WEAR RATE MODELLING AND ANALYSIS OF FRICTION STIR WELDING OF AL6061 /SIC COMPOSITE

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Abstract— Al 6061 metal matrix composites with SiC are increasingly becoming popular in automotive, aerospace and electronics industries, in view of their excellent mechanical properties and wear resistance. Metal matrix composites (MMC_s) have emerged as an important class of materials, which are increasingly being utilized in recent years. Their wide application as structural materials needs proper development of suited joining processes. The present study investigates the effect of joining parameters like tool rotation speed, welding speed, axial force and different % wt. of SiCp on the wear rate (W) and wear resistance (R). Central composite design (CCD) was employed in developing an efficient mathematical model for wear rate. Analysis of variance (ANOVA) was used to test the adequacy of the developed mathematical model. The contour plots were generated to study the effect of process parameters as well as their interactions.

Keywords— Metal Matrix Composites, Friction Stir Welding, Welding Parameters and Contour Plot.

I. INTRODUCTION

Advanced materials like aluminum metal matrix composites (MMCs) have attracted considerable attention due to their appealing mechanical properties and a clear potential for aerospace applications. The implementation of MMCs is restricted and they are not widely used in the aviation industry, in part because of the difficulties that are related to the joining of these metals by conventional welding processes [1,2]. Friction stir welding (FSW) [3] is being considered as a prospective joining process to solve this problem. As a solid-state joining process, FSW can eliminate the welding defects associated with fusion welding processes. Several researchers carried out FSW using a single set of parameters while few others attempted to study the influence of process parameters on joint properties. Prado et al. examined the effect of rotational speed on tool wear of friction stir welded AA6061/20 vol % Al2O3 and observed that the tool wear was non linear [4]. Shindo et al. estimated the effect of welding speed on tool wear of friction stir welded A359/20 vol % SiC and noticed different degree of weld zone hardening [5]. Lee et al. compared the wear rate of friction stir welded AZ91/10 vol % SiC with parent composite and observed decrease in wear rate subsequent to FSW. However, he did not attempt to correlate the effect of FSW parameters on wear rate [6].

The present work, developing the mathematical model for correlating the interactive and higher order influences of the various FSW parameters such as the tool rotation speed, welding speed; axial force and different % wt. of SiC on the wear rate of friction stir welded Al6061/SiC The investigation into the influence of welding parameters has been carried out through the development of mathematical models based on response surface methodology (RSM).

II. EXPERIMENTAL PLANNING

In the present experimental study, the material to be joined was Al6061 alloy reinforced with SiC_p particles, at a composition of 0%wt., 5%wt., 10%wt., 15%wt. and 20%wt. and of 25 mm particle size. The MMC plates are fabricated by stir casting process with size 100mm x 50mm x 6mm and then the edges are prepared by the machining process. Microscopic examinations of the specimens were carried out using a scanning electron microscope (SEM). The chemical composition of AA6061 rods is presented in Table1.

Table.1 Chemical composition of Al6061 alloy

Material	Mg	Si	Fe	Mn	Cu	Cr	Zn	Ni	Ti	Al
Al6061 alloy **%wt.)**	0.95	0.54	0.22	0.13	0.17	0.09	0.08	0.02	0.01	Balance

These rectangular composite plates were fixed in the backing plates firmly with a specially designed fixture. A non consumable tool made of HSS with square geometry with a 16mm shoulder diameter and 5.8mm pin length. As shown in the fig 1.

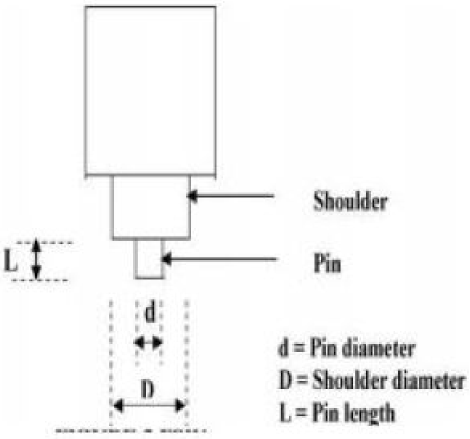

Fig. 1 Friction stir welding tool specification

The welding was carried out on a friction stir welding machine. The rotating tool was plunged into the abutting edges of the two plates until the shoulder touches the surface of the plates with a sufficient thrust force. After a dwell time of 15 seconds the tool head moves with fixed traverse speed. When the joint length ends, the tool is retracted automatically, and the same procedure is followed for various joints as per the design matrix.

As the range of individual factor was wide, a central composite rotatable four-factor, five-level factorial design matrix was selected. The decided levels of the selected process parameters with their units and notations are given in Table 2.

Table 2: Friction stir welding parameters and their levels

Factor	**Unit**	**Notation**	**Levels**				
			(-2)	**(-1)**	**0**	**(+1)**	**(+2)**
Rotational speed	rpm	*N*	1000	1075	1150	1225	1300
Welding speed	mm/minn	*S*	30	40	50	60	70
Axial Force	KN	*F*	4	5	6	7	8
Silicon Carbide	%wt.	*P*	0	5	10	15	20

The experiments were conducted as per the design matrix given in Table 3. It consists of 31 sets of coded conditions and comprising a full replication four-factor factorial design of 16 points, 8 star points, and 7 center points, was used. The upper and lower limits of the parameters were coded as +2 and −2, respectively.

The coded values for intermediate levels can be calculated by

$X_i=2[2X-(X_{max}+X_{min})]/(X_{max}-X_{min})$ (1)

where X_i is the required coded value of a variable X and X is any value of the variable from X_{min} to X_{max}. Welding has been carried out for a fixed time interval.

Table 3: Design matrix

Exp. No.	Coded factors				Actual factors				Wear rate $(\times 10^{-5}\ mm^3/m)$
	X_1	X_2	X_3	X_4	N	S	F	P	
1	-1	-1	-1	-1	1075	40	5	5	369
2	1	-1	-1	-1	1225	40	5	5	358
3	-1	1	-1	-1	1075	60	5	5	380
4	1	1	-1	-1	1125	60	5	5	366
5	-1	-1	1	-1	1075	40	7	5	374
6	1	-1	1	-1	1225	40	7	5	382
7	-1	1	1	-1	1075	60	7	5	368
8	1	1	1	-1	1225	60	7	5	380
9	-1	-1	-1	1	1075	40	5	15	233
10	1	-1	-1	1	1225	40	5	15	230
11	-1	1	-1	1	1075	60	5	15	234
12	1	1	-1	1	1225	60	5	15	242
13	-1	-1	1	1	1075	40	7	15	221
14	1	-1	1	1	1225	40	7	15	246
15	-1	1	1	1	1075	60	7	15	212
16	1	1	1	1	1225	60	7	15	241
17	-2	0	0	0	1000	50	6	10	320

18	2	0	0	0	1300	50	6	10	346
19	0	-2	0	0	1150	30	6	10	322
20	0	2	0	0	1150	70	6	10	317
21	0	0	-2	0	1150	50	4	10	319
22	0	0	2	0	1150	50	8	10	324
23	0	0	0	-2	1150	50	6	0	381
24	0	0	0	2	1150	50	6	20	144
25	0	0	0	0	1150	50	6	10	286
26	0	0	0	0	1150	50	6	10	276
27	0	0	0	0	1150	50	6	10	289
28	0	0	0	0	1150	50	6	10	311
29	0	0	0	0	1150	50	6	10	303
30	0	0	0	0	1150	50	6	10	290
31	0	0	0	0	1150	50	6	10	274

Specimens were extracted from each welded plate having dimensions 6 mm x 6 mm x 50 mm. The wear rate (W) was measured using DUCOM TR20-LE pin-on-disc wear apparatus. A computer aided data acquisition system was used to monitor the loss of height. The volumetric loss was computed by multiplying the cross section of the test pin with its loss of height. The wear rate (W) was calculated as follows.

W (mm3/m) = Volumetric loss / Sliding distance (2)

III. MATHEMATICAL MODELING

The mathematical relationship, obtained for analyzing the influences of the various dominant process parameters like tool rotation speed (N), welding speed (S), axial force (F) and different % wt. of SiCp (P) on the wear rate (W) and wear resistance (R) criteria is given by:

$$W = 3568.07 - (4.52X_1) - (5.63X_2) - (145.62X_3) - (14.43X_4) + (0.06X_2^2) + (6.79X_3^2) - (0.32X_4^2) + (0.08X_1 \times X_3) + (0.01X_1 \times X_4) - (0.36X_2 \times X_3) - (0.02X_2 \times X_4) - (0.59X_3 \times X_4) \quad (3)$$

Where W is wear rate and X_1, X_2, X_3, and X_4 represent the decoded values of tool rotation speed (N), welding speed (S), axial force (F) and different % wt. of SiCp (P) respectively. The developed mathematical model can be used to analyze the effects of process parameters on the wear rate (W).

IV. ANALYSIS OF THE DEVELOPED MATHEMATICAL MODEL

An analysis of variance (ANOVA) was performed for wear rate (W) is presented in Table 4. The standard percentage point of F distribution for 95% confidence limit is 4.06. As shown in Table 4, the *F* value is 0.53. The associated p-value for the model is lower than 0.05 (i.e. level of significance α=0.05, or 95 % confidence), which indicates that the model can be considered statistically significant.

Table 4: Analysis of variance for wear rate

Source of variation	DF	Sum of squares	Mean sum of squares	*F*- value	P- value
Regression	14	114439	8174.23	64.36	0
Linear	4	106123	879.49	6.92	0.002
Square	4	7217	1789.77	14.09	0
Interaction	6	1099	183.16	1.44	0.26
Residual Error	16	2032	127.01		
Lack of fit	10	953	95.33	0.53	
Pure Error	6	1079	179.81		
Total	30	116471			

The plot of normal probability of the residual for wear rate (W) is shown in Fig. 2. From the normal probability plots of residuals (i.e error = predicted value from model – actual value) in fig. 3, it is evident that the residuals lie reasonably close to a straight line implying that errors are distributed normally.

V. RESULT AND DISCUSSION

Based on the mathematical models given by Eq. 3 developed through experimental observations and response surface methodology, studies have been made to analyze the effect of the various process parameters on the wear rate. The contour plots were drawn for various combinations. The number represent in the plot were wear rate.

5.1 *Effect of tool rotational speed and welding speed on wear rate*

Fig.3 shows the effect of tool rotational speed on wear rate of friction stir welded Al6061/SiC composites. The wear rate decreases as tool rotational speed increases. Further increase in tool rotational speed leads to increased wear rate. Similarly, the wear rate decreases as welding speed increases. Further increase in welding speed, the wear rate increases.

5.2 *Effect of axial force and content of SiC on wear rate*

Fig.4 shows the effect of axial force on wear rate of friction stir welded Al6061/SiC composites. The wear rate decreases as axial force increases. Further increase in axial force, the wear rate increases. Similarly, the wear rate decreases as content of SiC increases. Further increase in content of SiC, the wear rate further decreases.

CONCLUSIONS

1. An empirical relationship was developed to predict the wear rate (W) of Al6061/SiCp MMC on FSW, incorporating process parameters. The developed relationship can be effectively used to predict the wear rate (W) on butt welded joints.
2. The adequacy of the developed mathematical model has also been tested through the analysis of variance (ANOVA).The results of the analysis justifying the closeness of fit of the mathematical model at 95% confidence level and 99% confidence level.
3. Welding parameters like tool rotation speed, welding speed, axial force and different % wt. of SiCp were found to have greater influence on wear rate (W).

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