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ED Machining of Particulate Reinforced MMC's

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***Abstract*—**This paper reports the optimal process conditions for machining of three different types of MMC's 65vol%SiC/A356.2; 10vol%SiC-5vol%quartz/Al and 30vol%SiC/A359 using PMEDM process. MRR, TWR, SR and surface integrity were evaluated after each trial and contributing process parameters were identified. The four responses were then collectively optimized using TOPSIS and optimal process conditions were identified for each type of MMC. The density of reinforced particles shields the matrix material from spark energy hence the high MRR and SR was observed with lowest reinforced particle. TWR was highest with Cu-Gr electrode due to disintegration of the weakly bonded particles in the composite electrode. Each workpiece was examined for surface integrity and ranked as per severity of surface defects observed and their rankings were used for arriving at the most optimal process settings for each workpiece.

***Keywords*—**Metal matrix composites (MMCs), Metal removal rate (MRR), Surface roughness (SR), Surface integrity (SI), Tool wear rate (TWR), Technique for order preference by similarity to ideal solution (TOPSIS).

I. Introduction

THE desire for improved efficiency drives researchers and practitioners towards development of newer materials with enhanced mechanical and physical properties. Composite materials are one such choice that are used to replace the existing high cost alloyed materials used for producing parts for high end applications such as aerospace, automobiles and other industries. A composite material is the multiphase, judicious artificial combination of different materials to attain a synergetic improvement of properties which are vastly superior to the individual materials. MMC's are one such category of composite materials made up of metallic matrix reinforced with ceramic particulate or fibrous form. Since 1940's, a number of composite material development has been reported and has attracted the attention of various researcher and practitioners [1]. The commonly used matrix materials are aluminum, magnesium, titanium reinforced with several ceramics such as SiC, B_4C, Al_2O_3, WC, SiO_2, Si_3N_4, AlN, TiB_2, ZrO_2, and Y_2O_3 depending upon their physical and chemical compatibility with matrix material [2]. Aluminum matrix material has been most widely used because of ease of processbility (FCC crystal structure), low melting point and low density. The application of MMC's in various sectors was limited by the high cost of production using conventional machining processes. This is due to the presence of high strength ceramic particulate that causes large surface damage along with excessive tool wear. Most researchers have thus opted for electric discharge machining (EDM) which has the capability to machine complex shapes with high accuracy and precision. In an EDM process, electric energy is utilized to form series of discrete sparks in the presence of dielectric at the smallest inter-electrode gap. However, this process of subsequent cooling and heating results in surface disintegrations like micro-cracks, voids, pores or material phase transformation at the machined surface [3]. To reduce such thermal shocks, many researchers have mixed additives in dielectric that facilitates higher discharge density at lower breakdown strength of dielectric [4].

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II. Literature Review

Many studies have reported the increased focus on enhancing material removal rate (MRR), and reducing surface roughness (SR) and tool wear rate (TWR) in an EDM process. These responses depend upon optimal settings of machining process parameters such as peak-current, supply voltage, pulse duration, polarity and dielectric. During ED-machining of composites the material is removed by melting and evaporation of matrix material. This causes gathering of reinforced WC particles resulting in unstable machining [5]. The presence of reinforced particles in matrix makes the composite brittle and less thermal conductive hence spalling was reported, which directly depends upon the spark energy [6], [7]. During ED-machining of 10%SiC/Al, current and pulse duration contributes largely in change of MRR. However, higher MRR resulted in poor dimensional control and overcut [3]. In another study, by varying the particle contents from 15-35%, the MRR improved at increased current and pulse duration up to certain level and reduced afterwards due to loss of spark energy [8]. The presence of dense reinforced particle in the machining zone act as a hindrance for plasma channel formation which can be resolved with proper flushing pressure [9]. TWR is also affected by peak current and pulse duration [3]. In other studies [10], [11] it was reported that current has direct effect on TWR but pulse on time has an inverse effect. Recently a square cross section protrusion is proposed to reduce the tool degradation during EDM [12]. The prolonged pulse on time declines the sparks intensity due to enlargement of crater size [13]. In another study conducted on AA2618 20%SiCand A356- 35%SiC composite, SR was found to be directly proportional to the spark energy [14]. Current was observed to be only dominating factor affecting SR as reported in another study [15]. It was also proposed that the use of powder mixed EDM helps to reduce the insulating strength of the dielectric resulting in smooth machining due to the formation of bridge between electrodes. Multiple discharge effect with constant pulse duration was studied during ED-machining of WC-Co composite in aluminum powder suspended in dielectric [16].

Most studies reported in the literature pertain to optimization of a single objective. Such studies do not provide a global ideal alternative for process optimization. This limitation is overcome by using various Multiple Criteria Decision Making (MCDM) tools and has been reported in many papers [17]-[21]. Also, studies related to machining of reinforced MMC's with EDM are few and not much is known about the process optimal settings. This paper reports the study of ED-machining parameters on MRR, TWR and surface finish while machining of aluminum matrix composites. The parts was machined using three different tool materials namely (i) Copper, (ii) copper-graphite composite (Cu-Gr) and (iii) fine grained graphite (Gr). Subsequently, the surface integrity was examined to rank each machined surfaces and a multiple decision making aid "TOPSIS" was applied to estimate the best alternative for each material.

III. Experiment Details

A pilot study was conducted to decide the factors and their levels that affect the machining responses. The trials were completed on a die sinking EDM machine (OSCARMAX Taiwan). Three different particulate reinforced MMC's materials were used during the study namely (i) 65vol%SiC/A356.2 supplied by CPS, USA, (ii) 10vol% SiC-5 vol% quartz/Al (composition: 96.13%Al, 0.498%Cu, 0.018%Mg, 2.063%Si, 0.424%Fe, 0.075%Mn, 0.384%Zn, 0.354%Pb, 0.035%Sn, 0.009%Ti, 0.011%Cr) prepared by stir casting method [23] and (iii) 30vol%SiC/A359 provided by MC-21,Inc.,USA. Based on the pilot study, six factors (workpiece, electrode, current, pulse-on, pulse-off, and dielectric) each varied at 3-levels were identified and are shown in Table I. The three levels used for dielectric were EDM oil, EDM oil mixed with Cu powder and EDM oil mixed with graphite powder. The powder concentration in EDM oil was set at 6 gm/liters. The experimental design was completed by using Taguchi's orthogonal arrays (OA) [22] to find the most desirable combination of factors for the desired responses.

TABLE I
Factors of Interest and There Levels

Factors (unit)	**Levels**		
	Level – 1	**Level – 2**	**Level – 3**
Workpiece (A)	65vol%SiC/A356.2(WI)	10vol%SiC-5vol% quartz/Al (WII)	30 vol% SiC/ A359(WIII)
Electrode (B)	Cu	Gr	Cu-Gr
Current(A) (C)	4	8	12
Pulse-on(μs) (D)	10	30	50
Pulse-off(μs) (E)	15	30	45
Dielectric (F)	EDM oil (D)	EDM oil (D)+ Cu Powder	EDM oil (D)+ Gr powder

L27 OA was used for experimentation with three repetitions and is given in Table II.

The parts were machined using cylindrical electrodes (diameter 18mm) as per the experimental plan of L27 array and MRR, TWR and SR were recorded in Table II. Three tool materials, electrolytic copper (Cu) , fined grained graphite (Gr, particle size 5.0μm) and copper-graphite composite (Cu-Gr, 50%Cu, Grade 673, resistivity 2.03μΩm, density 2.95g/cm3) were used for machining. To ensure uniform mixing of powder a stirring pedal set at 1400rpm was used during machining. The other process parameters such as voltage (~135V), flushing pressure (0.6kg/cm2), and working time (0.75 sec) were kept constant.

The eroding rate from both the tool and the workpiece was measured by subtracting the weight at the beginning and completion of machining using a digital weighing machine (Chyo (MJ-300), readability 0.001g). The eroding rate is calculated as below (1).

$$\text{Eroding rate} = \frac{(w_i - w_f)1000}{T}\ \text{mg/min} \quad (1)$$

where wi = weight before machining (mg) and wf = weight after machining (mg) (measured after cleaning the retained dielectric) and T= time for machining (minutes).

IV. Results

MRR, TWR and SR (responses) measured after each experiment with repetitions is presented in Table II. The responses were analyzed using statistical analysis of variance (ANOVA) technique. Signal to Noise Ratio (S/N) which is a ratio of magnitude of signal to the magnitude of random error in responses was used to analyze the results. S/N ratio condenses the multiple responses within the trial and quantifies the ability of a measurement system. S/N ratio depends on the type of responses measured such as "Higher is better" type (such as MRR) or 'Lower is better" (such as TWR and SR) and is given by (2) and (3) respectively.

$$(S/N)_{HB} = -10\log\left\{\frac{1}{r}\sum_{j=1}^{r}\left(\frac{1}{{y_j}^2}\right)\right\} \quad (2)$$

$$(S/N)_{LB} = -10\log\left\{\frac{1}{r}\sum_{j=1}^{r}\left({y_j}^2\right)\right\} \quad (3)$$

where r = number of repetitions

The Analysis of Variance (ANOVA) for the three responses is presented in Table III. This table also shows the significant parameters based on F test. The purpose of ANOVA was to establish the contributing factors to estimate MRR, TWR and SR. The ANOVA for MRR shows that workpiece material, peak current and pulse duration (on and off time) affected MRR. During pulse-off duration, the entrapped reinforced particles or debris between the two electrodes are flushed out with the pressure of dielectric fluid. ANOVA results for TWR showed tool material and pulse-on time as the significant factors. Cu-Gr electrode showed higher tool wear as compare to Cu and Gr electrode due the easy disintegration of less compactly packed particles.

TABLE II
L27 EXPERIMENTAL DESIGN AND RESULTS

Trial No.	Factors varied during each trial						Output responses									
	A	B	C	D	E	F	MRR			TWR			SR			SI
							I	II	III	I	II	III	I	II	III	
1	WI	Cu	4	10	15	D	3.11	2.17	2.14	0.89	0.72	0.72	1.97	1.87	1.97	7
2	WI	Cu	8	30	30	D+Cu	12.73	15.82	13.27	5.9	5.67	5.5	3.12	3.19	3.15	6
3	WI	Cu	12	45	45	D+Gr	25.99	20.35	22.06	10.74	9.87	9.99	3.58	3.77	3.58	5
4	WI	Gr	12	45	15	D+Cu	29.14	27	27.33	3.4	4.35	3.6	5.22	5.18	5.25	9
5	WI	Gr	4	10	30	D+Gr	3.14	3.6	3.2	1.1	0.25	0.57	3.17	3.23	3.23	6
6	WI	Gr	8	30	45	D	8.14	8.025	8.12	0.42	0.38	0.4	4.52	4.03	4.57	3
7	WI	Cu-Gr	8	30	15	D+Gr	17	9.93	14.22	93.87	78.42	88.32	3.11	3.06	3.15	6
8	WI	Cu-Gr	12	45	30	D	30.3	23.86	25.36	114.4	35.8	77.89	3.08	3.25	3.01	4
9	WI	Cu-Gr	4	10	45	D+Cu	3.57	2.7	3.2	12.22	5.43	7.6	3.78	3.8	3.62	1
10	WII	Cu	8	45	15	D+Gr	57.99	58.1	58	2.54	2.12	2.34	7.4	7.35	5.51	8
11	WII	Cu	12	10	30	D	67.34	44.5	54.32	6.5	7	6	9.42	11.14	6.24	6
12	WII	Cu	4	30	45	D+Cu	16.26	15.34	15.4	0.9	0.74	0.7	5.09	5.64	8.86	7
13	WII	Gr	4	30	15	D	11.4	30.45	14.32	0.65	0.2	0.478	5.76	6.17	5.96	9
14	WII	Gr	8	45	30	D+Cu	63.9	81.7	77.1	2.6	0.28	1.6	7.1	8.56	11.82	4
15	WII	Gr	12	10	45	D+Gr	21.23	21.45	21.3	2.1	1.36	1.5	5.28	5.6	5.21	5
16	WII	Cu-Gr	12	10	15	D+Cu	56.67	74.33	63.89	145.2	130.2	130.7	7.71	9.75	9	6
17	WII	Cu-Gr	4	30	30	D+Gr	10.08	11	10.3	20.33	23.92	22.88	18.5	16.65	17.54	6
18	WII	Cu-Gr	8	45	45	D	45.44	70	59.98	99.6	63.54	79.67	8.92	9	8.53	1
19	WIII	Cu	12	30	15	D+Cu	55.74	57.9	55.86	33.2	34.17	33.4	5.79	5.63	5.31	7
20	WIII	Cu	4	45	30	r	11.97	12.38	11.98	0.48	0.5	0.4	3.92	3.82	3.8	6
21	WIII	Cu	8	10	45	D	11.27	8.2	10.1	6.06	8.67	7.68	3.6	3.56	3.56	7
22	WIII	Gr	8	10	15	D+Gr	7.057	7.82	7.22	0.3	0.2	0.2	3.43	3.41	3.25	9
23	WIII	Gr	12	30	30	D	19.06	15.68	17.97	0.285	1.43	0.59	5	5.89	5.09	1
24	WIII	Gr	4	45	45	D+Cu	7.5	5.59	5.99	0.09	0.025	0.048	4.48	4.25	4.58	5
25	WIII	Cu-Gr	4	45	15	D	11.2	10.7	10.1	52.41	13.8	30.67	4.74	4.58	4.33	1
26	WIII	Cu-Gr	8	10	30	D+Cu	5.81	6.2	6.27	46.7	50.73	47	3.59	3.24	3.66	4
27	WIII	Cu-Gr	12	30	45	D+Gr	13.65	12.57	13.02	87.64	92.67	88.4	4.18	4.13	4.16	2

Similarly, for SR, no process parameter showed any effect on SR except the workpiece material. 65vol%SiC/A356.2 showed the lowest roughness as compared to the other two materials used in the study. The concentration of reinforced particles plays a major role in dispersing the spark energy channel resulting in shallow and hence lowers SR. The main effect plot represents the variation of MRR, TWR and SR with input parameters, as shown in Figs. 1 (a)-(c).

V. MULTIPLE CRITERIA DECISION MAKING

The optimization of the three responses individually would have thrown up vastly different parametric combinations of the machining parameters as the responses have conflicting requirements. MRR is a "higher the better" response while TWR and SR are "lower the better". To obtain globally optimized results, all the responses are optimized together. Surface integrity (SI), which is a subjective measure, was also considered for selecting optimal parameter combinations.

TABLE III
ANALYSIS OF VARIANCE FOR S/N RATIO OF RESPONSES

Factor designation	DOF	Sum of Squares(SS)			Variance (V)			F-Value		
		MRR	TWR	SR	MRR	TWR	SR	MRR	TWR	SR
A	2	596.93	42.27	291.036	298.466	21.23	145.518	40.12*	0.37	23.15*
B	2	35.46	6603.91	9.809	17.729	3301.96	4.904	2.38	57.13*	0.78
C	2	690.01	1621.97	6.166	345.006	810.98	3.083	46.37*	14.03*	0.49
D	2	290.26	17.10	22.751	145.129	8.55	11.375	19.51*	0.15	1.81
E	2	44.24	76.09	7.485	22.119	38.04	3.742	2.97*	0.66	0.60
F	2	28.04	14.29	4.871	14.022	7.14	2.435	1.88	0.12	0.39
Error	14	104.16	809.22	87.989	7.440	57.80	6.285			
Total	26	1789.10	9185.04							

* Significant factors

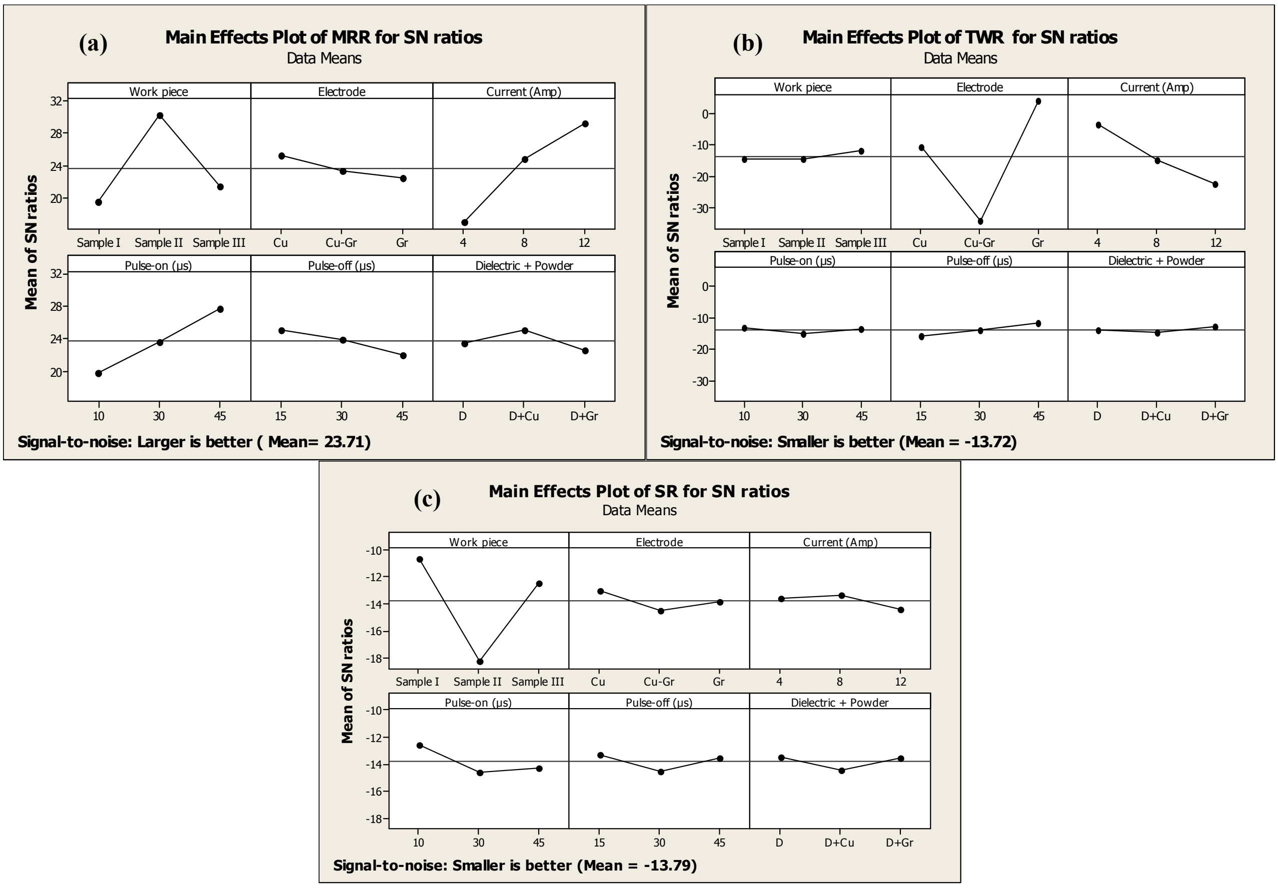

Fig 1 Main effect plots of responses (a) S/N ratio of MRR (b) S/N ratio of TWR (c) S/N ratio of SR

TABLE IV
EXPERIMENTAL RESULTS AND SEPARATION MEASURE OF WI

Trial No.	Attributes				Separation Measure	
	Mean MRR (mg/min) λ= 0.3	Mean TWR (mg/min)λ= 0.2	Mean SR (μm) λ= 0.3	SI (rank) λ= 0.2	S^+	S^-
1	2.47	0.77	1.93	7	0.15477	0.18747
2	13.94	5.69	3.15	6	0.09739	0.17601
3	22.8	10.2	3.64	5	0.07523	0.19109
4	27.82	3.78	5.21	9	0.09120	0.22942
5	3.3	0.64	3.21	6	0.15611	0.16892
6	8.095	0.4	4.37	3	0.15403	0.15595
7	13.71	86.87	3.10	6	0.17782	0.10719
8	26.50	76.03	3.11	4	0.14654	0.16133
9	3.15	8.41	3.73	1	0.18355	0.14099

TABLE V
RELATIVE CLOSENESS INDEX VALUE

Trial No.	D_i value	Trial No.	D_i value	Trial No.	D_i value
1	0.55	10	**0.86**[b]	19	**0.76**[b]
2	0.64	11	0.77	20	0.46
3	**0.72**[b]	12	0.63	21	0.44
4	**0.72**[b]	13	0.66	22	0.46
5	0.52	14	0.78	23	0.44
6	0.50	15	0.65	24	0.41
7	0.38[w]	16	0.47	25	0.31
8	0.52	17	0.44[w]	26	0.27
9	0.43	18	0.52	27	0.15[w]

b (Best option), **w** (Worst option)

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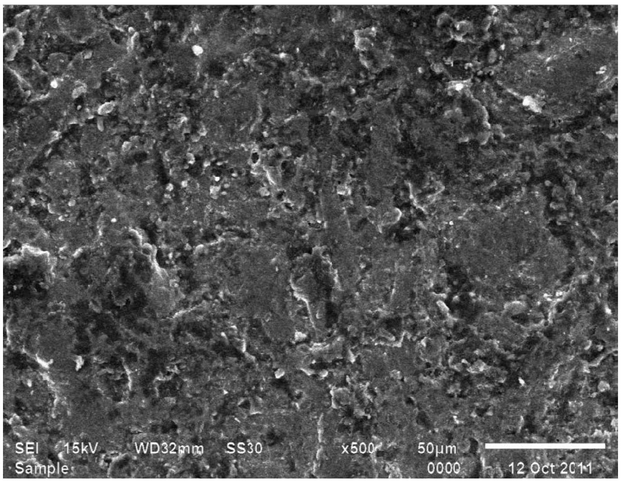

Fig. 2 (a) SEM of workpiece (WI) with input paratmeters setting as Trial No.4 and ranked as “9”

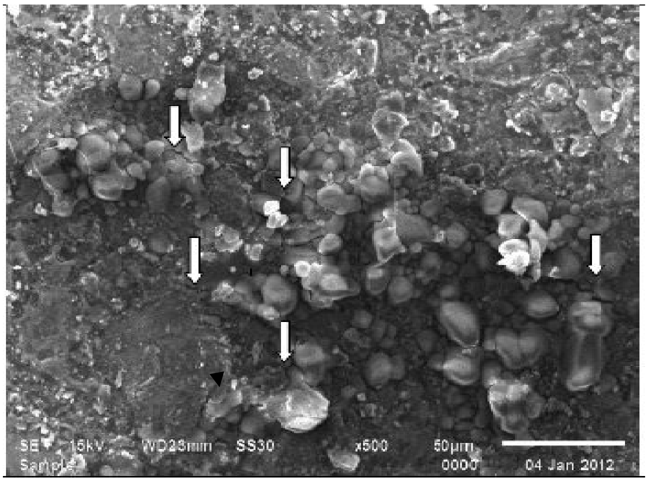

Fig. 2 (b) SEM showing surface defects of workpiece (WI) with input parameters setting as Trial No. 9 and ranked as “1”

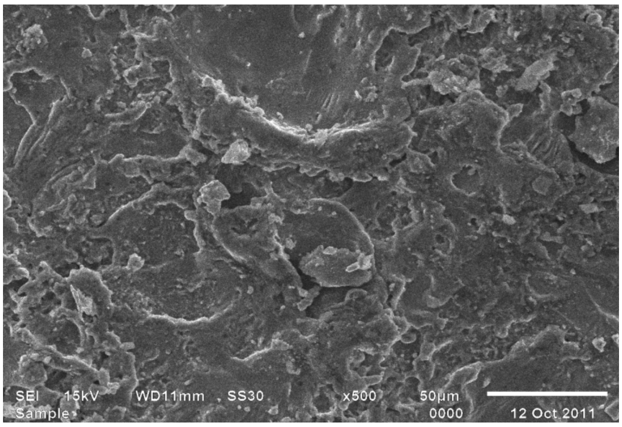

Fig. 3 (a) SEM of workpiece (WII) with input parameters setting as Trial No.13 and ranked as “9”

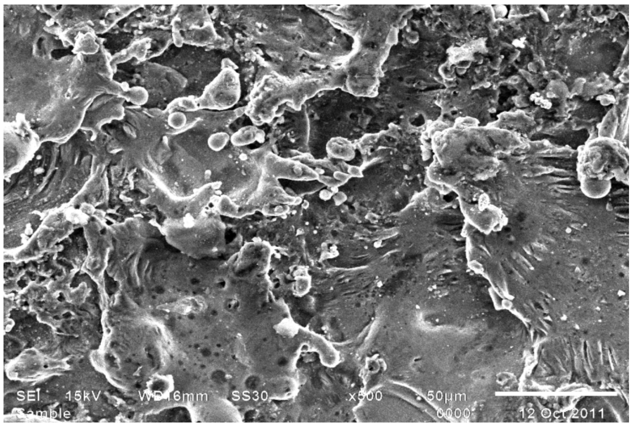

Fig. 3 (b) SEM of workpiece (WII) with input parameters setting as Trial No.18 and ranked as “1”

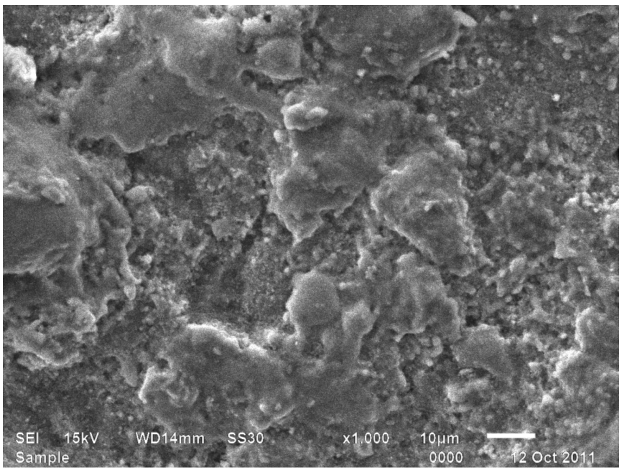

Fig. 4 (a) SEM of workpiece (WIII) with input parameters setting as Trial No.22 and ranked as “9”

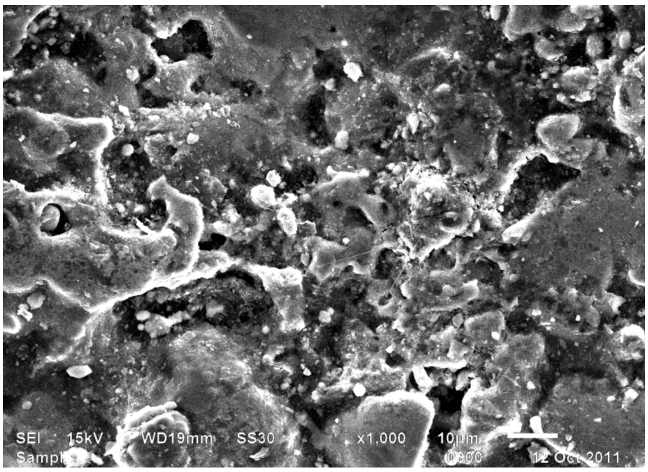

Fig. 4 (b) SEM of workpiece (WIII) with input parameters setting as Trial No.25 and ranked as “1”

To measure the quality of surface, a ranking method between 0-10 was used to define a machined surface, comparing each machined workpiece of same type. This ranking was completed considering the severity of common surface defects such as cracks, white layers (cracks formation zone) and voids. Cracks were categorized as the most severe defect and voids as the least severe (cracks>white layers> voids). The machined surface having least number of defects was ranked as 9, the highest rank, and the surface with most defects was ranked as 1. To illustrate, Fig. 2 (a) shows a machined surface (Trial 4) with least number of defects and ranked as 9 and Fig. 2 (b) with severe surface defects (Trial 9) for workpiece WI, ranked as 1. Similar metallographic pictures for the other two workpieces are presented in Figs. 3 and 4. The SEM of each workpiece was compared and the ranked in the same way and listed in last column of II. The four responses (MRR, TWR, SR and SI) were optimized collectively using TOPSIS. This technique helps to identify the "best" and the "worst" alternative [24] and has been used for evaluating and ranking alternatives in diverse fields [25].

A. Implementation of TOPSIS

TOPSIS, a multiple criteria decision making technique was applied for each workpiece to obtain the best setting of process parameters from the available alternatives. Nine trials were conducted for each type of MMC material and each trial could be a possible alternative. The matrix rij showing 9 alternatives for workpiece WI based on the information available from the experimentation is presented in Table IV. Each row of this matrix represents the 9 alternatives and each column represents the response. The matrix rij was first normalized using (4) to obtain scores for the comparison of criteria.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\left[\sum_i x_{ij}^2\right]}} \quad (4)$$

i= 1……….m; j= 1………k

The respective relative weights of the responses (λj) with a condition that $\lambda j \geq 0$ and $\sum \lambda j = 1$ was assigned based upon a peer discussion amongst practitioners. In this case, λj is the relative weight of the *ith* response. Responses such as MRR and SI are to be maximized and were assigned weights 0.3 and 0.2 respectively. Similarly, TWR and SR which are to be minimized were assigned with weights 0.2 and 0.3 respectively. The weighted matrix was computed using (5).

$$wij = \lambda j \times rij \quad (5)$$

Using the weighted matrix, the ideal (best (b)) value and the negative ideal (worst (w)) value were identified as follows:

b= { q+, *j*=1,2…..k} = { Max q*ij* for all *i; j*= 1,2…….k}
w= { q-, *j*= 1,2…….k}= {Min q*ij* for all *i; j*= 1,2…k}

The separation measures for each alternative were calculated using (6) and (7).

$$S^+ = \sqrt{\sum_j (q_{ij} - q_j^+)^2} \quad (6)$$

$$S^- = \sqrt{\sum_j (q_{ij} - q_j^-)^2} \quad (7)$$

where S^+ represents how far is each alternative from the best alternative (ideal) and S^- represents the distance of the same alternative from the non ideal alternative. The relative closeness index, C*i*, for a particular alternative to the best alternative is expressed by (8).

$$C_i = \frac{S^-}{(S^+ + S^-)} \quad i = 1,2\ldots n; 0 \leq C_i \leq 1 \quad (8)$$

C*i* for each alternative is presented in Table V. The C_i values for workpiece WI, arranged in descending order of the trials is represented as 3 or 4-2-1-5 or 8-6-9-7. The magnitude of the C_i value is an indicator of the trial numbers that are likely to give the most optimal solution. Thus, for workpiece WI, the optimal results are obtained when process settings used in trial 3 or 4 are used during machining while process settings used in trial 7 are the least preferred choice. Similarly, the optimal conditions for workpiece WII and WIII are represented by settings used in trial 10 and 19 respectively.

VI. Conclusion

This paper summarizes the effect of machine process parameters settings on ED-machining of MMC's. Peak current and pulse duration increases the spark energy which affected MRR. The density of reinforced particles shields the matrix material from spark energy, hence the high MRR and high SR were observed with lowest reinforced particle. The pulse-off duration at its lowest level is sufficient to remove entrapped debris particles by the flushing pressure of dielectric thus helping to improve MRR. TWR was highest with Cu-Gr electrode due to disintegration of the weakly bonded particles in the composite electrode. High current also affects significantly TWR adversely. Each workpiece was examined for surface integrity and ranked according to severity of the surface defects. All the four responses were then globally optimized using TOPSIS for each type of workpiece. From the process settings used in this experiment, workpiece WI gives optimal results at higher current and pulse-on time setting when machined with Cu or Gr electrode. Use of Cu or Gr electrode contributes to a globally optimized solution. Machining with Cu tool at higher pulse-off duration with Gr powder as additive in dielectric also produces better results. With Gr tool, lower pulse-on duration and Cu powder mixed dielectric medium may be used. For workpiece WII, optimum results are obtained when machined with Cu electrode at low pulse-off time. The amperage and pulse-on duration setting may be set at intermediate and highest level respectively with Gr powder suspended in dielectric. For workpiece WIII, similar current and pulse-on duration as in WII should be used. However, Cu powder mixed with dielectric would be preferable. Finally, PMEDM is a superior option as compare to simple EDM for machining of MMC's.

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