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Machinability analysis and characterization of aluminium hybrid metal matrix composite using WEDM

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The aluminium composites are being used for various number of applications like automobiles, aerospace, marine, construction, etc. Manufacturing industries keenly focus on improving their product quality by means of strength with reduction in cost. The hybrid metal matrix composites paved way for achieving those objectives through reinforcement of existing traditional materials. This work is also a novel approach of examining the suitability of aluminium alloy for aerospace and automobile application, by reinforcing with various proportions of Silicon Carbide (SiC) and Graphite (Gr). 5, 10 & 15% of SiC in combination with graphite of 1 & 2% by weight basis. Further the casted composite was explored for its machinability in Wire cut electrical discharge machining (WEDM) process. Voltage and current are the two control parameters chosen for the study with responses material removal rate and Kerf. The MRR is proportional to the production time and Kerf is proportional to dimensional accuracy. A hybrid Taguchi-GRA optimization technique was utilized for identifying optimal parameters for achieving the objective functions. Improved machining performance was shown by the composite containing 15% SiC and 1% Gr over the operating range of 65V and 3A in WEDM process. Finally, the optimized values were justified by using SEM imaging. The agglomeration occurs at 15% SiC addition to base aluminium metal.

Keywords*:* Aluminium hybrid composites, silicon carbide, Graphite, Wire EDM, Micromachining, Parameter optimization

1 Introduction

The aluminium metal matrix composites containing silicon carbide (SiC) was tested for its strength along with 2% molybdenum disulphide (MoS_2)[1]. Al5059 with 15% SiC reinforcement had resulted in good wear tolerance (loss by 0.0045g) which was identified through ANOVA and Taguchi analysis. Al7075 was studied for its strength when reinforced with fly ash cenosphere and graphite[2]. Increase in cenosphere content improved the hardness (by 5HRB) and tensile strength (by 35N/mm^2) whereas an adverse effect was obtained from the presence of graphite. However, the graphite content in the hybrid metal matrix contributed for producing high surface finish products during turning operation. Another attempt of reinforcing the same Al7075 with 2% Al2O3 and 2% graphite was carried out for its mechanical and micro-structural behavior. The squeeze casted hybrid composite were operated on WEDM for understanding their machinability and suitability for automobile applications[3]. Approximately 63.11% Brinell hardness and 16% ultimate strength were improved by squeeze casting than stir casting. It was also concluded that alumina reinforcement should not be increased beyond 2% owing to agglomeration.

AHP-DENG'S Method based aluminium composite was formed with 3µm sized SiC particle and evaluated for machinability in electrical based processes. Optimized input parameters were identified for WEDM of Al-SiC composite[4]. Silicon carbide (SiC) was used for reinforcing Al8009 to understand their bonding characteristics[5]. The strength improved by 6.8% and preheating temperature raised to 450 °C. The fracture takes place at transition zone, which widened from 1350µm to 3200µm resulting in ductile-brittle mixed facture. The AA5059 composite with nano and micro SiC was formed using Friction stir processing and characterized by the processing variables namely rotation speed, traverse speed, too tilt and tool offset[6]. The corrosion behavior of aluminium alloys can be improved by embedding 1% SiC into the base material[7]. The influence of temperature on corrosion characters were examined, which led to the finding of decomposition of SiC and formation of Al_4Cl_3 and spinel $MgO.Al_2O_3$ in the

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presence of MgO. Thus Al_2O_3 formed resulted in improvement of corrosion behavior.

The graphite also plays a significant role in deciding the wear behavior of material[8]. From the nature of wear resistance from graphite, the machinability of metal matrix composite gets reduced. Silicon carbide reinforcement on Aluminium material used for various applications involved in corrosive environments[9-12]. Wire-cut electrical discharge (WEDM) was carried out on Aluminium matrix composites for understanding of machinability[13-16]. Several machining outputs like MRR, SR, Dimensional deviation, etc. were considered during optimizing in Taguchi's method. AHP-DENG'S similarity method was useful for solving multi-criterion problems and identifying feasible solutions. It was easier for machining the matrix composites if proper operating conditions were identified[17]. The Taguchi-TOPSIS algorithm was used for optimizing the electrical parameters such as T_{on}, T_{off}, I, V, etc. for producing quality surface textures.

On agreement with surface finish, the dimensional accuracy (measured by deviation) also plays a vital role during machining[18]. The response surface methodology (RSM) was employed in examining the effects of electrical parameters on $ZrSiO_{4p}$/6063 Aluminium metal matrix composite. Using Box-Behnken design approach, the maximum desirability value was obtained at Pulse ON time of 112.02, Pulse OFF time of 59.13, IP = 120.53 and SV = 50.35. Surface modification could also be carried out using WEDM process[19]. Element transfer occurred between wire and work-piece was analyzed from micro-hardness, surface roughness and microstructure.The inclusion of carbon nanotubes or graphene nano particles into the metal matrix result in great improvement of both mechanical properties and tribological behaviour of base metal[20-22]. Based on the studies of several researchers, the influencing parameters considered for machinability evaluation of Aluminium alloys were identified to be voltage, pulse on time, pulse off time and current. However, the variation of several parameters would lead to complexity in decision making of proper cutting parameter selection. Hence in this work, only current and voltage variation have been chosen for analysis. Based on the research degree of freedom, there are two possible ways of representing entire work. The material character of proposed composite shall be studied and as latter part, the machinability of proposed composite was studied.

2 Preparation of Aluminium Matrix Composite

Commercially available grade of aluminium was used for the experimentation as base material. The reinforcement materials namely silicon carbide and graphite were added to the base aluminium. The process of addition of sized SiC& Gr reinforcement particles (about 120 micron sized) was done by stir casting method as shown in Fig. 1, where the aluminium was at molten state. Initially the aluminium was heated to molten condition in an inert environment at 600°C, in which the preheated additives were added. The amount of reinforcement was decided based on the literatures studied and decided to be within 15% for SiC and 5% for Gr. For the applications of aerospace, high load carrying capacity with light weight must be chosen[23]. In this work, 5, 10 & 15% by weight proportions of SiC with 1 & 2% by weight Gr were added with base aluminium metal to form hybrid metal matrix composites. The melt is poured into steel mold forming the required samples for experimentation.

3 Machining of Composite

All production industries focus on improving their product strength with reduction in processing time. Hence machinability of material plays an important role in deciding production rate. Here the machining of the hybrid composite was conducted on Sprincut Wire Cut EDM Electronica Machine as seen in Fig. 2 with adjustable input parameters of current and voltage[24,25]. Faster machining of products is delight to industries because of reduction in labor, power consumption, machine depreciation, etc. The responses measured were material removal rate and Kerf. Machining time dictates the time of processing and Kerf depicts the dimensional accuracy achievable.

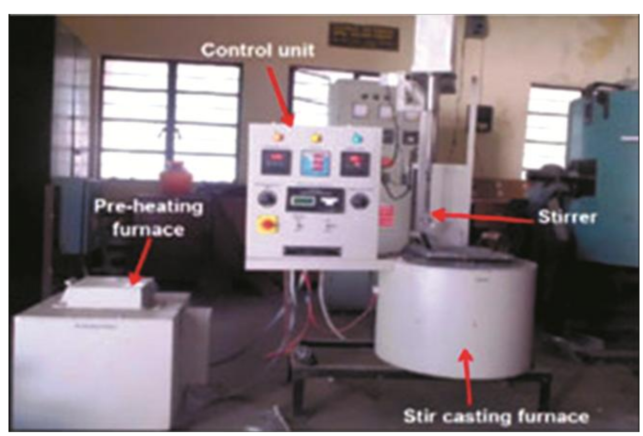

Fig. 1 — Stir casting unit along with control unit.

The design of experimental approach following Taguchi's orthogonal array methodology with 18 experimental runswas conducted. The input parameters and their levels are listed in Table 1.

4 Results & Discussion

4.1 Taguchi Analysis

Based on the experimental design constructed and carried out, the results were noted in Table 2. The full factorial model based working proves to be more expensive and time consuming. The Taguchi analysis provides way for arriving at the same end results with reduced number of experiments and it works on the basis of converting dimensional variables into non-dimensional S/N ratio values suiting to objective functions. The objective function of MRR has to be maximized whereas Kerf has to be minimized. In this study, L_{18} Orthogonal array was chosen with reference to Table 1, which would yield similar effects to that of full factorial design. The various levels for each parameter was chosen from earlier literature. Two different formula for maximization and minimization function as in eqn. 1 & 2, were employed in calculating their respective S/N ratio[26,27].

$$S/N = -10 \ln \frac{1}{n} \sum_{m=1}^{n} \frac{1}{r^2_m} \quad \ldots (1)$$

$$S/N = -10 \ln \frac{1}{n} \sum_{m=1}^{n} r^2_m \quad \ldots (2)$$

where,
m - Trial number
n – Total number of trials
r – Response value

The peak value from the obtained set of S/N ratio is considered to be the best process parameter. Based on this, the best values for each control parameter were chosen to obtain the optimal combination of parameters and thereby achieve an efficient output response. From the main effects plot for S/N ratio as shown in Fig. 3,

Fig. 2 — Sprincut WEDM Electronica.

Table 1 — Input parameters and their levels.

Parameter	L_1	L_2	L_3
Voltage (V)	65	75	-
Current (A)	1	2	3
Silicon carbide (%)	5	10	15
Graphite (%)	1	2	-

Table 2 — Output responses for the designed experimental runs.

Sl. No.	Voltage (V)	Current (A)	SiC (%)	Gr (%)	MRR (mm^3/min)	Kerf (mm)	SNR MRR	SNR Kerf
1	65	1	5	1	7.9815	0.2227	18.04171	13.0456
2	65	2	10	1	7.6124	0.2168	17.63043	13.27881
3	65	3	15	1	6.1909	0.1875	15.83508	14.53997
4	75	1	10	1	4.1569	0.2461	12.37539	12.17777
5	75	2	15	1	3.2438	0.2285	10.22108	12.82228
6	75	3	5	1	16.7712	0.2461	24.49128	12.17777
7	75	1	15	1	2.6728	0.2285	8.539329	12.82228
8	75	2	5	1	17.7367	0.2578	24.97746	11.77434
9	75	3	10	1	7.5336	0.1992	17.54005	14.01421
10	65	1	5	2	9.0161	0.2227	19.10037	13.0456
11	65	2	10	2	14.3388	0.2344	23.13026	12.60085
12	65	3	15	2	15.1561	0.2168	23.61175	13.27881
13	65	1	10	2	10.6208	0.2402	20.52314	12.38854
14	65	2	15	2	5.8543	0.2168	15.3495	13.27881
15	65	3	5	2	14.9743	0.1816	23.50693	14.81768
16	75	1	15	2	13.4334	0.2637	22.56372	11.5778
17	75	2	5	2	15.5115	0.2285	23.81308	12.82228
18	75	3	10	2	15.0685	0.2168	23.5614	13.27881

the optimized control parameters for having maximum value of MRR is given by: V= 65V; I = 3A; SiC = 5%; Gr = 2%. Similarly, for achieving lower Kerf value, the optimum process conditions are V= 65V; I = 3A; SiC = 15%; Gr = 2%. The interaction plot for S/N ratio of MRR and Kerf is shown in Fig. 4.

4.2 Grey Relational Analysis

According to the Grey Relational Grade, the degree of approximation among sequenceswasmeasured in GRA. The measured response values of the experiment were normalized between 0 and 1. Conversion of complex orthogonal multi objective functions into a simple single objective function problem can be effectively done using this method. When the factors goal and direction are different, then data should be pre–processed to the group of sequence called "grey relational generation". Data pre–processing is nothing but transferring original sequence into a comparable one. In order to achieve this, the experimental values are normalized between zero and one. The normalization can be done in various forms and the following equations 3 & 4 are used[28].

For "Larger the better",

$$x_i(k) = \frac{x_i(k) - \min(x_i^{\,0}(k))}{\max(x_i^{\,0}(k)) - \min(x_i^{\,0}(k))} \quad \ldots(3)$$

For "Smaller the better",

$$x_i(k) = \frac{\max(x_i^{\,0}(k)) - x_i^{\,0}(k)}{\max(x_i^{\,0}(k)) - \min(x_i^{\,0}(k))} \quad \ldots(4)$$

The Grey relation coefficient (GRC) and Grades (GRG) were calculated for the machining data obtained following the standard procedure of GRA. The processed values of the experimental results were provided in Table 3. From the GRG, the optimized value of the machining parameters to achieve the

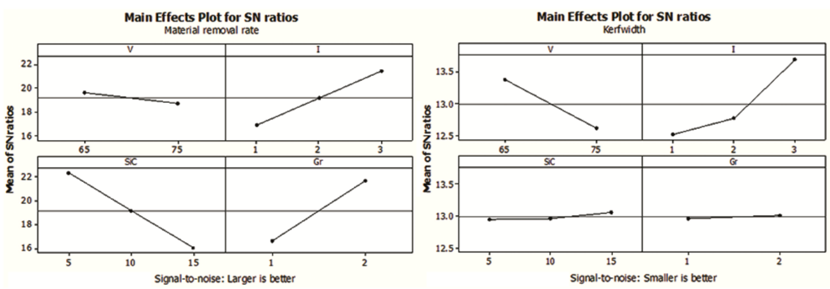

Fig. 3 — Main effects plot for S/N ratio of MRR and kerf.

Table 3 — Normalized values of output responses and grey relation grade values.

Sl. No.	MRR (mm^3/min)	Kerf (mm)	Normalized MRR	Normalized Kerf	GRC MRR	GRC Kerf	GRG
1	7.9815	0.2227	0.352	0.501	0.484	0.397	0.440
2	7.6124	0.2168	0.328	0.429	0.502	0.435	0.468
3	6.1909	0.1875	0.234	0.072	0.586	0.821	0.703
4	4.1569	0.2461	0.099	0.786	0.770	0.296	0.533
5	3.2438	0.2285	0.038	0.571	0.897	0.366	0.632
6	16.7712	0.2461	0.936	0.786	0.261	0.296	0.278
7	2.6728	0.2285	0.000	0.571	1.000	0.366	0.683
8	17.7367	0.2578	1.000	0.928	0.248	0.262	0.255
9	7.5336	0.1992	0.323	0.214	0.506	0.606	0.556
10	9.0161	0.2227	0.421	0.501	0.439	0.397	0.418
11	14.3388	0.2344	0.774	0.643	0.299	0.339	0.319
12	15.1561	0.2168	0.829	0.429	0.285	0.435	0.360
13	10.6208	0.2402	0.528	0.714	0.385	0.316	0.350
14	5.8543	0.2168	0.211	0.429	0.610	0.435	0.522
15	14.9743	0.1816	0.817	0.000	0.288	1.000	0.644
16	13.4334	0.2637	0.714	1.000	0.316	0.248	0.282
17	15.5115	0.2285	0.852	0.571	0.279	0.366	0.323
18	15.0685	0.2168	0.823	0.429	0.286	0.435	0.361

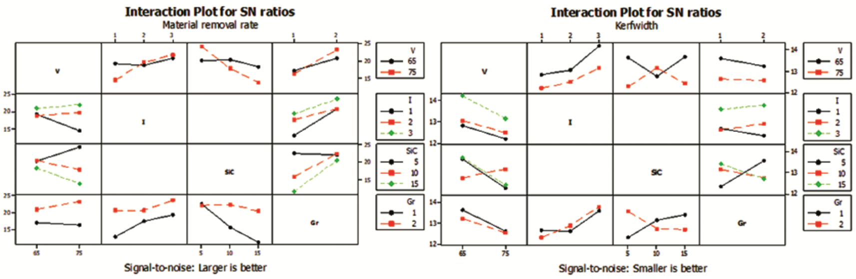

Fig. 4 — Interaction plot for S/N ratio of MRR and kerf.

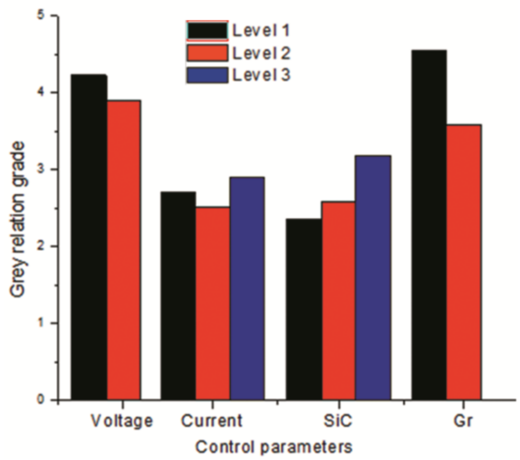

Fig. 5 — Optimum levels of control parameters.

objectives were identified. The optimum process parameters were acquired from the average value of Grey Relational Grades for each level of the input parameters as shown in Fig. 5 [29,30].

The optimum parameter combination for obtaining maximum MRRand low Kerf is identified from Fig. 5. The levels with larger values of each parameter is considered as the optimum values. Hence first level 65V for Voltage, third level 3A for current, third level 15% of SiC and first level 1% of Gr should be used to achieve the expected outcome. Thus the multi objective function with various direction of the output was reframed and solved as a single objective function.

5 Scanning Electron Microscope Analysis

The microstructure examination of hybrid composite reinforced with varying proportions of silicon carbide and graphite can be easily done on scanning electron microscope. The uniform distribution of reinforcement material was evaluated by this methodology. The micro particle presence were evidenced through higher magnification of composite under investigation. The SEM images were taken on the machined surface of stir casted composite material. From Fig. 6, the uniform

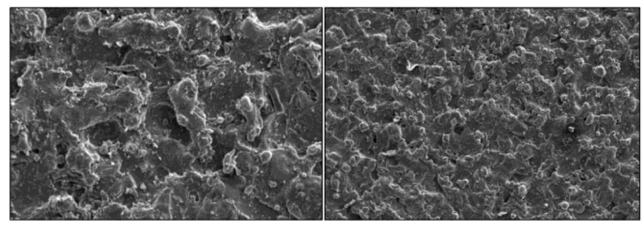

Fig. 6 — SEM image of Al-5 SiC composite with 1 & 2 wt. % graphite.
WD 20.2 mm x500 50µm WD 20.2 mm x200 20

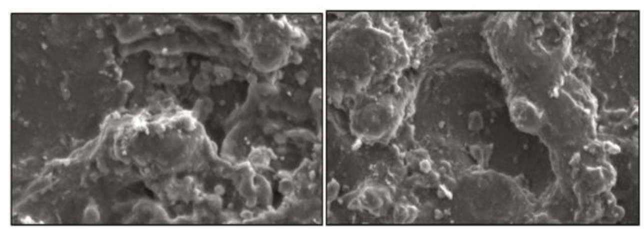

Fig. 7 — SEM image of Al-10 SiC composite with 1 & 2 wt. % graphite.
WD 20.2 mm x2.0k 20µm WD 20.2 mm x1.5k 30µm

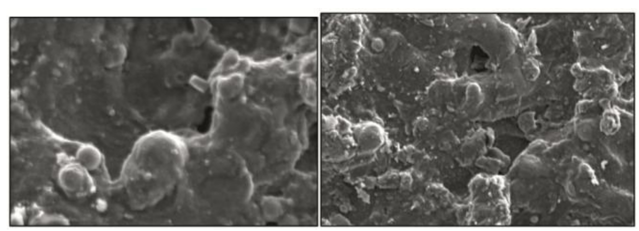

Fig. 8 — SEM image of Al-15 SiC composite with 1 & 2 wt. % graphite.
WD 21.0 mm x2.0k 20µm WD 21.1 mm x1.0k 50µm

distribution of SiC into base metal was evidenced. The microstructure of composite showed better grain formation with 2% Gr on comparison with 1%Gr in Al-5%SiC. The 10% SiC content addition to base metal have produced agglomerated grains for both % of Gr as that in Fig. 7. The graphite has occupied the grain boundary of silicon carbide cluster formed. The weight proportion of silicon carbide was limited to 15% owing to agglomeration inside the base Aluminium material from Fig. 8. Also from Fig. 8, the increased amount of SiC had led to increase in

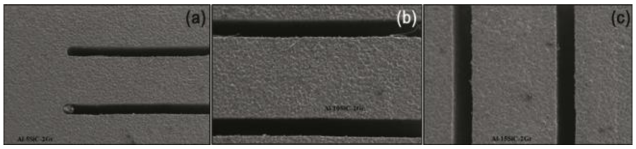

Fig. 9 — SEM image of (a) Al-5SiC-2Gr , (b) Al-10SiC-2Gr and (c)Al-15SiC-2Gr composite after WEDM.
WD 20.4 mm x30 1mm WD 20.0 mm x50 1mm WD 13.5 mm x50 1mm

clustering of atoms inside the base metal. This may be caused due to improper mixing of metals or poor stirring during the casting process. The graphite also reacted to provide weak interfacing of materials. This may led to poor atomic bonding efficiency and provided increased material removal during machining. The microstructure has improved surface texture during machining as seen in Fig. 9.

6 Conclusions

The present study aimed at fabricating hybrid metal matrix composites of aluminium with Silicon carbide and Graphite in stir casting. The composite formed with the addition of graphite have improved surface texture of proposed composite owing to the lubrication nature. From the Fig. (6-9), the clear improvement in surface texture of composite was evidential.The Wire electric discharge machining operation was carried out on the formed composites following Taguchi's L_{18} orthogonal array. Based on the results obtained from the experimentation, the optimization problem was framed with contradictory objective functions and their suitable solutions were achieved through Taguchi method and Grey relational analysis. The optimum control parameter values for satisfying the framed objective function are:

(i) Optimum control parameters for having maximum MRR is given by: V= 65V; I = 3A; SiC = 5%; Gr = 2%.

(ii) Optimum control parameters for having low Kerf is given by: V= 65V; I = 3A; SiC = 15%; Gr = 2%.

(iii) GRA results revealed the optimum parameter combination for achieving maximum MRR with minimum Kerf as V = 65V; I = 3A; SiC = 15% and Gr = 1%.

(iv) The addition of graphite have enhanced the surface texture of hybrid composite owing to its lubrication behavior.

(v) The silicon carbide addition could be restricted within 15% as further increase would result in cluster formation and may lead to brittleness.

(vi) A 5% SiC results in equal distribution of reinforcement on the base metal.

(vii) Validation experiment was conducted with the optimized parameter combination and the results were found to be deviating only by 3%. This could be caused by the influence of operating environment.

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