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WEDM process parameter optimization for newly developed hybrid Al/(SiC + Gr + Fe_2O_3) – MMC

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The particulate reinforced metal matrix composites have unparalleled properties which find their applications in various fields such as aerospace, automotive, defense amongst others. The poor machinability of MMCs hinders the potential use of such materials in the industries. Therefore, an experimental study is conducted to explore the wire electrical discharge machining (WEDM) of a fabricated hybrid Al/(SiC + Gr + Fe_2O_3) – MMC and reported in this research article. The various parameters having marked effect on surface roughness (SR) of machined surface such as peak current, pulse-on-time, pulse-off-time, wire tension, and feed rate have been investigated. The experimental design is based on the techniques of Taguchi. $L^{27}(3^{13})$ orthogonal array, ANOVA and S/N ratios (dB) were employed to identify the significant parameters. The WEDM parameters have been optimized subject to minimum machined surface roughness height, R_a (μm). The confirmatory tests have revealed an improvement in surface finish if an optimum combination of parameters is used.

Keywords: Hybrid Al/MMC, WEDM, Taguchi method, surface roughness height.

Introduction

The metal matrix composites (MMC) have drawn focus from the many of industries owing to their exciting mechanical and structural properties and micro-structures. These properties are ideally suited for application in automotive, aviation, space and electronic sectors[1–3]. Stir casting is an important variant of liquid-metallurgy rout to fabricate the MMC material in bulk size[4]. However, machining is desired to remove unwanted material so as to shape the bulk work material to a finished component. The poor machinability of MMCs poses a challenge when industries demand the components made of such materials with intricate shapes and high surface finish[5]. Advanced machining processes namely electrical discharge machining can be used for machining MMC material to produce complex shapes with excellent precision and economy[6]. But many problems have been witnessed by the manufacturing engineers during processing of such materials through WEDM (wire electrical discharge machining) processes which includes irregular material removal rate, high frequency of wire breakage, and poor surface finish[7]. In usual practice, it is very difficult to select the suitable WEDM control parameters and is highly dependent on the experience of the machine operator as well as machining tables provided by the manufacturer for the material to be machined[8]. Thus in order to get the optimum quality characteristics and to ensure economic production of the parts to be machined, it is very important to optimize the operating parameters. Taguchi method based design of experiment can be effectively used to optimize the machining process parameters to improve the major performance measures[9,10]. Recently, development of hybrid MMC materials which include two or more than two type of reinforcements has gained significant importance in enhancing the properties of metal matrix composites[11]. Till-to-date, no substantial work is being carried out to understand the machinablity of hybrid metal matrix composites which could hinder their potential use for suitable industrial applications. It was therefore authors had decided to conduct a machining study wherein stir cast method was utilized to prepare the work piece specimens of hybrid Al/(SiC + Gr + Fe_2O_3) – MMC. The selected material marginally newer in terms of combination of matrix and reinforcement phase in comparison of material developed by other researchers elsewhere[12–15]. Interestingly, a good quality machined surface improves wear resistance and fatigue strength of the work material[16]. So, considering SR as performance criterion in machining study of hybrid MMC as mentioned above, Taguchi method based orthogonal array experiments were conducted. Further, ANOVA and S/N ratios (*dB*) were effectively used to identify the optimal parametric combination for minimizing surface roughness height (SR, R_a).

Literature review:

The wire electrical discharge machining (WEDM) is an electrical spark-erosion process which removes workpiece material by means of a series of recurring electrical spark[8]. The spark conditions are influenced by various WEDM parameters along with presence of ceramic reinforcements embedded to metallic phase which further affect the machine performance criterion such as surface roughness (R_a). SR is desired to be minimized for precision components. Yue *et al.*[17] adopted strategy of varying one factor at a time to explore machining behaviour of Al/Al_2O_3 MMCs. The sizes of particles had significant influence in determining the banding and surface roughness of work pieces. Gatto and Iulian[18] studied the machining of two MMC materials. As per their study, the 20% SiC_W/2009 Al alloy composite has exhibited higher SR than that of 15% SiC_W/2009 Al alloy composite while both of materials machined under same range of machining parameters. Guo *et al.*[19] examined the wire EDM process of Al_2O_3 reinforced Al MMC. The researchers reported and justified the reason for decrease in roughness at higher pulse energy. Manna and Bhattacharyya[7] evaluated machining behavior of Al-SiC_p MMC employing the Taguchi's L_{18} mixed OA (orthogonal array) experiments and formulated mathematical models relating to the WEDM performance characteristics such as MRR, gap current, SR, and spark gap for the effective machining of MMC material. Patil and Brahmankar[10] conducted preliminary experiments followed by Taguchi's orthogonal experiments to carry out machining study on Al/Al_2O_3 MMCs. The researchers claimed that Al/ Al_2O_{3p}/22% composite was associated with lesser surface finish and cutting speed in comparison of Al/ Al_2O_{3p}/10% composite while machining operations were performed on WEDM set-up. Lal *et al.*[15] employed Taguchi method for parametric optimization in WEDM process of a newly prepared hybrid composite via stir casting process using 15 wt% Al_2O_3/ SiC particulates (7.5% each) in matrix material (Al - 7075 alloy). It was reported on the basis of ANOVA that pulse on time, pulse current and pulse off time had significant effect on SR. Harmesh Kumar *et al.*[20] employed RSM to optimize the wire-EDM machining parameters for minimizing surface roughness i.e. R_a. Literature survey on the WEDM of MMCs reveals that apart from contribution and setting of machining control parameters the presence of the ceramic particulates in host matrix material also dominates the machining performance criterion such as MRR, SR and wire breakage. The material removal mechanism of ceramic particulate reinforced MMC is different than metal and alloys because of high thermal diffusivity and melting point of the ceramic particulates. The ceramic particulates either gets dislodged from the melted host matrix material or detected in recast layer of the machined work material increasing the SR in general. Further, the machinability of hybrid MMCs is not yet explored to greater extent. Furthermore, literature review also hinted about selection of matrix material/reinforcements as well fabrication of MMCs and hybrid MMCs via stir casting rout.

Materials and methods:

Fabrication of hybrid specimens:

For this purpose, commercial available aluminum alloy is taken as the matrix material SiC, Gr, Fe_2O_3 particles were used as reinforced particles while considering Al alloy (AA6061) as matrix material. Gultekin *et al.*[20] discussed the importance of Gr particles in Al/SiC MMC to improve wear resistance of Brake pad/disc systems forautomobiles. So combination of SiC (10–20 wt% age) and Gr (3–5 wt.% age) can be useful in such application and in addition to these reinforcements, cheaper reinforcements (such as Fe_2O_3) can be used to reduce the cost of Gr. Thus, hybrid Al/(11 wt.% SiC + 3 wt.% Gr + 3 wt.% Fe_2O_3) – MMC was fabricated using stir casting set-up shown elsewhere[13]. As suggested by Manna *et al.*[13] furnace temperature requirements for melting matrix material and attaining pre-heating temperature of matrix/reinforcements were fulfilled by three furnaces of capacity of 550°C, 1250°C and 1050°C. These furnaces were simultaneously used for backing of clay coated metal mold cavity, pre-heating of (SiC + Gr + Fe_2O_3), and melting Al-matrix reinforced particles and respectively. Aluminum was preheated to 45°C for 2 h before melting in a furnace of capacity[12]. The temperature of the aluminum alloy was raised above its liquid state temperature (660°C) to melt the aluminum pieces and then cooled to just below the liquid temperature to keep slurry in a semi-solid state[4]. Sludge removal from molten matrix metal was done during each casting operation to maintain its purity. The reinforced (SiC + Gr + Fe_2O_3) particulates were simultaneously pre-heated to 1150°C for 2 h in another furnace of capacity 1250°C. The clay coated metal mold made of IS – 1079/3.15 mm thick steel sheet was pre-heated simultaneously at 400°C for 2 h in the third furnace of capacity 550°C. Preheated particulates of (SiC + Gr + Fe_2O_3) from the second furnace were taken and added to the molten Al-matrix at 680±10°C. The mixture of the pre-heated reinforced particles and molten matrix was stirred up thoroughly to form a proper heterogeneous mixture. Melt mixture is then poured into the preheated metal mold cavity and allowed it for solidification. Stir cast round specimen was removed and cleaned for further machining operation to prepare test pieces for property testing and workpiece for machining experiments.The fabricated stir cast hybrid MMC samples turned and part-off into small circular work piece specimens (36 mm dia.×10 mm thick prior to WEDM experiments.

Design of experiment:

Taguchi method is applied for process optimization and identification of optimal parametric combinations for given responses. It's special design of orthogonal arrays involves study of entire parameter space employing a small number of experiments. Further, in this method, the selection of suitable orthogonal array is made by calculation of thetotal degrees of freedom[10]. In order to select an orthogonal array (OA), following inequality must be satisfied: total degree of freedom (DOF) of the OA ≥ total DOF is required for the experiment. There are six parameters having three levels each with no interaction, the total DOF required is 6×2 = 12, as for a three level parameter, there are two DOF (number of levels minus). Thus, a standard three level OA L_{27} was selected with possibility of considering interactions among the factors for this experimental work. Table 3 shows the assignment of parameters with L_{27} (3^{13}) OA.

Table 1. Experimental parameters of WEDM along with their levels

Sr. No.	Control parameter	Level 1	Level 2	Level 3	Unit
1.	I_P	80	100	120	A
2.	T_{on}	0.5	0.8	1.1	µs
3.	T_{off}	12	16	20	µs
4.	W_F	5	7	9	m/min
5.	W_T	850	1000	1200	g
6.	V_G	25	30	35	V

Table 2. Results of L_{27} OA experiments

Exp. No.	I_P	T_{on}	T_{off}	W_F	W_T	V_G	SR (Avg.) R_a	SR (Avg.) S/N ratio
1.	1	1	1	1	1	1	0.98	0.19
2.	1	1	1	1	2	2	1.23	–1.83
3.	1	1	1	1	3	3	1.46	–3.26
4.	1	2	2	2	1	1	1.06	0.02
5.	1	2	2	2	2	2	1.24	–1.83
6.	1	2	2	2	3	3	1.25	–1.91
7.	1	3	3	3	1	1	0.987	–1.01
8.	1	3	3	3	2	2	1.66	–4.39
9.	1	3	3	3	3	3	1.75	–4.88
10.	2	1	2	3	1	2	1.45	–3.23
11.	2	1	2	3	2	3	1.54	–3.77
12.	2	1	2	3	3	1	1.92	–5.68
13.	2	2	3	1	1	2	1.34	–2.54
14.	2	2	3	1	2	3	1.47	–3.33
15.	2	2	3	1	3	1	1.88	–5.50
16.	2	3	1	2	1	2	1.46	–3.26
17.	2	3	1	2	2	3	1.27	–2.06
18.	2	3	1	2	3	1	1.44	–3.19
19.	3	1	3	2	1	3	1.35	–2.57
20.	3	1	3	2	2	1	1.55	–3.78
21.	3	1	3	2	3	2	1.58	–3.96
22.	3	2	1	3	1	3	0.997	0.29
23.	3	2	1	3	2	1	1.35	–2.58
24.	3	2	1	3	3	2	1.67	–4.43
25.	3	3	2	1	1	3	1.43	–3.12
26.	3	3	2	1	2	1	1.65	–4.37
27.	3	3	2	1	3	2	1.44	–3.15

Machine tool used and experiments:

Electronica Sprincut-734 WEDM machine tool was used to perform machining experiments to study effects of the

Table 3. Mean of surface roughness at different level of parameters

Factor	I_P	T_{on}	T_{off}	W_F	W_T	V_G
1	1.309	1.45	1.522	1.431	1.261	1.44
2	1.53	1.378	1.447	1.357	1.439	1.45
3	1.458	1.469	1.33	1.509	1.599	1.403
Delta	0.221	0.091	0.192	0.152	0.338	0.047
Rank	2	5	3	4	1	6

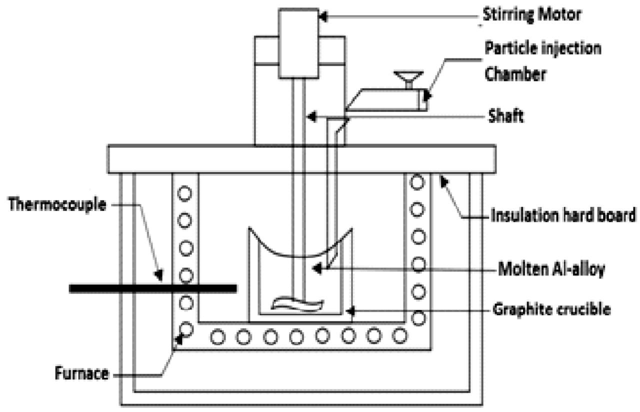

Fig. 1. Schematic diagram of liquid stir cast set up.

machining process variable such as pulse-on-time (T_{on}), pulse-off-time (T_{off}), spark gap set voltage (SV), peak current (I_p), wire feed (WF) and wire tension (WT) on surface roughness height R_a (μm). The range of these control parameters was based upon preliminary experiments. Some of the factors which could affect the performance measures to a little extent are kept constant i.e. flushing pressure (0.833 MPa), specific resistance of dielectric (1–3 mA), dielectric fluid temperature (25–27°C), pulse peak voltage setting (100 V), wire type (0.25 mm-diameter brass wire) and carried out the experiments. Hybrid MMC samples were machined to rectangular shape (6 mm×5 mm×5 mm) as shown in Fig. 2. The machined surface roughness height was measured at three different positions (sides of the specimen) and the average values were taken for analyzing the machined surface quality using surface texture measuring instrument Surfcom 130A, Zeiss, Japan. It has stylus radius 2 μm, evaluation length 4.0 mm and cut off values 0.8 mm.

Fig. 2. Machined specimen (Exp. 8) (size: 6 mm×5 mm×5 mm).

Results and discussion

Analysis of S/N ratios:

The S/N ratio is defined in mathematical form for Lower-the-better (i.e. minimize, example: surface roughness height):

$$\eta = -10 \log_{10} \left[1/n \sum_{i=1}^{n} y_i^2 \right]$$

where, η denotes the S/N ratio (*dB*) computed from experimentally observed values; y_i represents the experimentally observed value of the *i*-th experiment, and '*n*' is the repeated number of each experiment. Table 4 represents the L_{27} (3^{13}) the orthogonal array, results of experiments as well as S/N ratio for surface roughness height, R_a (μm). Additionally, S/N plots are used to determine the levels that keep the process in its target value, in a visual way. Further, calculated the S/N ratio Minitab software and plotted S/N ratio (*dB*) graphs for optimization of WEDM parameters for SR. Notably, the optimal level of process parameters is the level with the highest S/N ratio.

From Fig. 3, it is observed that for lower surface roughness height (SR), the optimum WEDM parameter setting is $A_1B_2C_3D_2E_1F_3$. Thus, it is determined that for lower surface roughness height (R_a, μm), the optimal WEDM parameter setting is 80 A pulse peak current (I_p), 0.8 μs pulse-on-time (T_{on}), 20 μs pulse-off-time (T_{off}), 7 m/min wire feed rate (W_F), 850 g wire tension and 35 V spark gap set voltage (SV).

Table 3 represents rank of different parameters of WEDM for minimum surface roughness height, R_a. The spark energy is required to be constrained to reduce surface roughness as indicated from the S/N ratio plot (Fig. 3). It becomes

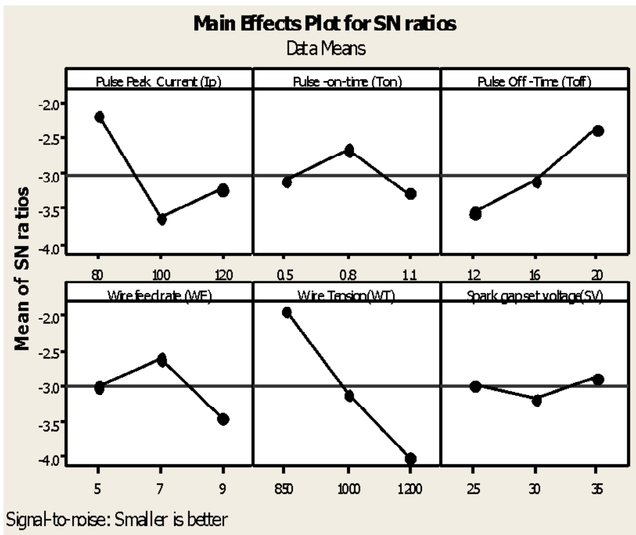

Fig. 3. S/N ratio plot of SR.

difficult to prioritize the contribution of parameters affecting SR because of the presence of non-conductive reinforcements and also due to the formation of recast/re-solidified layer of low melting point Al matrix which may dominate the surface texture during WEDM of composite materials. The pulse energy is governed to greater extent by pulse peak current. The crater size increases with increase in peak current. Hence, increase in SR (R_a, μm) was noticed when machining operations were carried out at middle and high level setting values of peak current (Fig. 3). The maximum surface roughness height (R_a, μm) was noted at high level setting value of pulse-on-time, it is may be due to formation of craters, overlapping and grouping of craters on the machined surfaces owing to increased pulse energy. Further, the SR can be affected from vibration and wear rate of the electrode wire which in turns influenced by wire feed. The moderate setting of it is associated with minimizing surface roughness height (R_a, μm) as per S/N ratio plot (Fig. 3). The low wire feed causes high wire wear rate in general and which can produce poor surface finish over the machined surface. On the other hand, at high wire feed, the wire electrode may produce better surface finish but increased amplitude of vibration may deteriorate the machined surface structure due to collisions of wire electrode with ceramic particles or arcing in machining zone. Further, influence of wire tension is clearly witnessed in machining of MMC materials. The low wire tension setting is recommended for reducing surface roughness height (R_a, μm).

The basic aim in construction ANOVA table is to identify the significant parameters affecting the considered response. The indicator i.e. *p* value decides whether an individual term in the ANOVA model is significant or not. From ANOVA (Table 4) it is obvious that the most significant parameter is wire tension (WT) followed by pulse peak current (I_p) which affects the surface roughness height, R_a (μm).

Table 4. ANOVA table for surface roughness height, R_a (μm)

Factor	DF	Seq MS	Adj SS	Adj MS	F	P
I_P	2	0.248	0.248	0.124	4.620	0.02
T_{on}	2	0.074	0.074	0.037	1.380	0.28
T_{off}	2	0.199	0.199	0.099	3.710	0.05
W_F	2	0.097	0.097	0.049	1.810	0.20
W_T	2	0.607	0.607	0.304	11.32	0.00
V_G	2	0.020	0.020	0.010	0.370	0.70
RE	14	0.12	0.355	0.026		
TE	26	1.365				

*RE = Residual Error, TE = Total Error.

Prediction of optimal performance:

The estimated mean of SR at optimum condition i.e. $A_1B_2C_3D_2E_1F_3$ is calculated as given below.

$$SR_{opt} = A_1 + B_2 + C_3 + D_2 + E_1 + F_3 - 5T_{SR}$$

where, T_{SR} = 1.462 is overall average of SR [corresponding to all the 81 (i.e. 27×3)]. The calculated values of average SR at optimum levels i.e. $A_1B_2C_3D_2E_1F_3$ are: A_1 = 1.309, B_2 = 1.378, C_3 = 1.33, D_2 = 1.357, E_1 = 1.261 and F_3 = 1.403 (Table 3).

SR_{opt} = 0.992 μm.

Confirmatory tests:

After the selection of optimum machining parameters, the confirmatory tests were performed to validate the improvement in SR. Table 5 compares the surface roughness values obtained from initial machining parameters vis-à-vis optimal parametric combination. The surface roughness height (R_a, μm) is reduced from 1.32 to 1.04 μm. It reveals that the optimization of WEDM process parameters can improve the machined surface finish. Further, an error of 4.8% was noticed when actual SR at optimal condition was compared with predicted value of SR (0.992).

Table 5. Surface roughness values obtained from initial machining parameters vis-à-vis optimal parametric combination

Response	Initial machining parameters	Optimal parametric combination
	$A_2B_2C_2D_2E_2F_2$	$A_1B_2C_3D_2E_1F_3$
SR (R_a)	1.32 μm	1.044 μm

Conclusions

The hybrid Al/(SiC + Gr + Fe_2O_3) – MMC workpiece samples were fabricated by stir casting technique. These samples were then prepared as specimen for conducting machining experiments on WEDM machine tool. A parametric study has been carried out to study the effects of various machining parameters on surface roughness height (R_a, μm). Based on the results following conclusions drawn are listed below:

(i) The most significant machining parameters which affects surface roughness height, (R_a, μm) during WEDM are wire tension (WT) and pulse peak current (I_p).

(ii) The combination of optimum parameters for which surface roughness height (R_a, μm) is likely to minimized is $A_1B_2C_3D_2E_1F_3$.

(iii) The stir cast hybrid can be machined effectively by WEDM. The Taguchi method which proves to be effective in reducing surface roughness height (R_a) from 1.32 μm to 1.04 μm.

(iv) ANOVA reveals that wire tension by pulse peak current had significant effect on SR and needed to pay more attention while machining the considered hybrid MMC within the given operating parameters of WEDM.

(v) The spark energy is required to be constrained to reduce surface roughness which insists the use of lower peak current and pule-on-time within the selected range of parameters.

Abbreviations

Metal matrix composites, MMC; S/N, Signal to Noise; Electrical discharge machining, EDM; DOF, Degree of Freedom; Material removal rate, MRR; Peak current, I_p; Surface roughness, SR; Pulse-on-time, T_{on}; Cutting speed, CS; Pulse off-time, T_{off}; Design of experiments, DOE; Wire feed rate, W_F; Orthogonal array, OA; Wire tension, W_T; Analysis of variance, ANOVA; Spark gap set voltage, V_G.

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