Optimization of Process Parameters for Friction Stir Welding of Cast Alloy AA7075 by Taguchi Method

Dhairya Partap Sing, Vikram Singh, Sudhir Kumar

Abstract**—**This investigation proposes Friction stir welding technique to solve the fusion welding problems. Objectives of this investigation are fabrication of AA7075-10%wt. Silicon carbide (SiC) aluminum metal matrix composite and optimization of optimal process parameters of friction stir welded AA7075-10%wt. SiC Composites. Composites were prepared by the mechanical stir casting process. Experiments were performed with four process parameters such as tool rotational speed, weld speed, axial force and tool geometry considering three levels of each. The quality characteristics considered is joint efficiency (JE). The welding experiments were conducted using L_{27} orthogonal array. An orthogonal array and design of experiments were used to give best possible welding parameters that give optimal JE. The fabricated welded joints using rotational speed of 1500 rpm, welding speed (1.3 mm/sec), axial force (7 k/n) of and tool geometry (square) give best possible results. Experimental result reveals that the tool rotation speed, welding speed and axial force are the significant process parameters affecting the welding performance. The predicted optimal value of percentage JE is 95.621. The confirmation tests also have been done for verifying the results.

Keywords**—**Metal matrix composite, axial force, joint efficiency, rotational speed, traverse speed, tool geometry.

I. Introduction

DUE to the technology innovation in the area of composite materials, designers have the choice to select suitable engineering materials for specific applications. Therefore, composite materials are more suitable than conventional materials for different applications like automobile, aerospace ship building and medical industries. Friction stir welding is a solid state welding process invented by The Welding Institute (TWI) of UK in 1991. Friction stir welding produces a joint stronger than the fusion arc welded joint and strongly used in auto, aerospace and ship building industries [1]. Metal matrix composite (MMC) is the combination of metal and reinforcement. Aluminium, magnesium and titanium are the common matrix metals with characteristic such as light weight and temperature resistance. The typical reinforcing ceramics are Al_2O_3, SiC and B_4C. These can be used as long fibres, short whiskers or particles in either an irregular or spherical shape [2]. The fabrication techniques vary considerably depending upon the choice of matrix and the reinforcement material. Among the variety of manufacturing processes available for discontinuous MMC production, stir casting is generally accepted [3]. This stir casting process is the most economical of all the available routes for production of MMCs. It is able to sustain high productivity rates and allow very large size components to be fabricated. The fabrication cost of composites using a stir casting method is about one-third to one-half with that of other competing methods; and for high volume production it is projected that costs will fall to one-tenth [4]. This mechanical entrapment is promoted by a vigorous agitation which also promotes wetting. As the reinforcement is forced into the matrix, it is essential to continue mixing, in order to ensure proper interface bonding between the matrix and particulate [5]. To design a high-quality weld system, a powerful tool also known as the Taguchi method, can be used. This method provides not only an efficient approach, but also a systematic approach to optimize designs for better performance and quality [6]. It is well known that for any welding process the main difficulty is the selection of process parameters and their optimum values that would produce good quality joint. Few works are reported in literature related to optimization of FSW process parameters using Taguchi method for single quality characteristics. But the performance of any process depends on various quality characteristics so it is necessary to select optimum set of parameters that improves the various quality characteristics [7]. Friction stir welding tool's profiles like straight cylindrical, tapercylindrical, threaded cylindrical, square, and triangular with combinations of 15, 18, and 21 mm shoulders were used by Elangovan and Balasubramanian to join 6061 aluminum alloy. In the paper, square pins provided superior tensile properties with least number of defects [8]. Palanivel et al. studied the effect of tool pin profiles on mechanical and metallurgical properties of dissimilar 6351-5083 H111 aluminum alloy welds. Tool pin profiles such as straight cylindrical, threaded cylindrical, square, tapered square, and tapered octagon were used for the purpose, square straight tool gives the best result [9]. Vijay and Murugan study the effects of FSW tool profiles such as square, hexagon, and octagon, and concentric circular grooved shoulders on stir cast MMC welded joints [10].

Critical review of literature in the present investigation revealed that hot cracking and porosity were the major issues in fusion welding. To minimize the problem, friction stir welding with optimized process parameters was proposed. In this experimental work, the process parameters and their combined effects on weld qualities were analyzed for finding optimal JE. The Taguchi approach and analysis of variance (ANOVA) techniques were used for analyzing the raw data.

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The effects of the selected FSW process parameters (rotational speed, welding speed, axial force and types of tool pin geometry) on the selected performance were investigated. These investigations are based on the raw data effects and signal-to-noise (S/N) ratio effects plot. The optimum values of process parameters for each of the performance characteristics were established through the raw data analysis. The optimal values of FSW parameters were verified using three confirmation experiments.

II. Experimental Procedure

A. Material

Aluminium alloy 7075 was used as base material in this work. It is the most widely used high strength aluminium alloy and has gathered wide acceptance in the fabrication of light mass structures require high strength to weight ratio, high wear resistance and creep resistance. The chemical composition of the AA7075 is shown in Table I.

TABLE I
CHEMICAL COMPOSITION OF AA7075

Element	Mg	Mn	Zn	Fe	Cu	Si	Cu	Al
Wt%	2.1	0.12	5.1	0.35	1.2	0.58	1.2	Bal

Reinforcements like Al_2O_3, SiC and TiC are generally used in industrial application. The reinforcement of largest commercial volume is SiC by a significant margin, followed by Al_2O_3 and TiC. SiC is highly wear resistant and also has good mechanical properties including high temperature strength and thermal shock resistance. SiC produces its high mechanical strength in temperatures as high as 1,400 °C. It produces higher chemical corrosion resistance than other ceramics. Hence, SiC has been selected as reinforcement. SiC powder having a size of 20-40 μm was chosen as reinforcement particles because they have high wear and temperature resistance.

B. Fabrication of Composite

In this work AA7075 with 10wt.%SiC MMC was prepared by the mechanical stir casting process. Experimental set-up of mechanical stir casting process is represented by Fig. 1. Heat treatment of reinforcement particles is necessary for improving their wet ability with the matrix [11]. Hence, the SiC particles were heated in an oven at 700 °C for 8 hours to improve the wettability. The stir casting furnace is mounted on ground. The temperature of furnace is to be precisely measured and accurately controlled (±2 °C) for fraction of solid in the semi-solid alloy. Two thermocouples and one PID controller are used for this purpose. Stainless steel material was selected for the stirrer rod and for the impeller because of its corrosion resistance and stability at high temperatures. The stirrer was connected to 1 HP DC motor through flexible link. AA7075 placed in the furnace degassing of molten metal was carried out by passing nitrogen gas through the melt after covering the melt with a flux. The melt was cleaned by taking out the dross collected on the melt surface with a perforated flat spoon. The melt was maintained at a temperature between 750 to 800 °C for 1 hour. Vortex was created in the melt using a mechanical stirrer. Preheated 10 wt.%SiC particles were added to the melt during stirring. Stirring was carried out for 10 min, at 650 rpm for 7075 Al alloy and composites with 10 wt.% SiC reinforcements. Al alloy and composites were cast by pouring the liquid mixture in preheated cast iron die (diameter 60 mm and length 110 mm).

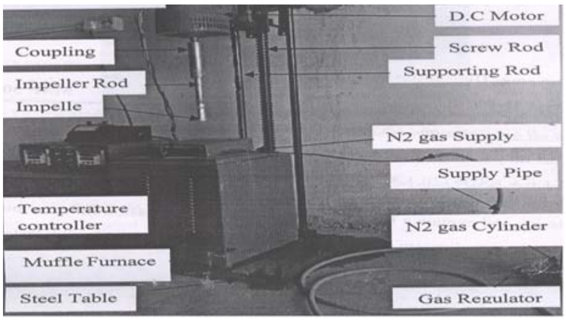

Fig. 1 Experimental Set-Up of Stir Casting

C. Characterization of MMC

Microstructure

The specimens for microscopic examination were prepared by adopting standard metallographic procedure. Well cleaned samples were etched with Keller reagent to reveal the microstructure. Keller reagent was a solution mixture of 1% hydrofluoric acid, 1.5% hydrochloric acid, 2.5% nitric acid and balance of distilled water. The specimens are now observed for microstructure using Radial Metallurgical Microscope fitted with inter video Win DVRCCD digital camera, which is interfaced to a personal computer for image capture. Fig. 2 shows microstructure of AA7075/10%wt.SiC composite. The uniform distribution of reinforcement is most important factor in the fabrication of composites. Fig. 2 shows the distribution of reinforcements in the matrix with SiC particles as black and ivory white respectively. These are uniformly distributed in the matrix, no porosity or clustering of particle is observed in optical examination. It indicates a good bonding between the reinforcement particles and the matrix alloy.

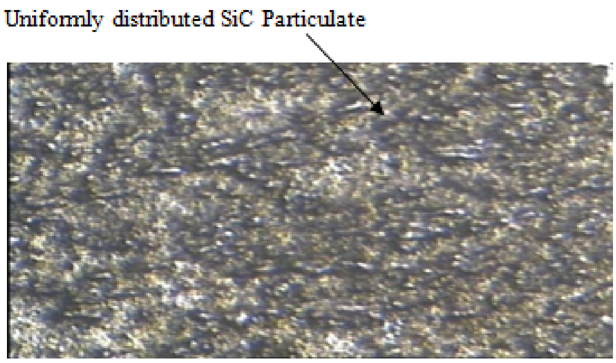

Fig. 2 Optical Microstructure of AA7075/10%wt.SiC Composite

X-Ray Diffraction Analysis

X-Ray diffraction analysis is commonly used to identify phases in materials by comparing their diffraction patterns with those from known reference. The intensity of the X-Ray peak obtained obtained for a given phase depends on its proportion and size in the material. Photographic view of XRD machine is shown in Fig. 3. The sample were scanned with a scanning speed of 1.5 kcps in 2 theta range of 10-1000 at 20/min goinometer rotation and the intensities were recorded at a chart speed of 20 mm/min. Diffractometer being interfaced with Brucker Diffract plus X-Ray diffraction software provides 'd' values directly on diffraction pattern. According to the figure, the highest peak confirms the presence of base element aluminium of the matrix alloy AA7075. The other constituent elements like Fe, Mg, Si, Cr, Zn and SiC are confirmed by smaller peaks. The reinforcement Sic is confirmed at their respective peaks.

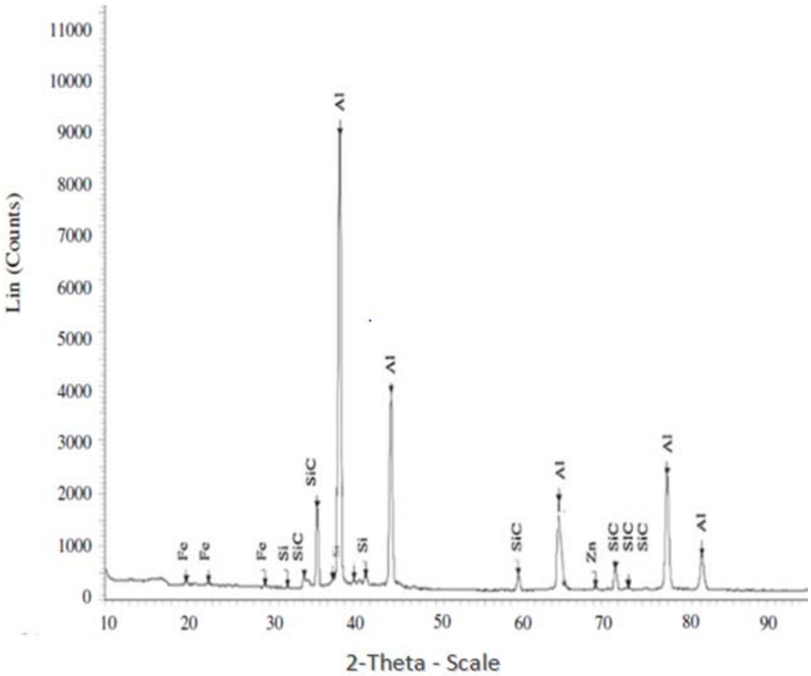

Fig. 3 X-RD curves of composite AA7075/10%wt.SiC

D.Selection of Process Parameters and Their Ranges

The Taguchi method, developed by Dr. Genichi Taguchi, refers to the technique of quality engineering. Taguchi's parameter design can not only reduce product cost and improve quality, but also reduce experimental time interval [15]. In this work, L_{27} orthogonal array was chosen due to its capability to check the interactions among the process parameters were rotational speed, welding speed, axial force and tool geometry and their range shown in Table III. All these process parameters and their ranges were selected after the pilot experiments. S/N ratio, for each control factor is calculated to find the effect of welding parameters on the response characteristic. The signals are indicators of the effect on the average responses. The noises are measures of influence on the deviations from the average responses, which accounts for the sensitiveness of the experiment output to the noise factors. In this study, the S/N ratio was chosen according to the criterion 'the larger-the-better', in order to maximize the response. The S/N ratio of the larger expressed as [15].

$$S/N = -10 \log \frac{1}{n} \left(\sum_{i=1}^{n} 1/yi^2\right)$$

where, n is the number of repetitions of the experiment and yi is the average measured value of experimental data. The tools made of high speed steel with different pin profile (Square, Hexagonal and Octagonal) were used in the present work. The geometry of the tools and friction stir welding set-up shown in Fig. 4. Welding process parameters and their levels were selected by pilot experiments which are shown in Table II.

TABLE II
WELDING PROCESS PARAMETERS AND THEIR LEVELS

Symbol	Process Parameters	Level 1	Level 2	Level 3
A	Tool Rotational Speed (rpm)	1300	1500	1700
B	Welding speed (mm/sec)	.8	1.3	1.8
C	Axial force/kN	5	7	9
D	Tool geometry	Square	Hexagonal	Octagonal

Analysis of mean and S/N ratio for each experiment gives optimum level of process parameters for higher JE of the weld. Mean responses of raw data and S/N ratios of JE for each parameter at all levels are calculated by Minitab 17 and presented in Table III and response table for means and s/n ratio is shown by Tables IV and V respectively. It was observed that trial number 14 has highest JE. Therefore, parametric values at trial number 14 give maximum JE among all trial runs. Taguchi methodology was used for exact optimal setting of welding process parameters for optimum performance. The difference between maximum and minimum average JE of each input process parameter gives an idea about most important controllable factors. So, ANOVA was implemented. The purpose of ANOVA is to investigate the effect of parameters. NOVA analysis was carried out for a level of significance of 5%, i.e. for 95% level of confidence. If the calculated F-ratio is more than the tabulated value i.e. 5.14 for parameter and 4.53 for interactions at confidence level, then the effect is significant. Percentage contribution gives the significant contribution on response. Further, the percentage JE in Table III is analyzed with ANOVA. The ANOVA of the JE is tabulated in Table VII. This table clearly shows that rotational speed has maximum contribution (44.26 %) followed by welding speed (23.57%) and axial force (16.19%). It can be seen from Table VII that AXB interaction has only significant influence of 14.09% compared to other interactions.

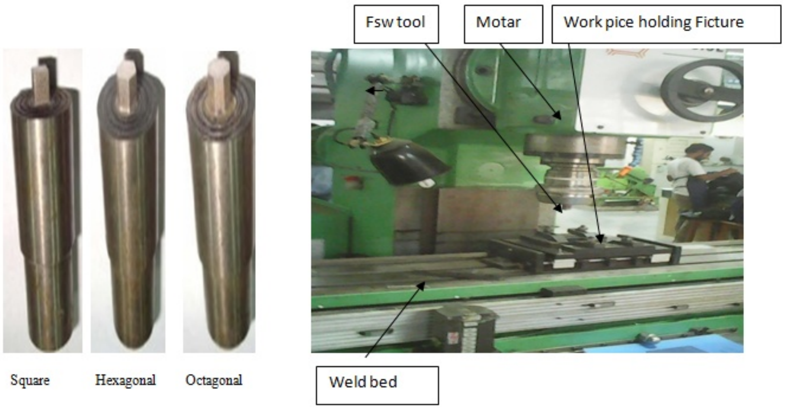

Fig. 4 Fabricated tools and experimental set-up of F.S.W

TABLE III
PERCENTAGE OF JE RESULTS OF FSW JOINTS

S.NO	Tool Rotational Speed	Welding Speed	Axial Force	Tool Geometry	Percentage JE (J.E)	S/N ratio (J.E)
1	1300	0.8	5	S	68.88	36.7621
2	1300	0.8	7	H	77.61	37.7988
3	1300	0.8	9	O	73.21	37.2913
4	1300	1.3	5	H	78.29	37.8744
5	1300	1.3	7	O	83.83	38.4682
6	1300	1.3	9	S	75.83	37.5967
7	1300	1.8	5	O	67.29	36.559
8	1300	1.8	7	S	74.02	37.3876
9	1300	1.8	9	H	71.39	37.0727
10	1500	0.8	5	H	72.94	37.2594
11	1500	0.8	7	O	83.18	38.4001
12	1500	0.8	9	S	76.99	37.7288
13	1500	1.3	5	O	89.72	39.0577
14	1500	1.3	7	S	96.88	39.7251
15	1500	1.3	9	H	92.55	39.328
16	1500	1.8	5	S	88.21	38.9102
17	1500	1.8	7	H	91.04	39.1847
18	1500	1.8	9	O	88.83	38.9717
19	1700	0.8	5	O	75.11	37.5142
20	1700	0.8	7	S	87.15	38.8053
21	1700	0.8	9	H	77.69	37.8078
22	1700	1.3	5	S	83.53	38.4368
23	1700	1.3	7	H	88.51	38.9396
24	1700	1.3	9	O	81.39	38.211
25	1700	1.8	5	H	75.7	37.582
26	1700	1.8	7	O	81	38.1694
27	1700	1.8	9	S	77.7	37.8089

TABLE IV
RESPONSE TABLE FOR MEANS

Level	Rotational Speed	Welding Speed	Axial Force	Tool Geometry
1	239.1	247.1	249.6	260.1
2	278.3	274.8	272.2	258.8
3	259.6	255.1	255.2	258.1
Delta	39.2	27.7	22.7	2
Rank	1	2	3	4

TABLE V
RESPONSE TABLE FOR SN RATIO

Level	Rotational Speed	Welding Speed	Axial Force	Tool Geometry
1	47.55	47.84	47.9	48.26
2	48.86	48.76	48.67	48.22
3	48.27	48.09	48.11	48.2
Delta	1.31	0.92	0.77	0.06
Rank	1	2	3	4

III. RESULTS AND DISCUSSIONS

The response table data are clearly graphically presented by Figs. 5 (a)-(d). The JE reflects the impact of welding process parameters on performance characteristics. In other words, larger JE value corresponds to high quality performance. Therefore, optimal welding process parameters are corresponding to larger value of JE.

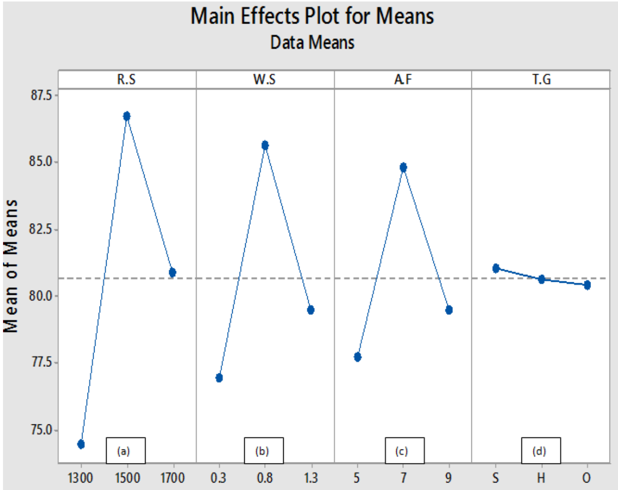

Fig. 5 Effect of process parameters for JE

A. Effect of Rotational Speed on JE

Fig. 5 (a) shows the effect of tool rotational speed on JE of friction stir welded AA7075-10%wt.SiC MMC joints. The maximum JE was obtained at the rotational speed of 1500 r/min. At a lower (1300 r/min) and higher rotational speed (1700 r/min), the JE of joint was poor. When the rotational speed was increased from 1300 r/min, correspondingly the JE also increased and reached a maximum at 1500 r/min. If the rotational speed was increased above 1500 r/min, the JE of the joint was decreased. A lower tool rotational speed (1300 r/min) produced a lower heating condition as well as poor stirring action by the tool pin and improper consolidation of work material by the tool shoulder [12]. Hence a lower JE was obtained. The increase in rotational speed increased the heat input per unit length of the joint, which causes a greater uniform grain refinement resulting in improved JE. A significant increase in the rotational speed (i.e. more than 1500 r/min) may produce an excessive release of stirred material on the top surfaces, which resulted in the formation of micro voids into the stirred zone. The rise in temperature as well as lower cooling rate and coarsening of grains at more than desired temperature may also reduce the tensile properties at high rotational speed [14].

B. Effect of Welding Speed on JE

Fig. 5 (b) shows the effect of welding speed on JE of friction stir welded AA7075-10%wt.SiC MMC joint. The tensile strength of FSW joint was low at the lower welding speed of 0.8 mm/s. The JE was increased with increase in welding speed until the maximum of 1.3 mm/s. Further increase in welding speed decreased the tensile strength of FSW joint. It can be observed that a higher welding speed decreases the frictional heat input to the work material, which creates poor plastic flow of the metal and causes some voids like defects in the welded joint. This restricts grain growth and causes reduction in the width of the weld. Hence poor JE is obtained.

C. Effect of Axial Force on JE

Fig. 5 (c) shows the effect of axial force on JE of friction stir welded AA7075-10%wt.SiC composite joints. The lowest strength was obtained at axial load of 5 KN and 9 kN. The JE of composite joint was increased with increase in axial load up to a maximum load of 7 kN.

TABLE VI
RESPONSE TABLE FOR JE

Welding parameter	Level 1	Level 2	Level 3	Max-Min
Tool Rotation	74.4833	**86.7044**	80.8644	12.2211
Welding Speed	77.5288	**85.6144**	79.4644	8.0856
Axial force	77.74	**84.8022**	79.5088	7.0622
Tool Geometry	**81.0211**	80.6355	80.3955	
Overall mean			80.75	

Further increase in axial load decreased the tensile strength of the joint. During the FSW process, the rotation of tool produces a large amount of heat input which brings the metal to become very hot and plastic state. The axial force is more responsible for the plunge depth of the tool pin into the work piece [13]. The joining of materials depends on the extrusion process by axial force and the rotation of tool pin which propelled the plasticized material. At a lower axial force (5 kN), the lowest frictional heat is generated which is not sufficient to generate an adequate plastic state. At a higher axial force (9 kN) the plunge depth of the tool into the work piece is higher which drastically decreases the strength [14]. The joint fabricated with an axial force (7 kN) produced a finer grain structure with uniform distribution of reinforcement particle in the stir zone and resulted higher JE value. Hence sufficient axial force is required to form good weld.

D. Effect of Tool Pin Profile on J.E

TABLE VII
POOLED ANOVA FOR S/N RATIO (J.E)

Source	DOF	Seq SS	Adj SS	Adj MS	F Ratio	P	%PC
Rotational Speed	2	7.7023	7.70234	3.85117	128.48	0.000	44.22
Welding Speed	2	4.0548	4.05477	2.02739	67.64	0.000	23.44
Axial Force	2	2.8523	2.85229	1.42615	47.58	0.000	16.59
Tool Geometry	2	0.0152	0.01517	0.00759	0.25	0.784	
Rotational Speed*Welding Speed	4	2.2855	2.28549	0.57137	19.06	0.001	13.70
Rotational Speed* Axial Force	4	0.0625	0.06253	0.01563	0.52	0.725	
Welding Speed* Axial Force	4	0.4679	0.46788	0.11697	3.90	0.068	
Residual Error	6	0.1798	0.17984	0.02997			2.04
Total	26	17.603					100

Fig. 5 (d) shows the different values of JE for different types of tool pin profile. It is observed that the square type tool pin profile gives the maximum value of JE. The square type of tool pin profile produces good material stir quality during welding. Since, the tool has four edges, the point of each edge acts as an individual cutting tool that causes maximum deformation in the material. Hence, good surface finish and defect free joints are formed. Hexagonal and octagonal type tool pin profile produces insufficient mixing because tool pin is incapable of deforming appropriate material during rotation.

IV. Optimization of Process Parameters for JE

As per Taguchi methodology, response table was used to calculate average JE for each input process parameter at different levels. The calculated JE for welding parameters at levels 1–3 is reported in Table VII. In other words, larger JE value corresponds to high quality performance. Therefore, optimal welding process parameters are corresponding to large value of JE which is represented in Table VI. Therefore $A_2B_2C_2D_1$ with tool rotation speed of 1500 rpm, welding speed of 1.3 mm/sec, axial force 7 kN and tool geometry of square is the optimum combination of process parameters for response optimization in welding of composites.

The confirmation experiments were conducted at the selected optimum levels ($A_2B_2C_2D_1$) to verify the quality characteristics for welding of AA7075/10%SiC composite using high speed steel tools. After the optimal level has been selected, one could predict the using the equation [15]:

$$\mu_{predicted} = \mu_m + \sum_{i=1}^{n}(\mu_o - \mu_m) \qquad (1)$$

where, µm is the mean response, µo is the mean response at optimal level. n is the number of factor that affects the response. It is very essential to perform a confirmatory experiment in the parameter design, particularly when less numbers of data are utilized for optimal. The confirmation experiment is used to verify the improvement in the quality characteristics.

$$\mu\text{predicted mean} = A_2+B_2+C_2-2T$$

where T = overall mean = 80.75 where, the values of A_2, B_2 and C_2 are taken from the Table VI. A2=Average value at the Second level of tool rotational speed = 86.7044. B2 = Average value of at the second level of welding speed = 85.6144. C2 = Average value of at the second level of tilt angle = 84.8022. Substituting the values of various terms in the above equation:

$$\mu\text{predicted mean} = 86.7044+85.6144+84.8022-2*80.75$$

$$\mu\text{predicted mean} = 95.621$$

The 95% confidence interval of confirmation experiment (Cl_{CE}) was calculated by [15]:

$$Cl_{CE} = \sqrt{F_{\alpha}(1, f_e)V_e\left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \qquad (2)$$

where, Ve is the error variance, Fα (1, fe) is the F-ratio at a confidence level of (1-α) against DOF, 1 and error degree of freedom fe .α is confidence level [15].

$$n_{eff} = \frac{N}{1+[\text{TotalDOFassociatedintheestimateofmean}]}$$

where, N is the total number of results = 81 and R is the sample size for confirmation experiment = 3.

$$n_{eff} = \frac{81}{1+[2+2+2]}$$

$n_{eff} = 11.571$; Error variance $V_e = 2.387$; f_e= error, DOF= 6; F (1, 6) = 5.14 (Tabulated F-ratio) [15]. So, $CL_{CE} = \pm 2.26$

Predicted optimum range for confirmation experiment is:

Predicted J.E+ CI_{CE}> Predicted J.E > Predicted J.E - CI_{CE}

95.621+2.26 >Predicted J.E>95.621 -2.26

97.881>Predicted J.E> 93.361

A. Verification of Optimal Parameters through Confirmation Test

For confirmation experiments, three tests were conducted at the optimum level ($A_2B_2C_2D_1$), which are shown in Table VIII. From this table, the estimated error between predicted mean values and experimental average value is 1.83% for JE. The average mean value of welded JE is found within the confidence interval as reported in Table VIII.

The JE of welded joints are lower than the base materials. This is due to the welded joint formed as the combination of many thin layers in the direction of the joint thickness. It is fact that the different layers of plasticized metal have different mechanical properties because the cooling patterns of the layers are different. The upper layer is directly exposed in air, so its cooling rate is faster than the intermediate layers. The heat generations at different process parameters are not proper for different joints, which affects the weld quality.

TABLE VIII
Responses of Optimum Levels of Process Parameters

Responses	Optimum welding Parameters		Confidence interval
	Predicted	Experimental	
J.E	95.621	93.874	97.881 > Predicted JE > 93.361

V. Conclusion

The following conclusions have been made from the present research work regarding the fabrication and welding of AA7075-10%wt. SiC MMC by FSW.

- Cast composite of 10%wt.SiC (particulate size 20-40 µm) is successfully fabricated using mechanical stir casting process under the controlled conditions.
- Microstructures of AA 7075 and AA7075-10%wt. SiC reveal a fairly uniform and homogeneous distribution of reinforcing particles of SiC.
- The X-RD patterns of cast composite sample confirm the presence of the base element aluminum and the other constituents of matrix alloy.
- The presence of hard phase constituents SiC is confirmed at respective peaks. No peeks of brittle phase Al_4C_3 are observed in the pattern.
- The optimal level of process parameters for optimum multi response quality targets was obtained as $A_2B_2C_2D_1$,

tool rotational speed of 1500 rpm (level 2), welding speed 1.3 mm/sec (level 2), axial force 7 kn (level 2) and tool geometry is square (level 1).

- The result demonstrated that the tool rotational speed has the strongest effect on the response characteristic among the other process parameters.
- ANOVA result reveals that tool rotational speed maximum influence (44.22%) is followed by welding speed (23.44%) and axial (16.59%).

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