Taguchi Method based parametric optimization of process parameters for better surface finish during WEDM of newly developed hybrid Al/(SiC + Gr + Fe_2O_3)-MMC

Amresh Kumar[a*], Neelkant Grover[b], Alakesh Manna[c]

[a] Ph.D. Research Scholar,IKG-PTU Jalandhar, CGC College of Engineering, Mohali,Punjab, India

[b]Associate Professor, Department of Mechanical Engineering IKG-PTU Campus, Jalandhar, Punjab, India

[c]Professor and Former Head, Department of Mechanical Engineering, PEC, University of Technology, Chandigarh, India

*amresh.panjla@gmail.com

Abstract: The particulate reinforced aluminum metal matrix composites have unprecedented properties thereby increase their applications in the different fields such as aerospace, automotive, defense etc. But poor machinability of such materials resists their applications. The poor machinability because of high tool wear, poor surface finish, built-up-edge formation etc. that were identified by the various researchers when Al-metal matrix composites were machined by any well known conventional machining processes. Keeping in view, this study is focused on experimental investigation during WEDM of fabricated hybrid Al/(10wt.% SiC + 3wt.% Gr + 3wt.% Fe_2O_3)-MMC. The effects of WEDM control parameters such as peak current ($_{IP}$), pulse-on time (Ton), pulse-off, time (Toff), wire feed (WF) and wire tension (WT) on machined surface roughness height (SR) were investigated. Taguchi method based design of experiment, $L_{27}(3^{13})$ orthogonal array, ANOVA and S/N Ratios(dB) were employed to identify the significant parameters and optimization of WEDM parameters for better surface finish i.e. minimization of machined surface roughness height, Ra (µm). The confirmation test results revealed that the optimal combination of parameters improved the surface finish.

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

I. INTRODUCTION

The metal matrix composites (MMCs) were developed in the 1970s for high-performance applications using continuous fibers and whiskers for reinforcement [1]. Aluminum-matrix composites employing ceramic-particle reinforcement and amenable to inexpensive net shape processes such as casting and extrusion have led to the application of these materials in automotive brakes, drive shafts, and cylinder liners [2]. Fig. 1 shows some typical applications of Al metal matrix composites. Recent market forecasts for MMC that this material has bright in future [1,2]. Despite the superior mechanical and physical properties of particulate Al-metal-matrix composites, their poor machinability has been the main deterrent to their substitution for metal parts. Metal matrix composites (MMCs) can be machined by many non-traditional machining methods like water jet machining, laser cutting etc. but these processes are limited to linear cutting [3]. Electrical discharge machining (EDM) shows higher capability for cutting complex shapes with high precision and economy for these materials. But many problems and difficulties have been faced by the manufacturing engineers during processing of the composite materials by well-known conventional and nonconventional machining methods e.g. turning, wire electrical discharge machining (WEDM) of Al/SiC-MMC, are high and rapid tool wear, irregular material removal rate, high frequency of wire breakage, and very poor surface finish etc. as claimed by Manna and Bhattacharyya [3, 4]. Usually, the selection of appropriate machining parameters is difficult and relies heavily on the operators experience and the machining parameters tables provided by the machine-tool builder for the target material [3]. Hence, the optimization of operating parameters is of great importance where the economy and quality of a machined part play a key role. Taguchi method based design of experiment can be effectively used to optimize the machining process parameters for better performance quality. In this investigation, effectively employed the Taguchi method based design of experiments, $L_{27}(3^{13})$ orthogonal array, ANOVA and S/N Ratios(dB) to identify the significant parameters and optimization of WEDM parameters for better surface finish i.e. minimization of machined surface roughness height, Ra (µm) during WEDM of stair cast hybrid Al/(10wt.% SiC + 3wt.% Gr + 3wt.% Fe_2O_3)-MMC.

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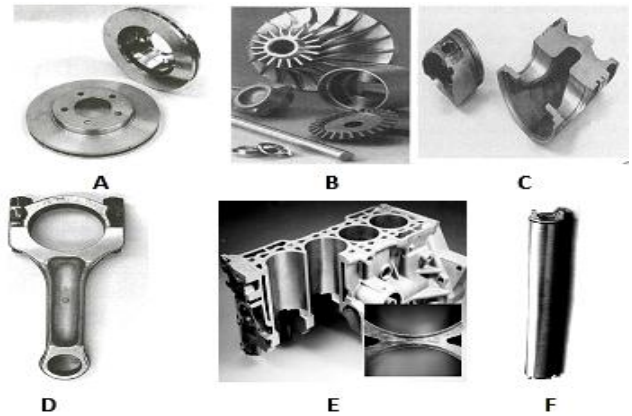

Fig.1 Typical application of Al MMCs

II. WEDM OF ALUMINUM MMC

Al matrix base composites are more often used in aerospace and automobile industry and they are usually reinforced by Al_2O_3, SiC, C, B_4C, Gr etc. materials [2, 8]. The study of WEDM of MMCs has received much attention by many researchers in the recent year. Manna and Bhattacharyya [3] applied Taguchi design of experiment and Gauss elimination method to identify the optimal WEDM parameters and develop mathematical relations respectively for machining of Al/SiC-MMC. Authors explained that the open-gap voltage was found to be the most significant influencing machining parameters, for controlling the MRR followed by pulse-on period, meanwhile, surface roughness was found to be affected significantly by wire tension and spark gap voltage setting. Patil and Brahmankar [5] determined the MRR during WEDM of silicon carbide particulate-reinforced aluminium matrix composites using dimensional analysis. This work proposed a semi-empirical model for MRR for WEDM based on thermo physical properties of the work piece. But they claimed that increased percentage of ceramic particulates in the MMC results in decreasing the MRR. Shandilya et al. [06] undertook a study to determine the wire breakage frequency during WEDM of MMCs. Authors claimed that the frequency of wire breakage increases with increase in pulse-on time during machining of MMCs. They also claimed that the wire breakage frequency increases with increase in the SiC. Literature survey on the WEDM of MMCs reveals that the machining of composite was done by some of the researchers but still applied research is required to better understanding the process and optimization of the parameters for quality machining. Keeping in view, in the present experimental investigation, the machining study was done during WEDM of fabricated hybrid Al/(10wt.% SiC + 3wt.% Gr + 3wt.% Fe_2O_3)-MMC.

Table 1 Chemical composition of Al alloy used as metal Matrix (in wt%)

Matrix alloy	Si	Fe	Cu	Mn	Mg	Zn	Ti
AA6061	0.6	0.7	0.3	0.15	0.9	0.25	0.15
				Balance is Al			

Table 2 Physical and mechanical properties of Aluminium Alloy and Hybrid Al MMC

Hybrid Al MMC	Density	Hardness	Ultimate tensile strength (MPa)
AA6061	2.71	88 BHN	67
Hybrid Al/(10wt.% SiC + 3wt.% Gr + 3wt.% Fe_2O_3)-MMC.	2.84	97.8 BHN	90.1

IIIA. FABRICATION OF HYBRID MMC AND PREPARATION OF WORKPIECE SPECIMENS

The liquid stir casting technique has been successfully applied for fabrication of MMC and hybrid MMC [7,8]. The hybrid Al/(10wt.% SiC + 3wt.% Gr + 3wt.% Fe_2O_3)-MMC workpiece samples were fabricated by liquid stir-casting. The commercially available Aluminum alloy is used as the matrix material and SiC, Gr, and Fe_2O_3 particles were used as reinforced particles. Three electric furnaces are simultaneously used during casting of hybrid Al/(10wt.% SiC + 3wt.% Gr + 3wt.% Fe_2O_3)-MMC. Three furnaces of capacity 1250^0C, 1050^0C and 550^0C are simultaneously used for melting Al-matrix, pre-heating of (SiC + Gr + Fe_2O_3) reinforced particles and backing of clay coated metal mold cavity respectively. The following steps were carried out during fabrication of hybrid MMC by stir casting as follows:

- Aluminum was preheated to 450^0C for 2 hrs before melting in a furnace of capacity 1150^0C. The temperature of the aluminum was raised above its liquid state temperature (660^0C) to melt the aluminum pieces and then cooled to just below the liquid temperature to keep slurry in a semi-solid state. 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 1150^0C for 2 hrs in another furnace of capacity 1250^0C.
- The clay coated metal mold made of IS-1079/3.15mm thick steel sheet was pre-heated simultaneously at 400^0C for 2 hrs in the third furnace of capacity 550^0C.

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- Preheated particulates of (SiC + Gr + Fe_2O_3) from the second furnace were taken and added to the molten Al-matrix at 680 ± 10^0C. 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.

IIIB Design of experiment

Taguchi method based design of experiment, ANOVA and S/N Ratio (dB) were employed for this experimental research investigation. Taguchi design provides a simple, efficient and systematic approach to optimize designs for performance, quality, and cost [9]. The main trust of the Taguchi's DOE technique is the use of parameter design, which is an engineering method for product or process design that focuses on determining the parameter (factor) settings producing the best level of a quality characteristic (performance measure) with minimum variation. The present work aims to analyze the effects of WEDM process variables on the quality characteristic such as surface roughness and the combination of control variables that would optimize the selected quality characteristic. The selection of suitable orthogonal array for the experiments is made by calculation of the total degrees of freedom [Ross]. This total degree of freedom is determined by levels of design parameters and interaction between design parameters if any once the required degrees of freedom are known, then next step is to select an appropriate orthogonal array to fit the specific task. The selected orthogonal array (OA) must satisfy the following inequality. Total degree of freedom (DOF) of the OA ≥ total DOF is required for the experiment. With six parameters, each at three levels, and considering no interaction, the total DOF required is 6×2= 12, since a three-level parameter has two DOF (number of levels minus 1). Hence, an L27 OA(a standard three-level OA) was selected with possibility of considering interactions among the factors for this experimental work. The $L_{27}(3^{13})$ OA with assignment of parameters is shown in table 3.

IIIC Machine Tool used and Experiments

Electronica Sprincut-734 Wire Electrical Discharge Machine (WEDM) was used for experiments. Study the effects of the machining process variable such as pulse-on time (Ton), pulse-off, time (Toff), spark gap set voltage (SV), peak current (I_P), wire feed (WF) and wire tension (WT) on surface roughness height(R_a,µm). 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. The machined surface roughness height was measured at three different positions and the average values were taken for analyzing the machined surface quality using surface texture measuring instrument Surfcom 130A, Zeiss, Japan.

IIID S/N Ratio and Analysis of Variance

In the Taguchi method S/N ratio(dB), the term 'signal' stands for the desirable value (mean) for the response characteristic and the term 'noise' stands for the undesirable value (S.D.) for the output characteristic. The S/N ratio is defined in mathematical form for Higher-the-better (i.e. maximize, Example: material removal rate) is

$$\eta = -10\log_{10}[1/n \sum_{i=1}^{n} 1/y_i^2] \qquad (1)$$

and for Lower-the-better (i.e. minimize, example: surface roughness height):

$$\eta = -10\log_{10}[1/n \sum_{i=1}^{n} y_i^2] \qquad (2)$$

Where, η denotes the S/N ratio(dB) computed from experimentally observed values; y_i represents the experimentally observed value of the ith experiment, and 'n' is the repeated number of each experiment. Notably, in L_{27} array, each experiment was conducted three times. The S/N ratios were determined from experimentally acquired results and identified the optimal parameters. The ANOVA table was constructed based on acquired results and identified the significant parameter. If the "Model P value" is very small (less than 0.05) then the terms in the model have a significant effect on the response [9].

Table 3 WEDM parameters and their levels considered for experiments

S. No.	Input Parameters	Level			Unit
		1	2	3	
1.	A:Peak Current(Ip)	80	100	120	A
2.	B:Pulse on -Time (Ton)	.5	.8	1.1	µs
3.	C:Pulse Off -Time (Toff)	12	16	20	µs
4.	D:Wire feed rate (WF)	5	7	9	m/min
5.	E:Wire Tension(WT)	850	1000	1200	g
6.	F: Spark gap set voltage(SV)	25	30	35	V

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IV. Results and Discussion

Table 4 represents the $L_{27}(3^{13})$ the orthogonal array, experimental results and S/N Ratio graph for surface roughness height, Ra(µm). The machined surface roughness height of particulate reinforced MMC specimens affected by the size, distribution, disintegration and thermo-physical properties of the reinforced particulates present in the MMC. Fig. 2 shows the S/N graphs for surface roughness height, Ra (µm). From Fig. 2 it identified that for lower surface roughness height(SR), the optimum WEDM parameter setting is 80A peak current (I_P), 0.8 µs pulse-on-time (Ton), 20µs pulse-off time, 7 m/min wire feed rate, 850 g wire tension and 35 V Spark gap set voltage.

Table 4 L27(313) orthogonal array, experimental results and S/N Ratios for SR

Exp No	Pulse Peak Current (Ip)	Pulse On-Time (Ton)	Pulse Off -Time (Toff)	Wire feed rate (WF)	Wire Tension (WT)	Spark gap set voltage(SV	SR	S/N Ratio for SR
1	1	1	1	1	1	1	0.9780	0.19322
2	1	1	1	1	2	2	1.2340	-1.82630
3	1	1	1	1	3	3	1.4560	-3.26323
4	1	2	2	2	1	1	0.9980	0.01739
5	1	2	2	2	2	2	1.2350	-1.83334
6	1	2	2	2	3	3	1.2460	-1.91036
7	1	3	3	3	1	1	1.1234	-1.01069
8	1	3	3	3	2	2	1.6570	-4.38645
9	1	3	3	3	3	3	1.7540	-4.88059
10	2	1	2	3	1	2	1.4500	-3.22736
11	2	1	2	3	2	3	1.5430	-3.76732
12	2	1	2	3	3	1	1.9230	-5.67959
13	2	2	3	1	1	2	1.3400	-2.54210
14	2	2	3	1	2	3	1.4680	-3.33452
15	2	2	3	1	3	1	1.8840	-5.50162
16	2	3	1	2	1	2	1.4560	-3.26323
17	2	3	1	2	2	3	1.2670	-2.05553
18	2	3	1	2	3	1	1.4430	-3.18533
19	3	1	3	2	1	3	1.3450	-2.57445
20	3	1	3	2	2	1	1.5460	-3.78419
21	3	1	3	2	3	2	1.5780	-3.96214
22	3	2	1	3	1	3	0.9670	0.29147
23	3	2	1	3	2	1	1.3460	-2.58090
24	3	2	1	3	3	2	1.6660	-4.43350
25	3	3	2	1	1	3	1.4320	-3.11886
26	3	3	2	1	2	1	1.6530	-4.36546
27	3	3	2	1	3	2	1.4370	-3.14914

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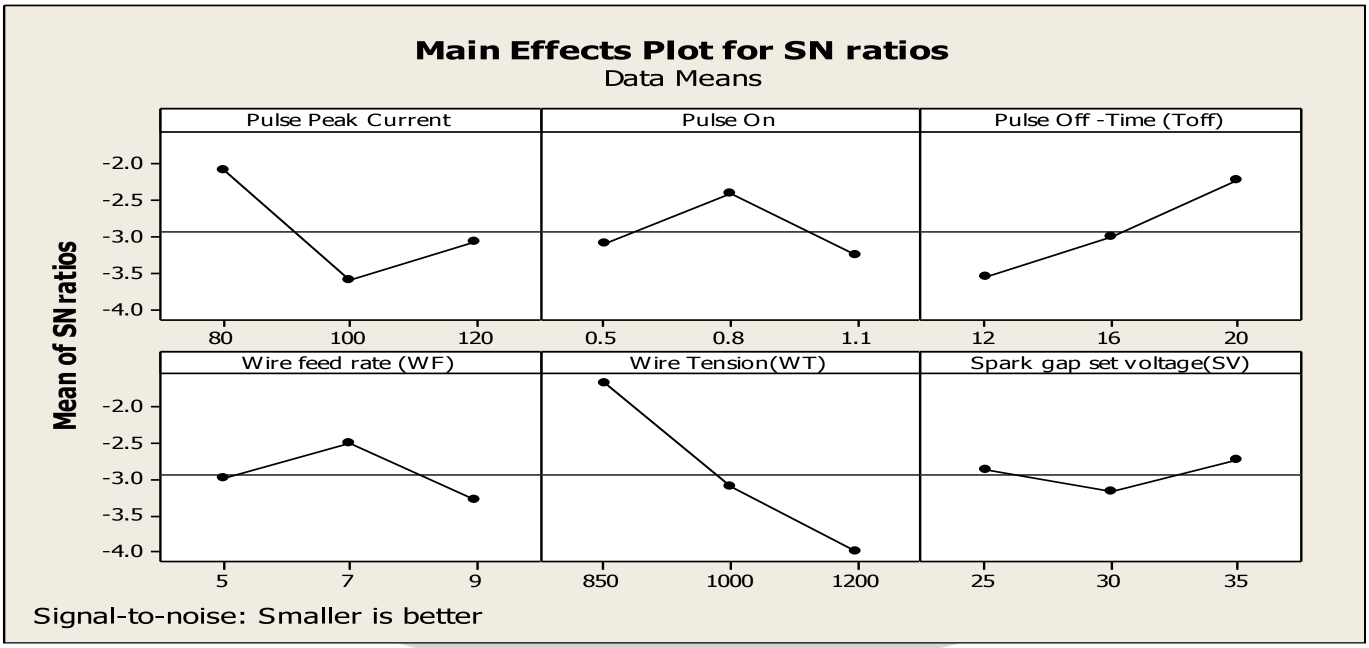

Fig. 2 S/N ratios plot for SR

Therefore, moderate level of wire feed rate and spark gap set voltage produces minimum SR. The parametric combination for minimum SR is parameter A (level 1, S/N = -2.100) B (level 2, S/N = -2.425), parameter C (level 3, S/N = -2.236), parameter D (level 2, S/N = -2.506) , parameter E (level 1, S/N = -1.693) , parameter F (level 3, S/N = -2.735) i.e $A_1B_2C_3D_2E_1F_3$ (Table 3). Table 5 represents rank of different parameters of WEDM for minimum surface roughness height, Ra. Utilized the experimentally acquired results and constructed the analysis of variance (ANOVA) Table 6. The basic aim in construction ANOVA table is to identify the significant parameters for surface roughness height. According to the 95% confidence level, the control parameter corresponding to the high 'F value' represents the significant parameter for the particular response. It causes maximum variation in the response characteristics [9]. The indicator i.e. 'P value' decides whether an individual term in the ANOVA model is significant or not. From ANOVA, it is clear that the parameters wire tension (WT) and pulse peak current (Ip) are identified as most significant and significant parameters respectively for surface roughness height, Ra (μm).

Table 5 S/N Ratios and rank of control parameters for SR

Level	Pulse Peak Current	Pulse On	Pulse Off - Time (Toff)	Wire feed rate (WF)	Wire Tension(WT)	Spark gap set voltage(SV)
1	-2.100	-3.099	-3.553	-2.990	-1.693	-2.877
2	-3.617	-2.425	-3.004	-2.506	-3.104	-3.180
3	-3.075	-3.268	-2.236	-3.297	-3.996	-2.735
Delta	1.517	0.843	1.317	0.792	2.303	0.446
Rank	2	4	3	5	1	6

Table 6 ANOVA for Surface Roughness (SR)

Source	DF	Seq MS	Adj SS	Adj MS	F	P
A: Pulse Peak Current(Ip)	2	0.24763	0.24763	0.12381	4.62	0.029
B:Pulse on -Time (Ton)	2	0.07386	0.07386	0.03693	1.38	0.285
C:Pulse Off -Time (Toff)	2	0.19882	0.19882	0.09941	3.71	0.045
D:Wire feed rate (WF)	2	0.09703	0.09703	0.04851	1.81	0.200
E:Wire Tension(WT)	2	0.60741	0.60741	0.30371	11.32	0.001
F: Spark gap set voltage(SV)	2	0.01960	0.01960	0.00980	0.37	0.700
Error	14	0.37559	0.37559	0.02683		
Total	26	1.61993				

V. Confirmatory Tests

Since the optimal level of the machining parameters is selected, the confirmation tests were carried out to verify the improvement of performance characteristics. The results of confirmation experiment are compared with the outcome of Taguchi method and initial conditions of design operating parameters. Table 7 represents the compared

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results of the selected optimal and initial design of machining parameters. The initial design machining parameters are A_2, B_2, C2, D_2, E_2 and F_2. The surface roughness height (Ra,µm) is reduced from 1.32 to 1.044 µm and the value will be obviously decreasing as compared with the results in Table 4. It reveals that the optimization of WEDM process parameters can be improved the machined surface finish.

Table 7 Confirmatory Experiments

Response	Initial machining parameters	Optimal Parametric Combination
	$A_2B_2C_2D_2E_2F_2$	$A_1B_2C_3D_2E_1F_3$
Surface Roughness	1.32 µm	1.044 µm

VI. CONCLUSION

The hybrid Al/(10wt.% SiC + 3wt.% Gr + 3wt.% Fe2O3)-MMC workpiece samples were fabricated by stir casting technique. The fabricated MMC samples were utilized and prepared the workpiece specimens for machining experiments on WEDM, and analyzing the effect of various machining parameters on surface roughness height (Ra, µm). Based on the acquired results and analysis of the results the following conclusions are drawn and listed below.

1.The hybrid Al/(10wt.% SiC + 3wt.% Gr + 3wt.% Fe2O3)-MMC can be prepared using stir casting technique . Improvement in mechanical properties of the prepared hyrid MMC has been noticed over matrix material. The newly prepared Al hybrid MMC has low density (2.84 g/cc), high tensile strength (90.1 MPa) and high hardness (97.8 BHN). It indicates that such material with high strength to weight ratio can be used for various applications in automotive and aviation industry.

2. The WEDM parameters such as wire tension (WT) and pulse peak current (Ip), are identified as most significant and significant influencing parameters respectively for surface roughness height, Ra (µm).

3. The optimal parametric combination to minimize the surface roughness height, Ra (µm) is A1B2C3D2E1F3.

4. The newly developed Al/(10wt.% SiC + 3wt.% Gr + 3wt.% Fe2O3)-MMC can be machined

effectively by WEDM. The Taguchi method proves to be effective in reducing surface roughness height (Ra) from 1.32 µm to 1.044 µm (based upon optimal setting).

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