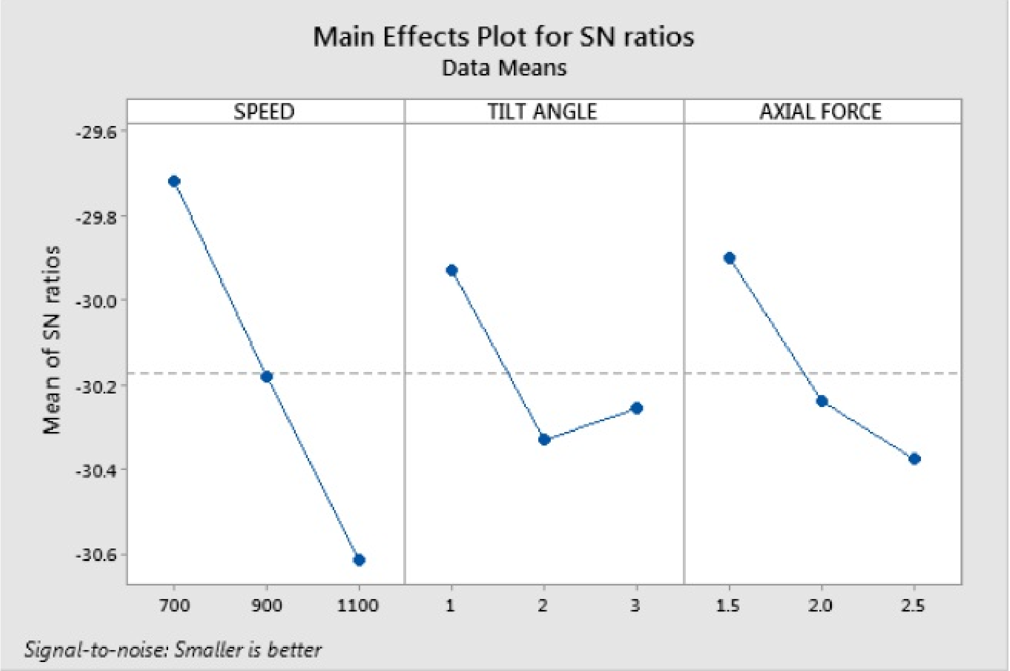

Figure 10: S/N ratio plot for HV.

Table 7: Confirmation test results of HV with experimental and predicted values using taguchi method

	Optimal HV parameters	
	Experimental values	Predicted values
Setting level	Speed-1100Rpm, Tilt angle-3^0, Axial force-2.5 KN	Speed-1100Rpm, Tilt angle-3^0, Axial force-2.5 KN
HV	37	36.89

From table 5, table 6, and table 7 the confirmation test results demonstrate that there is a very less relative error between the experimental and predicted value using taguchi approach.

5. Conclusion

This article presented FSW process on AA6061 and 7075 aluminum alloys using taguchi design approach. By observing the outcome of taguchi, it has been concluded that both the rotational speed of tool and angel of tilt are the more dominant parameters that mold on the mechanical attributes than the axial force acting on the welded joints. Following are the conclusions made from the experimental study and taguchi optimization:

- As the tool rotational speed increases, effectively TS also increased, and the same result will be observed from tilt angle and axial force for TS.
- As the tool rotational speed increases, effectively IS has been increased up to 900 rpm and started decreasing at 1100 rpm, and in the same manner axial force also effects (increased up to 2.5KN and started decreasing at 3 KN), if tilt angle increases, effectively IS also increased.
- As the tool rotational speed increases, effectively HV also increases, and in the same manner Tilt angle also effects, if axial force increases, effectively HV will be increases up to 2.5KN and slightly decreases at 3KN.
- It is observed that IS initially increased with an increase in tool rotational speed, tilt angle and axial force. But the IS decreased with further increase in these parameters after reaching a maximum value.

6. Future Scope

The dissimilar friction stir welding of AA7079 and AA8050 aluminum alloy jointed efficiently applying straight cylindrical tool. Further the response surface method (RSM) was used to develop the model. The developed mathematical model was optimized using the simulated annealing algorithm optimizing technique to maximize the corrosion resistance of the friction stir welded AA2219 aluminum alloy joints. Mathematical models are developed to study the individual and interaction effects of input variables on the performance characteristics of joints. FSW parameters are optimized to maximize the yield strength and weld nugget micro hardness of the welded joints.

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