Manufacturing Rev. **9**, 34 (2022)

https://doi.org/10.1051/mfreview/2022032

Manufacturing Review
Available online at:
https://mfr.edp-open.org

RESEARCH ARTICLE

OPEN ACCESS

Optimization of FSW parameters of AA6061-6 wt.% SiC composite plates

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Received: 30 March 2022 / Accepted: 7 October 2022

Abstract. AA6061-SiC composites are the most preferred materials for applications in the automobile and aerospace sector due to their superior properties. The FSW process is one of the novel solid states joining processes that overcome almost all the difficulties of the fusion welding process because the process that operates well below the melting point of the metals to be joined, consumes less energy, environment-friendly, and versatile, no shielding gas or filler metal is used. The welding parameters such as tool rotational speed, axial force, and tool pin profile play a major role in deciding the joint strength and hardness of the weld zone. Taguchi method was employed in this study to scrutinize the impact of welding processing factors, including rotational, speed, axial load, and pin profile on ultimate tensile strength, microhardness of weld zone. The results reveal that the welded joints produced at 750 rpm of tool rotational speed, the axial load of 6 kN using a square pin tool profile that exhibits higher UTS. The Vickers's hardness of AA6061-6 wt.% SiC composites was found to be superior at tool rotational speed of 900 rpm, the axial force of 6kN using cylindrical tool pin. The ANOVA Findings based on Vickers's hardness are tool profile: 53.84%, tool rotational speed: 20.16%, and axial force: 21.32%.

Keywords: Friction stir welding / Taguchi parametric design approach / S/N ratio / ANOVA

1 Introduction

The usage of aluminum matrix composites in the field of structural applications, aerospace, marine, automotives and sports steadily increasing due to its properties such as high specific strength, high specific modulus and good wear resistance. Aluminum matrix with the ceramic particles in the ductile matrix led to increase in desirable properties such as strength, elastic modulus, wear resistance and decreases component weight, low thermal shock, and low coefficient of thermal expansion compared to the conventional metals and alloys. But the joining of aluminum matrix composite by fusion welding results in reduced joint strength due to oxide inclusions, solidification shrinkage, porosity, distortion, more residual stress, formation of intermetallic compounds due to chemical reactions between the matrix and reinforcement, etc. The Friction Stir Welding (FSW) is a recently developed joining process for the metals that are difficult to weld using conventional fusion welding methods. This technique is being used for welding of similar as well as dissimilar metals and composites with ease. This process has eliminated the need of filler metals that are commonly used in conventional fusion welding techniques. Sanjay Kumar et al. [1] reported in his work of friction stir welding of A6061 and A6082 alloys that the rotational speed is most significant process parameter that has the highest influence on tensile strength and hardness, followed by tool pin profile and tool tilt. His work revealed that the percentage contribution of rotational speed and types of tool pin profile for tensile strength and hardness are 92.49%, 89.68% and 4.39%, 8.29%, respectively. The percentage contribution of tool tilt angle is 3.00% for tensile strength whereas tilt angle is not significant parameter for hardness. Rajesh Pankaj Sharma et al. [2] investigated on Friction Stir Welded AA8052 aluminum alloy joint and the S/N values for each process specification were calculated using an orthogonal array of L9 design. They obtained higher tensile strengh,Microhardness values at 1150 rpm and 28.5 mm/min, using a cylinder pin. A combination of 1150 rpm and 32.5 mm/s and a conical cylindrical pin provided the best impact toughness results. Kaveripakkam Suban Ashraff Aliet al. [3] studied and concluded that mechanical properties and factors for the process of friction stir welded AA6061 MMC's with SiC and B_4C are the reinforcements. For MMC's with 10% SiC and 3% B_4C reinforcement, the maximum UTS was approximately 172.8 MPa. As the percentage of SiC and B_4C increase, the percentage of elongation decreased. It was observed that the higher strength, improved wear properties and hardness by adding more SiC content. For 10 wt.% SiC reinforcement the

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Table 1. Chemical composition of Matrix material AA6061.

Elements	Mg	Cu	Zn	Fe	Mn	Si	Ni	Pb	Ti	Sn	Al
%	0.81	0.323	0.14	0.153	0.024	0.662	<0.050	0.024	0.107	0.01	Balance

wear rate was as high as 12 g/s with a load of 30 N. The wear rate reduced for lower values of load and increased with B_4C reinforcement. Khaled Boulahem et al. [4] revealed that the work model of ultimate tensile strength prediction and investigation on microstructural characterization of friction stir welded AA2024-T3. The welded joint with tool rotational speed of 750 rpm, tool traverse speed of 100 mm/min, and tool shoulder diameter of 12 mm performed the maximum ultimate tensile strength of 385 MPa which is 84% of the base metal. The increase of the tool rotation speed led to the increase in the ultimate tensile strength and reached a maximum value and then decreased. The increase of the tool traverse speed or of the tool shoulder diameter resulted in the decrease of ultimate tensile strength. Mohamadreza Nourani et al. [5] in his work of Friction Stir Welding of 6061 Aluminum Alloy reported that the most significant parameter on the weld quality is the rotational speed, followed by the axial force and transverse speed. The tool rotational speed showed the highest significance about 51% followed by the normal force 38% and the welding transverse speed 11%. Kanwer S. Arora et al. investigated that the UTS of welds is predominantly exaggerated by the speed of the welding and diameter of the shoulder [6]. The optimum FSW parameters for pure Mg, according to D. Ahmadkhaniha et al., are tool rotation of 1600 rpm, welding speed of 63 mm/min, the saturation depth of 0.1 mm, and tilt angle of 2° [7]. According to A. Heidarzadeh et al., the superior welded joints were produced at rotating tool speeds of 700 to 1100 rpm, welding speed rates of 50 to 100 mm/min, and a tensile load of 1.5 to 2.5 kN [8]. Ugendersingarapuet et al. concluded that the rotational tool speed and welding speed have a substantial impact on ultimate tensile strength, microhardness, and yield strength [9]. According to Venkata Rao et al., showed in their work on AA2219 FSW welded joints showed that the joints produced with a hexagon profiled tool has a significant effect in the nugget region of the weld, and also the joints fabricated with this tool have a better hardness [10]. Ramanjaneyulu Kadaganchi et al. observed that hexagonal profile tool joints had a greater influence on vibration and smooth flow of material. As a result of this, there is an increase in the tensile strength and percentage of elongation [11]. H. Doude, et al in his work the butt friction stir welded (FSWed) panels of AA 2219-T87 reported that The location of the volumetric defect depends on the material flow which can be affected by the rotational speed of the tool. For the threaded tool the voids present near the crown indicated rotational speed above the optimal parameters and voids present in the root indicated rotational speeds below the optimal weld parameters [12]. According to Kalaiselva et al., the optimal FSW parameters for aluminum boron carbide composite plates are rotating tool speed of 996.936 rpm, welding speed of 1.329 mm/s, and axial force of 9.306 kN, with a reinforcement of 12% [13]. Dinaharana et al. observed that the ZrB_2 particles in the weld nugget are distributed uniformly [14]. Murugan et al. found that the UTS of the FSW joint rises as the weight percent of AlNp particles in the composite increases and that the size of AlNp particles in the weld zone decreases [15]. According to Vijay et al., the Al-10 wt.% TiB2 FSW joints produced using the square pin tool profile exhibited higher tensile strength [16]. Ashok Kumar et al. reported that the AA6061-T6-20 wt.% AlNp FSW composites have a high joint efficiency [17]. Bhagyashekar et al. reported with the aim of the FSW joints produced at 750 rpm rotating tool speed with a 5 kN axial load and a square pin tool profile have a higher UTS [18]. Sivaiah et al. concluded that the cutting speed of 1200 rpm, feed rate of 0.096 mm/rev, depth of cut of 0.6 mm, and cryogenic environment were the best machining settings for P-H stainless steel based on decreased surface roughness [19]. D.P. Florence et al in his work reported that the optimum process parameters for SiC/AA1050 surface composites is tool rotational speed of 1000 rpm and transverse speed of 15mm/min, Future scope of FSP involved in making surface composites to viable for commercial applications [20]. K. Ramesha, P.D. et al in his work Friction Stir Welding (FSW) dissimilar aluminium alloys of AA 7075-O and AA 5052-O grade found that The optimized process parameters for better micro hardness are as follows: tool rotational speed of 1200 rpm, feed of 120 mm/min, tool offset of 1 mm, and cylindrical tapered pin tool profile; while the optimized design of process parameters for better tensile strength are as follows: tool rotational speed of 1400 rpm, feed of 120 mm/min, tool offset of 1 mm and cylindrical tapered pin profile [21]. Austine D. D'Souza et al in his work observed that the contribution based on ultimate tensile stress (UTS) in terms of percentage, the tool pin profile is 41%, tool rotational speed is 29%, and tool feed is 22%, showing that the tool pin contour has maximum bearing on the output quality characteristics, i.e., UTS of the FSW joint. The optimum UTS predicted by the Taguchi analysis was 88.29 MPa, whereas the confirmation experiments gave a result of 80.54 MPa [22]. In this study, an attempt has been made to produce AA6061-6 wt.% SiC composites in a cost-effective way by stir casting process. FSW is used to join AA6061-6 wt% SiC plates. The effect of various friction stir weld parameters on UTS and Vickers's hardness was studied using design of experiments by L9 orthogonal array.

2 Experimentation

2.1 Materials

The AA6061 was selected as the alloying material for the research due to its outstanding welding characteristics. The chemical composition of matrix material is as shown in Table 1. The ingots of AA6061 are heated to a temperature of about 800 °C or till the ingot melts in an electric arc furnace.

Table 2. Design levels of FSW parameters.

Sl. No	Parameters	Code	Unit	Level-1	Level-2	Level-3
1	Tool profile	TP	P	Cylindrical	Square	Taper cylindrical
2	Rotational tool speed	TR	rpm	600	750	900
3	Axial force	AF	kN	4	5	6

Fig. 1. Friction stir welded plates.

The degassing tablet (hexachloro ethane) is added to the molten metal. The dissolved gases in the melt are absorbed by degassing tablets. The formed slag is taken out using foundry tools. The molten metal is thoroughly mixed for 10 min with a stirrer; the silicon carbide particles of size 60 μm and 6 wt.% were added as reinforcement to the stirred molten metal, to produce AA6061-6 wt.% SiC castings. The casting is then machined into rectangular composite plates measuring 100 mm × 50 mm × 6 mm in size.

2.2 Taguchi approach

Dr. Taguchi of Nippon Telephones and Telegraph Company, Japan has developed a method based on "Orthogonal array" experiments which gives much reduced "variance" for the experiment with "optimum settings" of control parameters.

In Taguchi Method, the word "optimization" implies "determination of best levels of control factors". In turn, the best levels of control factors are those that maximize the Signal-to-Noise ratios. The Signal-to-Noise ratios are log functions of desired output characteristics. The experiments, that are conducted to determine the best levels, are based on "Orthogonal Arrays", are balanced with respect to all control factors and yet are minimum in number. This in turn implies that the resources (materials and time) required for the experiments are also minimum.

2.3 Selected FSW parameters and their levels

In the present study, the predominant FSW parameters like Tool rotation speed (600 rpm, 800 rpm & 900 rpm), Tool profile (Cylindrical, Square & Taper cylindrical), and Axial force (4 kN, 5 kN, & 6 kN) are the selected process parameter, the welding speed used for this process is constant about 50 mm/min because the welding speed has an inverse effect on ultimate tensile strength. In the case of FSW of aluminum alloys, at higher speeds generates the low heat inputs, which result in faster cooling rates of the welded joint. This can significantly reduce the extent of metallurgical transformations taking place during welding, resulting in reduction of strength of individual regions across the welds The higher welding speeds causes insufficient plasticized material transportation from advancing side to the retreating side and reduction in the softened area due to faster cooling rates at weld zone which lead to macro level defects like tunnels in weld region.

2.4 Orthogonal array experiment

The effect of above-mentioned factors was studied using Taguchi L9 (3^3) orthogonal array design. The Ultimate Tensile Strength (UTS) and Vickers hardness was taken as the response parameter. The objective was to achieve a maximum value of the response. Minitab statistical software

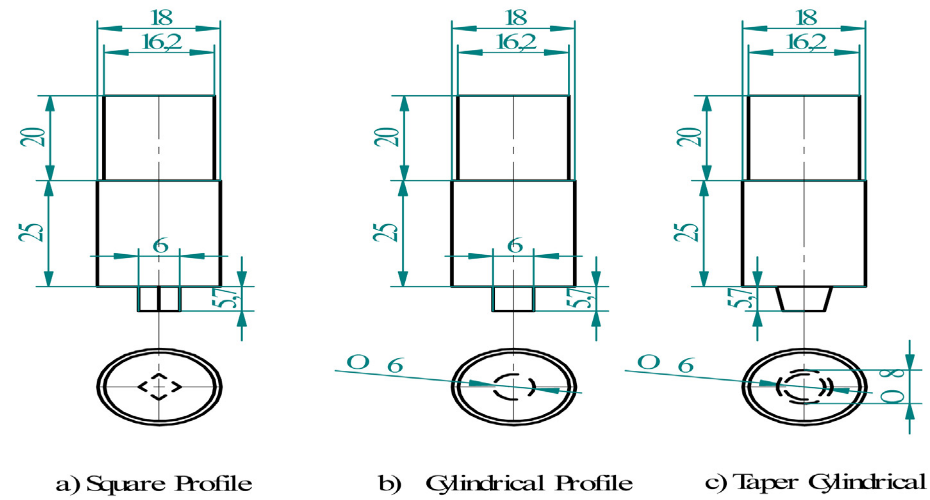

Fig. 2. FSW tool pin profile.

Table 3. The experimental UTS values of AA6061-6 wt.% SiC FS welded composites.

Sl. No	Tool profile	Tool rotation speed (rpm)	Axial force (kN)	UTS (N/mm^2)
1.	Cylindrical	600	4	93.50
2.	Cylindrical	750	5	95.8
3.	Cylindrical	900	6	97.6
4.	Square	600	5	110.9
5.	Square	750	6	120.3
6.	Square	900	4	109.3
7.	Tapered Cylindrical	600	6	105.2
8.	Tapered Cylindrical	750	4	102.8
9.	Tapered Cylindrical	900	5	98.36

was used to develop experiment matrix, as presented in Table 2 and subsequent data analysis

2.5 Tensile and Vickers hardness testing

After preparing the orthogonal array, next step in Taguchi optimization scheme is to carry out the experiments as per design matrix on a computer-controlled numerical vertical FSW machine as according to the parameters outlined in the experimental plan. Figure 1 shows the friction stir welded plates. The UTS test samples were cut from friction stir welded joints as per ASTM E-8/16a.

The UTS tests were deliberated using a UTM (Universal Testing Machine), and Vickers' hardness test at the weld zone was examined using Vickers' hardness equipment. Figure 2 depicts the tool profile in details. The Minitab V18 software used for the L9 orthogonal array analysis.

2.6 ANOVA

Analysis of variance (ANOVA) is similar to regression in that it is used to investigate and model the relationship between a response variable and one or more predictor variables. Analysis of variance (ANOVA) of the overall grade is done to show the significant parameters. If the *P* value for a factor becomes less than 0.05 then that factor is considered as significant factor at 95% confidence level. Statistical software with an analytical tool of ANOVA is used to determine which parameter significantly affects the performance characteristics.

2.7 S/N ratio

In Taguchi designs, a measure of robustness used to identify control factors that reduce variability in a product or process by minimizing the effects of uncontrollable factors (noise factors). Control factors are those design and process parameters that can be controlled. Noise factors cannot be controlled during production or product use, but can be controlled during experimentation.

3 Results and discussion

3.1 UTS response in terms of (S/N) ratio

The effects of FSW parameters on ultimate tensile strength (UTS) and Vickers's hardness (HV) of AA6061-6 wt.% SiC composite, as well as the influence of each welding parameter on the response, were evaluated in terms of

Table 4. Ultimate tensile strength values in terms of the S/N ratio and mean.

	S/N Ratio			Mean		
Level	Tool profile	Tool rotation speed	Axial force	Tool profile	Tool rotation speed	Axial force
1	39.61	40.25	40.14	95.63	103.20	101.87
2	41.09	40.49	40.13	113.50	106.30	101.69
3	40.18	40.14	40.61	102.12	101.75	107.70
Delta	1.48	0.35	0.48	17.87	4.55	6.01
Rank	1	3	2	1	3	2

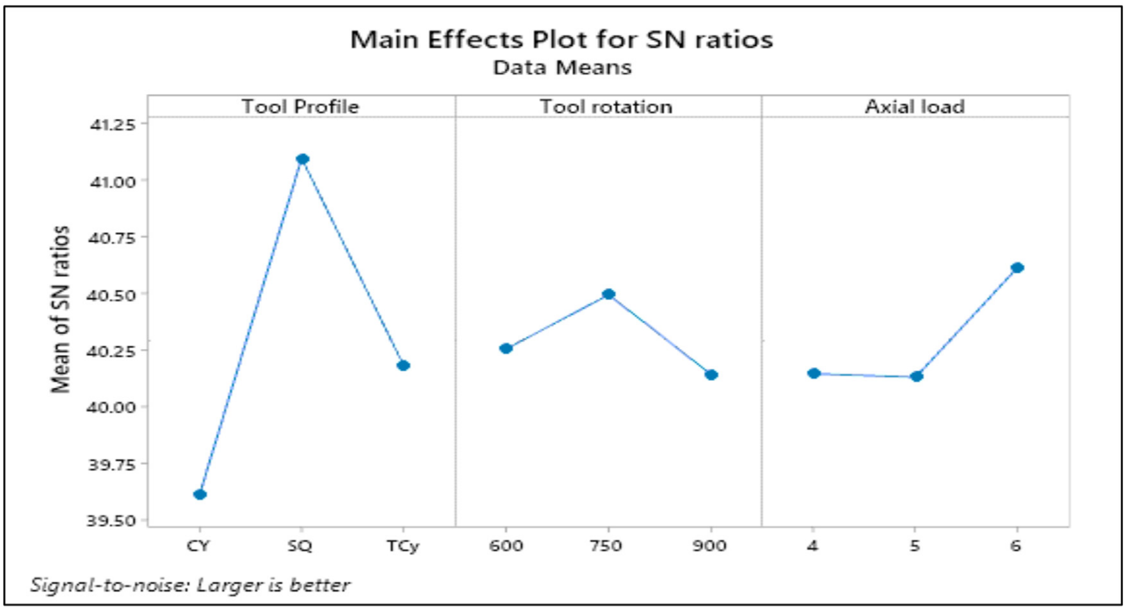

Fig. 3. Ultimate tensile strength main effect plot in terms of S/N ratios.

means and S/N ratios for the respective factor. The optimal S/N ratio condition is selected to optimize the response, are found using the equation (1).

$$\text{S/N (Ratio) Larger the better} = -10log_{10}\frac{1}{n}\sum\nolimits_{i=1}\frac{1}{y^2 * i}, \quad (1)$$

where n − quantity of replications; y_i − detected response value.

Table 3 depicts the experimental UTS values of AA6061-6 wt.% SiC FS welded composites, while Table 4 provides UTS values in terms of S/N ratio and mean.

3.1.1 Effect of rotational speed on Ultimate tensile strength

Figure 3 depicts the UTS main effect plot about S/N ratios. From Figure 3 it is seen that the ultimate tensile strength increases and reaches the extreme value once the tool rotational speed is 750 rpm. The ultimate tensile strength declines with a subsequent increase in tool rotational speed from 750 to 900 rpm. This is due to the fact that tool rotational speed is responsible for stirring and mixing of plasticized material around the rotating tool pin which in turn increase the temperature of the plasticized material. When the tool rotational speed increases (above 750 rpm) higher heat is generated in the stir zone due to increase of relative velocity between rotating tool and the substrate. Increased heat input increases grain growth and dissolution of Mg_2Si precipitates at weld zone which leads to weak joint strength [17]. Higher rotational speed leads to a higher temperature. As a result of this, freezing will be slow in the FSW zone after welding. Higher tool rotational speed generates the extra stirred materials which subsequently moved to the upper surface. This leads to defects in the FSW zone. Hence, the FSW shall be carried out at reasonable tool rotational speed [2]. The tensile strength of the joints decreases with increasing tool rotational speed, growing tool rotations leads to instability in the weld joint and can result in unsatisfactory consolidation of the plasticized material and thereby degradation of strength of joints formed with greater tool rotations [6].

3.1.2 Effect of tool pin profile on ultimate tensile strength

From Figure 4 it is observed that the ultimate tensile strength of FS welded specimen produced using square pin profile found to be superior due to fact that the pin profile plays crucial role in material flow and in turn regulates the welding speed, tool pin is used to shear the material to the back side during the translation of the tool and inserted rotating pin brings the

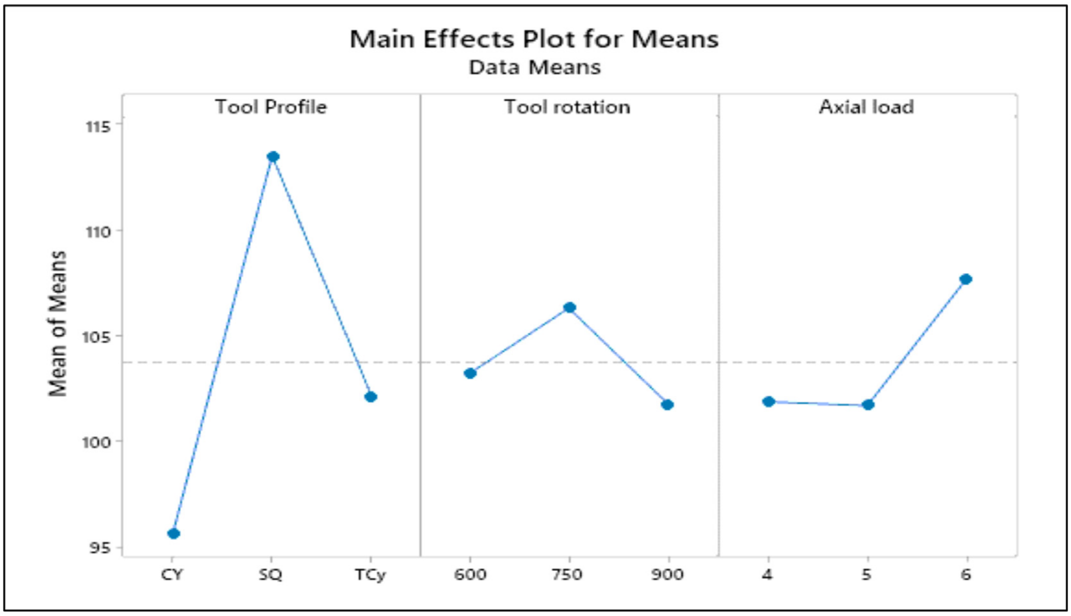

Fig. 4. Ultimate tensile strength main effect plot in terms of means.

Table 5. Vickers hardness values of AA6061-6 wt.% SiC friction stir welded composites.

Sl. No	Tool profile	Tool rotation speed (rpm)	Axial force (kN)	HV of Weld Zone
1.	Cylindrical	600	4	85.47
2.	Cylindrical	750	5	87.39
3.	Cylindrical	900	6	96.43
4.	Square	600	5	78.15
5.	Square	750	6	84.11
6.	Square	900	4	82.873
7.	Tapered cylindrical	600	6	87.41
8.	Tapered cylindrical	750	4	88.87
9.	Tapered cylindrical	900	5	86.99

material at both sides of the joint. The relationship between the static volume and swept volume decides the path for the flow of plasticized material from the leading edge to the trailing edge of the rotating tool. This ratio is equal to 1 for ST, 1.09 for tapered cylindrical, 1.01 for threaded cylindrical, 1.56 for square, and 2.3 for triangular pin profiles. The square pin profile produces 104 pulses/s and triangular pin profile produces 78 pulses/s at a speed of 1600 rpm. Though the ratio of the swept volume of the triangular pin is higher than the square pin profile, better tensile properties of square pin profile is due to increased number of pulses/s for the given speed. Therefore, the joint efficiency is high when the Aluminum Metal matrix Composites is welded using square pin tool and low when it is welded with triangular pin tool [17]. Therefore, UTS was found to be superior at a rotating tool speed of 750 rpm, axial force of 6 kN using square pin profile.

3.2 Vickers's Hardness (HV) response in terms of S/N ratio

Figure 5 shows The experimental weld nugget Vickers Hardness (HV) values of AA6061-6 wt.% SiC friction stir welded composites were converted into S/N ratio and mean. Table 5 shows the findings of the L9 orthogonal array and Table 6 depicts the Vickers hardness response table in terms of S/N ratio and mean.

3.2.1 Effect of rotational speed on hardness

Figure 6 shows the different hardness values of at different tool rotational speed. To produce a proper weld joint, moderate heat input is required. On such moderate heat input, the material will have minimal change in its mechanical properties as well as a defect free weld will be produced. This moderate heat input is obtained at 900 rpm. At this speed, the grain structure of the material recrystallizes and becomes fine and equisized. At 600 rpm, insufficient heat is produced resulting the improper mixing of plasticized metal. Therefore, it leads to weld defects like flaws, gaps in the weld zone [1]. At 900 rpm the tool rotational speed breaks the hard SiC particles to form fine grains in the structure at the weld zone during stirring, which improves the Vickers hardness. An excellent hardness of 96 HV

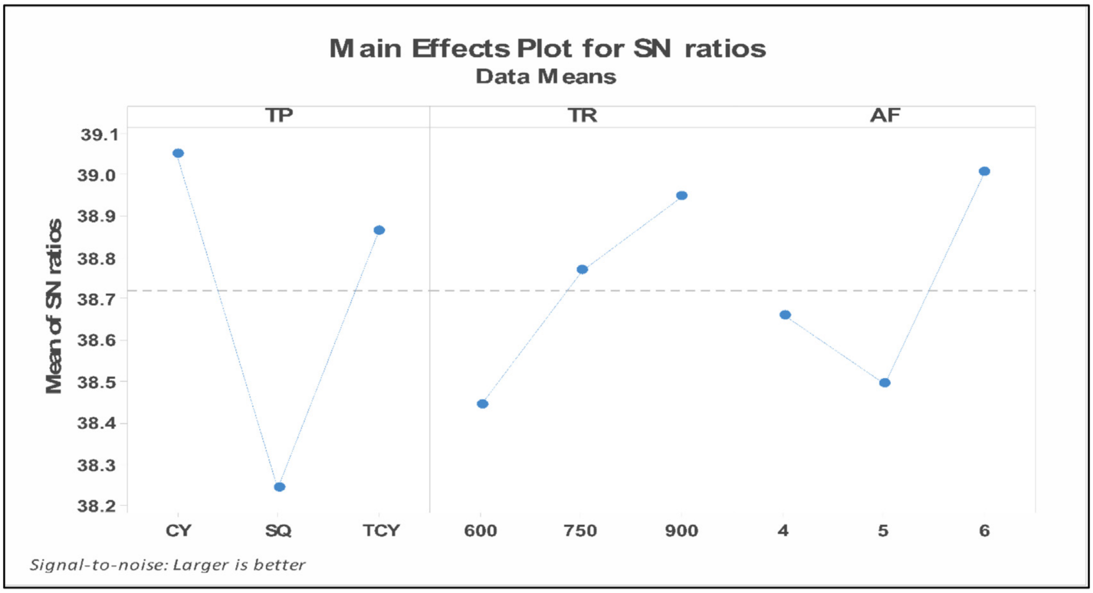

Fig. 5. Vickers hardness main effect plot in terms of S/N ratio.

Table 6. Vickers hardness response table for signal to noise ratios (S/N) & mean.

	S/N ratio			Mean		
Level	TP	TR	AF	TP	TR	AF
1	39.05	38.44	38.66	89.77	83.68	85.74
2	38.24	38.77	38.49	81.72	86.79	84.18
3	38.87	38.95	39.00	87.76	88.77	89.32
Delta	0.81	0.51	0.51	8.05	5.09	5.14
Rank	1	3	2	1	3	2

Table 7. UTS validation results.

S. No	Parameters	Optimum FSW process parameters based on Ultimate tensile strength in MPa		
		Prediction	Experiment	Error in %
1	Level	TP- 2 TR −2 AF-3	TP- 2 TR −2 AF-3	
2	Ultimate tensile strength (MPA)	119.7	120.3	0.50

Table 8. HV Validation results.

Sl. No	Parameters	Optimum FSW process parameters based on Vickers hardness		
		Prediction	Experiment	Error in %
1	Level	TP- 1 TR −3 AF-3	TP- 1 TR −3 AF-3	1.47
2	Vickers Hardness	95	96.4	

Table 9. ANOVA results-based on UTS.

Source	DF	Adj SS	Adj MS	F	P	Percentage of contribution (%)
Tool Profile	2	3.35084	1.67542	2612.74	0.000	83.7
Tool rotation	2	0.19342	0.09671	150.82	0.007	4.82
Axial load	2	0.45428	0.22714	354.21	0.003	11.35
Residual Error	2	0.00128	0.00064			0.13
Total	8	3.99983				

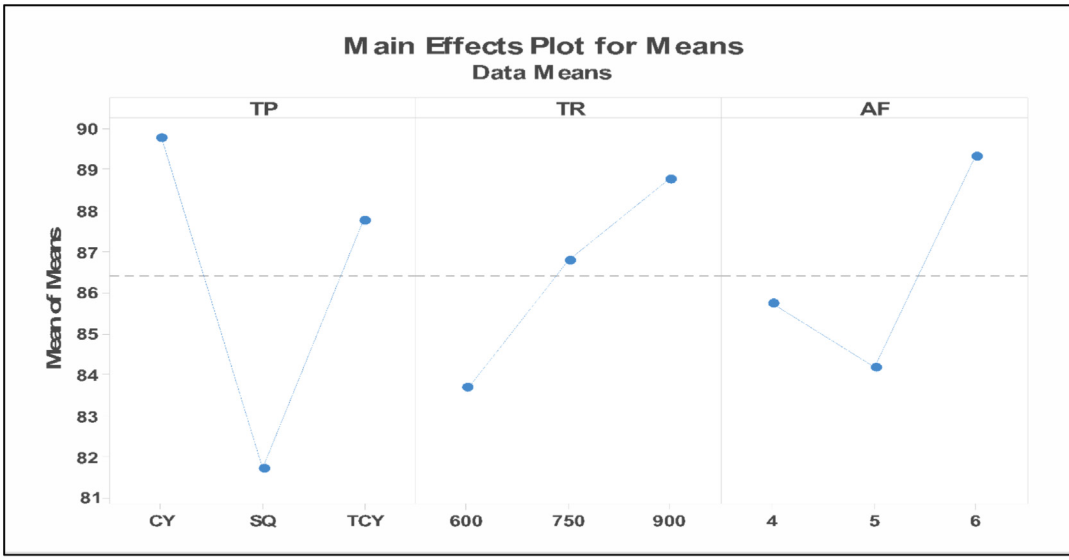

Fig. 6. Vickers Hardness main effect plot in terms of mean.

was found for SiC by about the tool rotational speed (900 rpm). The SiC intensified the hardness value in the FSW zone [5].

3.3 Validation test

Validation tests for predicated Taguchi optimal conditions must be carried out. The predicted values were checked under experimental conditions. Tables 7 and 8 show the findings of experimental UTS and Vickers hardness, results compared with the predicted values. From Tables 7 and 8 it has been observed that the predicted and experimental values for both UTS and HV are extremely similar.

3.4 Analysis of variance (ANOVA) results based on UTS

The ANOVA is a relatively recent method for defining the effect of each parameter on the process reaction. The ANOVA findings may be used to calculate the impact factor of each parameter. Table 9 depicts the ANOVA findings based on UTS. From, the ANOVA Table 9 for UTS, it is revealed that the tool rotational speed, tool profile, and axial load have P-value less than 0.05, thereby negating the unsound hypothesis and validating the fact that these parameters contribute significantly to the overall tensile strength of the FSW joint [1]. Figure 7 represents the FSW process parameter effectiveness based on UTS. From Figure 7, it is noticed that the percentage influence of FSW parameters based on UTS are as follows: Tool profile: 83.70%, Rotational Tool speed: 4.82%, and Axial force: 11.35%.

3.5 ANOVA based on Vickers hardness

Table 10 shows the ANOVA findings based on weld nugget Vickers hardness. The efficacy of FSW process parameters based on HV is depicted in Figure 8. From the ANOVA Table 10 for Vickers hardness, a P-value greater than 0.05 (>0.05) is not statistically important and shows the unsound hypothesis. This means, that the null hypothesis formulated for the statistical validation holds good and the alternative hypothesis is rejected. The null hypothesis framed for each of the parameters is that the parameters selected do not have an important effect on the Vickers hardness of the FSW joints. Thus, from the table, it shall be noted that the tool rotation speed, tool profile, and axial load have a P-value greater than 0.05, thus contributing minimally to the overall Vickers hardness of the FSW joint [1]. From Figure 8 it is noticed that the contribution percentage of FSW factors based on HV are Tool profile: 53.84%, tool rotational speed: 20.16%, and Axial force: 21.32%.

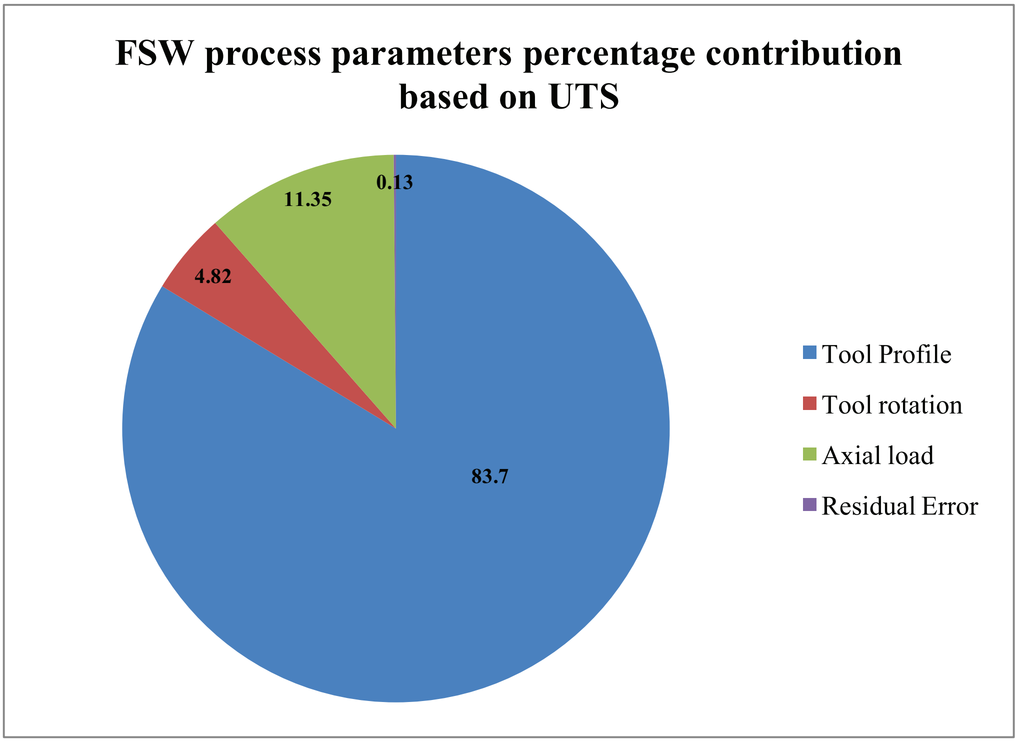

Fig. 7. FSW process parameter effectiveness based on UTM.

Table 10. ANOVA results based on Vickers hardness.

Source	DF	Adj SS	Adj MS	F-value	P-value	Percentage of contribution (%)
Tool profile	2	105.390	52.695	11.56	0.080	53.84
Tool rotation	2	39.474	19.737	4.33	0.188	20.16
Axial load	2	41.745	20.873	4.58	0.179	21.32
Residual error	2	9.118	4.559			4.65
Total	8	195.727				

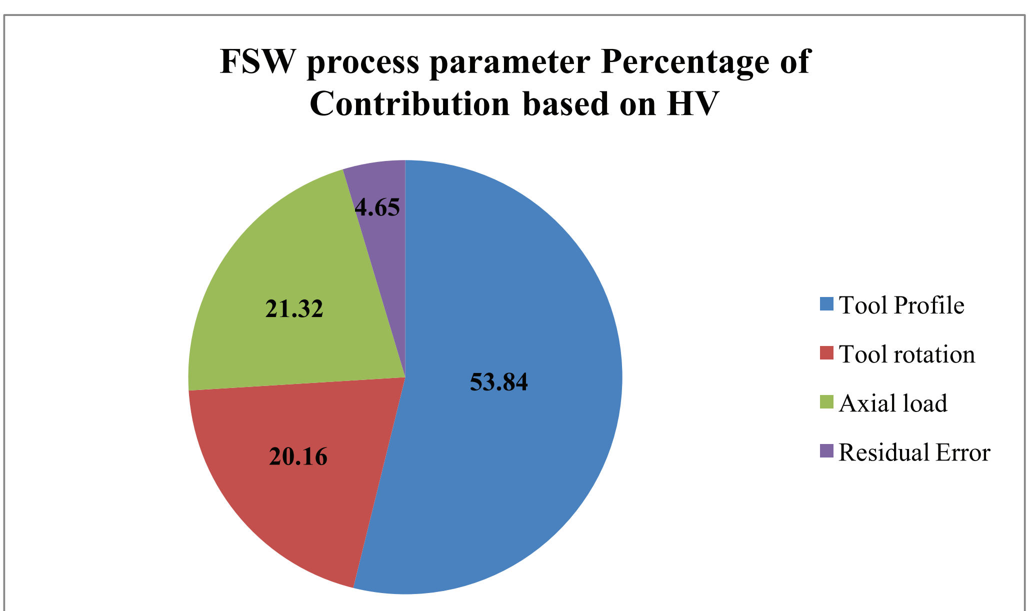

Fig. 8. FSW process parameter effectiveness based on HV.

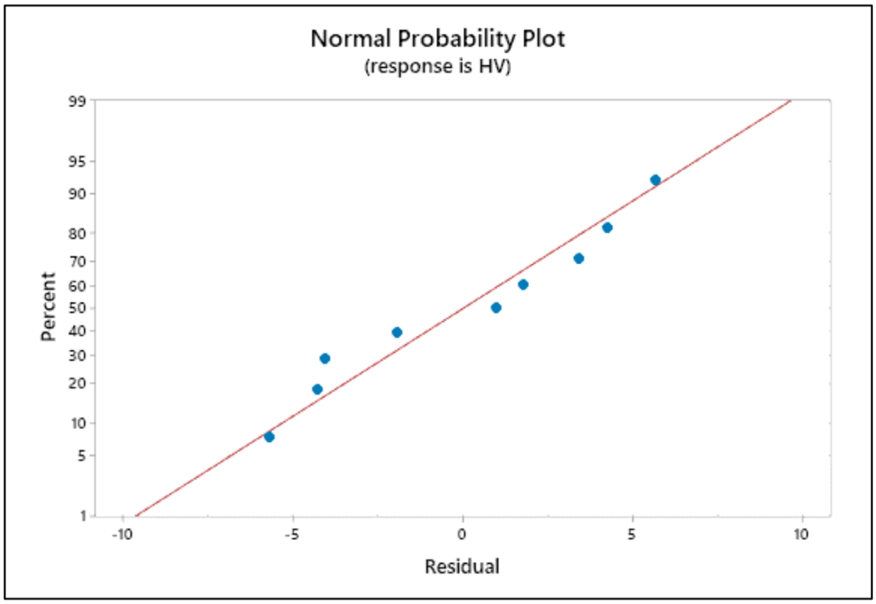

Fig. 9. UTS normal probability plot.

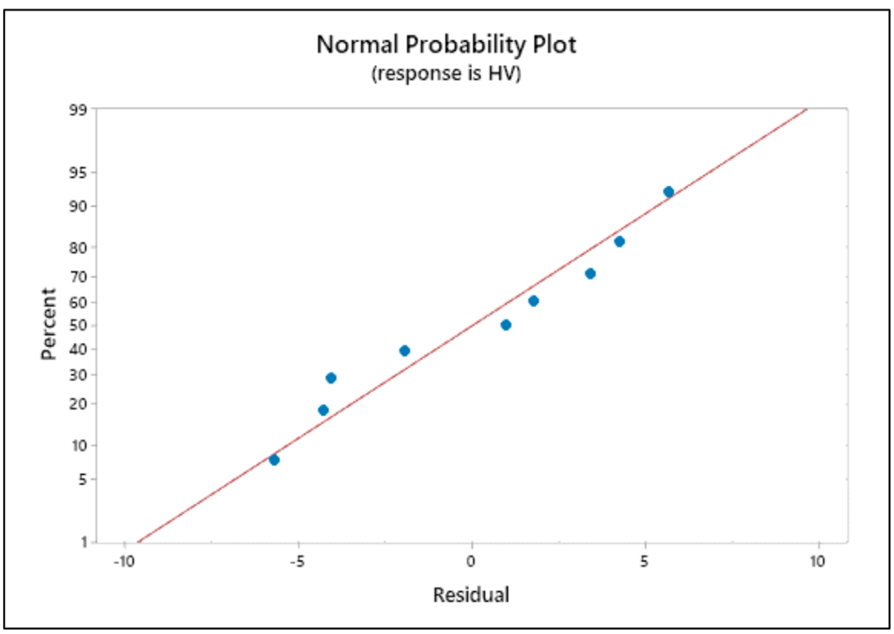

Fig. 10. Vickers hardness (HV) normal probability plot.

3.6 Predictive mathematical models

The mathematical models used for predicting UTS and HV of the dependent parameters were generated using Minitab software (linear regression analysis). It is a function of rotation of tool speed and axial force. The mathematical models developed from regression analysis are represented by equations (2) and (3).

$$\mathrm{UTS} = 92.8 - 0.0048\mathrm{TR} + 2.92\mathrm{AF}. \tag{2}$$

$$\mathrm{HV} = 64.7 + 0.0170\mathrm{TR} + 1.79\mathrm{AF}. \tag{3}$$

The residual plan was used to assess the relevance of the expected model coefficients. The straight-line plots suggest that the model errors are generally distributed and its coefficients are important. Figures 9 and 10 show the residual plots for UTS and HV. The residuals for both UTS & HV are close to the straight line as illustrated in Figures 9 and 10. The data implies that the generated model coefficients are significant.

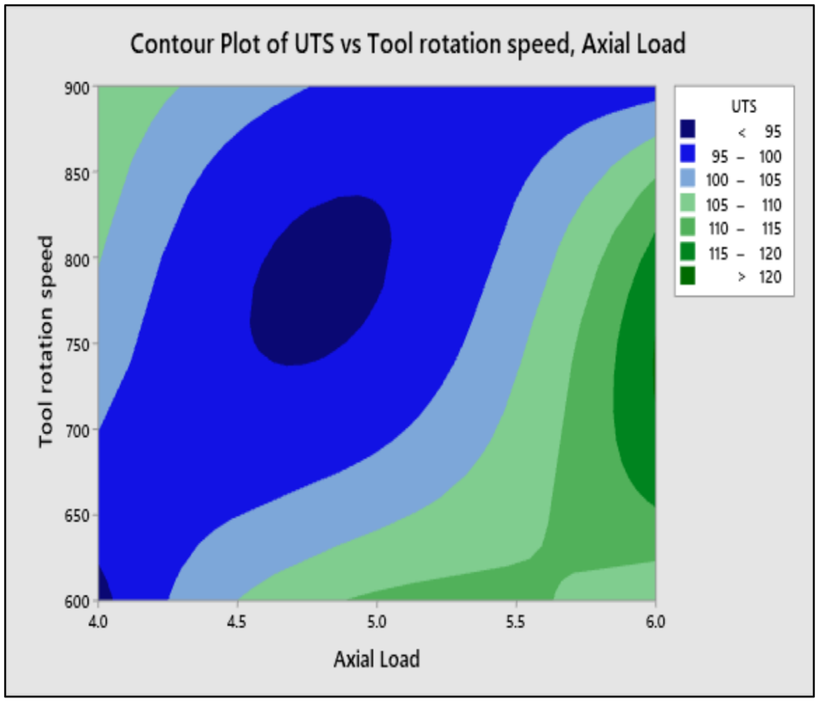

Fig. 11. Ultimate tensile strength contour plot.

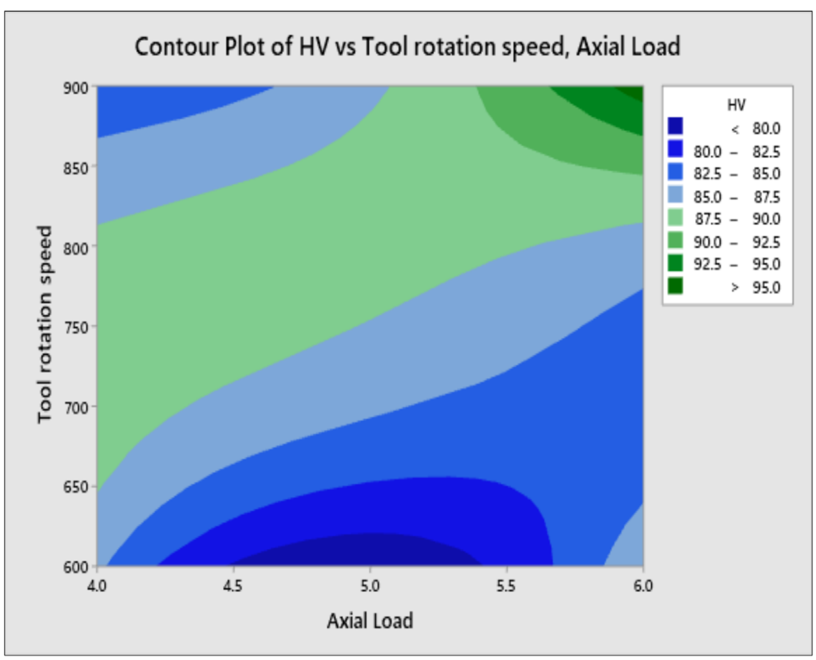

Fig. 12. Vickers hardness contour plot.

3.7 Contour plots

The contour plots were used to obtain the relation between the two control parameters and one response variable by discrete contours. The relationship between UTS, tool rotation speed, an axial force is shown in contour plot. From Figure 11, it is revealed that the appearance of maximum UTS is caused by a combination of high tool rotational speed and axial force due to fact that the increased strength of the welding, helping it to withstand tensile loads and vice versa. High tool rotational speeds induced a fine grain structure in the FSW region results in an increase of tensile strength [5]. Figure 12 depicts the contour plots between the Vickers hardness value, tool rotational speed, and axial force. From Figure 12, it is noticed that at a higher level of tool rotation speed and axial load, there is a generation of higher Vickers hardness value. The hardness value is starting to rise as rotational speeds and axial load is increased while in mediate restrictions of rotational speeds and axial load, the hardness values are diminished. An increase in stirring speed results in high heat input causes a defect in welds reduces the hardness [7].

4 Conclusions

The most influencing and optimum friction stir welding parameters of AA6061-6wt.%SiC composites were evaluated by using Taguchi L9 orthogonal array method. The overall results obtained are summarized as follows.
– AA6061-6wt.%SiC composites were produced by the stir casting technique and successfully friction stir welded.
– The UTS of AA6061-6wt.% SiC composites increases and reach the maximum value when the tool rotational speed is 750 rpm. The UTS decreases with a subsequent increase in tool rotational speed from 750 to 900 rpm. The UTS is found to be maximum at tool rotational speed 750 rpm, axial load 6 kN using square pin profile tool.
– The contribution of FSW process parameters in percentage (based on UTS): tool profile 83.7%, rotational tool speed 4.82%, and axial force 11.35%.
– The Vickers's hardness of AA6061-6wt.% SiC composites was found to be superior at tool rotational speed 900 rpm, the axial force of 6 kN using cylindrical tool pin.
– The contribution of FSW process parameters in percentage (based on HV) is tool profile: 53.84%, rotational tool speed: 20.16%, and axial force: 21.32%.

Future studies

Some suggestions are presented for future studies in the field of the friction stir process:
– To study the effect of a number of passes, wt.% of reinforcement on mechanical & corrosion properties of FSW composites.
– To study the influence of FSW parameters on tribology properties and corrosion behaviour.
– Optimization of FSW parameters of hybrid composites.

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Cite this article as: Venkatesh B.N., Umamaheshwar Hebbal, Siddappa P.N., Kousik S., Nagaraja T.K., Optimization of FSW parameters of AA6061-6 wt.% SiC composite plates, Manufacturing Rev. **9**, 34 (2022)