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Processing of Al_2O_3–SiC_w–TiC ceramic composite by powder mixed electric discharge grinding

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Abstract

Background: The machining of conductive alumina ceramic was successful by the electric discharge grinding (EDG). Therefore, the aim of the present work is to increase the material removal rate (MRR) during EDG of conductive alumina ceramic by addition of ceramic powder with dielectric.

Methods: To achieve the objective through experimental investigation is carried out and the influence of input process parameters (powder concentration, duty ratio, pulse on time, table speed and wheel speed) on surface roughness (SR), MRR and surface integrity has been studied. The fine grade silicon carbide powder of #1000 mesh sizes was mixed in dielectric medium with varying concentration to understand the influence of the powder concentration and its interaction with other process parameters during powder mixed electric discharge grinding (PMEDG). The central composite rotatable design (CCRD) has been used to plan the experiments. Optimization of the obtained statistical models of MRR and SR has been done to obtain highest MRR and lowest SR.

Result: It was observed that the MRR achieved by PMEDG was 3 – 10 times higher than EDG. It was found that all the process factors and interactions show significant contribution on SR. The SR obtained by PMEDG was 2 – 4 times higher than EDG.

Conclusions: It has been established that the PMEDG process is a better option for processing of Al_2O_3–SiC_w–TiC ceramic material as preliminary operation before EDG to achieve high MRR. In the present work the surface and subsurface damages were also assessed and characterized by the scanning electron microscope (SEM).

Keywords: Electric discharge grinding, Electric discharge machining, Powder mixed electric discharge grinding, Conductive alumina ceramic

Background

The need of economical machining process is demanded in present day situations, to fulfill the expectations of manufacturing industries. The process should have capability of obtaining high material removal rate (MRR), low surface roughness (SR) and good surface integrity (defect free surface). But, due to physical and mechanical properties of conductive alumina ceramic materials which are retained at elevated temperatures and corrosive environments, makes machining difficult by conventional processes. Experiencing increasing use of alumina ceramics in modern manufacturing industries (Azarafza et al. 2013; Darolia 2013; Mendez-Vilas 2012; Mohanty et al. 2013; Senthil Kumar et al. 2004; Sornakumar et al. 1995; Sugano et al. 2013; Yeniyol et al. 2013), few attempts of processing by electric discharge machining (EDM) (Patel et al. 2009a, 2009b, 2009c) and conventional diamond grinding (Patnaik Durgumahanti et al. 2010; Singh et al. 2011; Verma et al. 2010) have been reported successful in the recent past. The results (Patel et al. 2009a, 2009b, 2009c; Patnaik Durgumahanti et al. 2010; Singh et al. 2011; Verma et al. 2010) were interesting, which motivated to explore grey field of processing extremely hard and brittle materials. Therefore, the process like electric discharge grinding (EDG) which deploys the advantages of its parent processes like EDM and conventional diamond grinding and is based on

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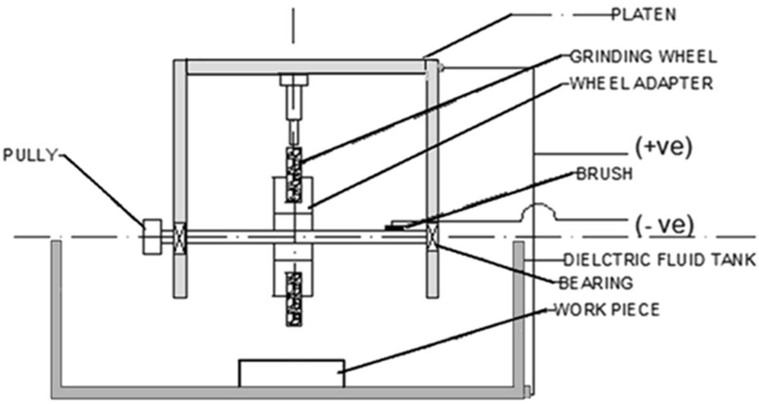

Fig. 1 Schematical diagram of the setup

thermo-mechanical concept of machining was focused. The process has been addressed as thermo-mechanical, due to the utilization of thermal energy for work softening (Koshy et al. 1996) by sparking and mechanical energy for abrasion of work material (Koshy et al. 1996) by grinding. Further, the area of study has been expanded to find out the effect of powder mixed dielectric usages in EDG (Satyarthi and Pandey 2012). The process physics of powder mixed electric discharge machining (PMEDM) has been conceived to understand the role of powder mixed dielectric in EDG. In the following section a brief literature review has been presented to describe the effects of powder mixing in the dielectric during EDM. Thereafter, few attempts made in PMEDG of Al_2O_3–SiC_w–TiC ceramic has been discussed.

PMEDM of conductive ceramic materials

Numerous research attempts (Chow et al. 2008; Chow et al. 2000; Han et al. 2007; Kansal et al. 2005a, 2005b, 2006, 2007a, 2007b; Peças and Henriques 2003; Wong et al. 1998; Wu et al. 2005; Yeo et al. 2007) have been reported in the field of powder mixed electric discharge machining (PMEDM). In electric discharge machining (EDM), to achieve better surface finish negative polarity (tool + ve, work –ve) was found as one of the prominent factors (Wu et al. 2005). The negative polarity gave better results in PMEDM (Wong et al. 1998) than positive polarity (tool –ve, work + ve). Additional requirements for achieving good surface finish in PMEDM as reported in the literature were low pulse on time (Wong et al. 1998), low discharge current (Chow et al. 2000; Han et al. 2007), uniform dispersion of discharges (Chow et al. 2008; Chow et al. 2000; Wong et al. 1998), reduction in breakdown voltage (Han et al. 2007) and low discharge energy (Han et al. 2007; Wu et al. 2005; Yeo et al. 2007).

The incorporation of powder particles in the dielectric medium promotes bridging effect in the insulating dielectric (Chow et al. 2008; Chow et al. 2000; Kansal et al. 2007b). The bridging helped in the dispersion of single pulse discharge energy (Chow et al. 2008; Chow et al. 2000), into multiple sparks. The presence of conductive phase powder particles in the dielectric medium increased the spark gap (Chow et al. 2008; H. M. Chow et al. 2000; Kansal et al. 2007b) and helped in achieving stable machining (Han et al. 2007; Kansal et al. 2007b; Wong et al. 1998; Wu et al. 2005). The powder mixed in the dielectric supported reduction in insulating strength, being conductive in nature (Kansal et al. 2007b) which increased viscosity of dielectric fluid (Yeo et al. 2007). In plasma channel the heat flux decreased due to presence of powder in dielectric fluid and increased the rate of heat dissipation from tool-work interface (Yeo et al. 2007).

The researchers used different type of electrically conductive phase powders in their studies such as Al (0.1 g/L) (Chow et al. 2000; Wu et al. 2005), SiC (Chow et al. 2008; Chow et al. 2000; Satyarthi and Pandey 2012), silicon (Kansal et al. 2005a, 2005b, 2006, 2007a; Peças and Henriques 2003), graphite (Han et al. 2007; Kansal et al. 2005a, 2005b; Satyarthi and Pandey 2012), copper and tungsten

Fig. 2 Attached experimental setup on EDM machine

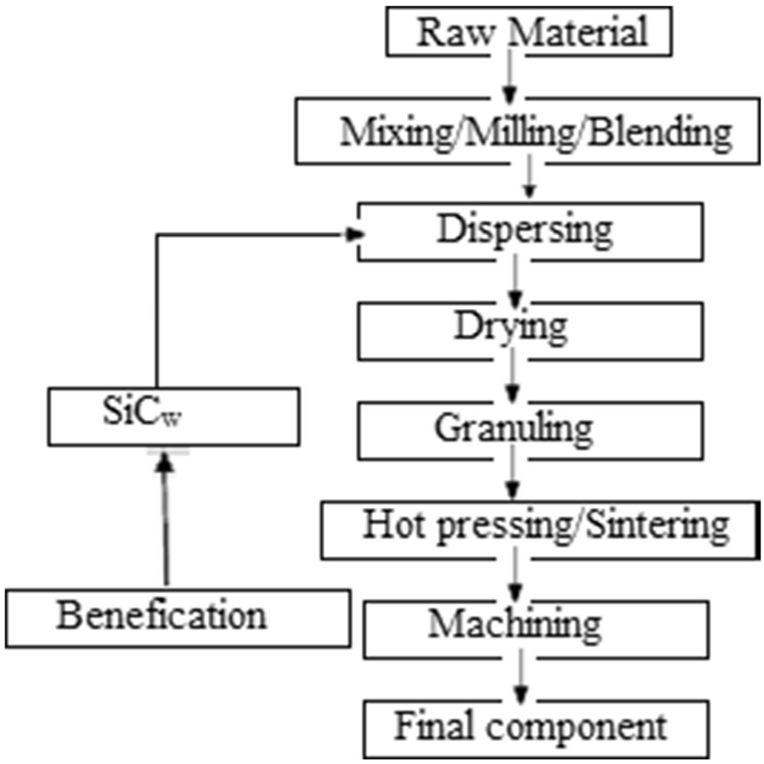

Fig. 3 Processing steps of Al_2O_3-SiC_w-TiC Composite (Courtesy; Industrial Ceramic Technology, Inc, USA)

(Bhattacharya et al. 2011). Wu et al. (2005) also used surfactant for separation of Al (0.25 g/L) for high concentration of powder in dielectric. Various dielectric mediums used were kerosene (Bhattacharya et al. 2011; Chow et al. 2000; Han et al. 2007; Kansal et al. 2005a, 2005b, 2006, 2007a, 2007b; Peças and Henriques 2003; Wong et al. 1998; Wu et al. 2005; Yeo et al. 2007), spark erosion oil (Bhattacharya et al. 2011) and water (Chow et al. 2008). The use of water as dielectric was mainly focused due to emphasis of manufacturers for initiation of green manufacturing technology. During experimentation with water as dielectric fluid it was observed that the electrical conductivity of the fluid was increased (Chow et al. 2008). The powder mixed machining helps in achieving reduced operating time of the same component than without powder (Peças and Henriques 2003), due to dis-integration of spark it results in high MRR.

The result of PMEDM showed increase in MRR (Chow et al. 2008; H. M. Chow et al. 2000; Kansal et al. 2005a, 2005b, 2007b; Zhao et al. 2002) and surface roughness (Chow et al. 2000; Kansal et al. 2007b; Zhao et al. 2002), whereas improved surface (Bhattacharya et al. 2011; Chow et al. 2008; Chow et al. 2000; Furutania et al. 2001; Han et al. 2007; Kansal et al. 2005a, 2005b, 2007a; Kumar and Batra 2012; Kumar et al. 2009; Peças and Henriques 2003; Wong et al. 1998; Wu et al. 2005) and mirror like surface (Peças and Henriques 2003) was also obtained. It is quite noticeable here to quote that the improved surface has been noticed with the conductive powders like Al (Wu et al. 2005), Si (Peças and Henriques 2003), and Cu (Bhattacharya et al. 2011). Even few researchers (Bhattacharya et al. 2011) mentioned that "to overcome problems of poor finish at high current settings in EDM, the dielectric should be mixed with powder", which showed that the addition of these powder particles induced surface modification rather than high quality machining to achieve reduced surface finish. This may be due to inclusion of the powders in the recast layer (surface modification), serving as filler material in the pits and voids of the recast, which resulted in reduced surface roughness (Bhattacharya et al. 2011; Wu et al. 2005). The improved MRR may be due to formation of minor craters which facilitated easy debris extrusion resulting in reduction of surface roughness (Chow et al. 2008). It was also

Table 1 Physical and mechanical properties of Al_2O_3–SiC_w–TiC (Patel et al. 2009a, 2009b, 2009c)

Hardness (H_v)	Fracture toughness K_{IC} (MPa (m) $^{0.5}$)	Thermal conductivity k (W/mK at 400°K)	Electrical Resistivity (Ωcm)	Density ρ (g/cm^3)
2400	9.6 ± 0.6	63	0.009	3.915

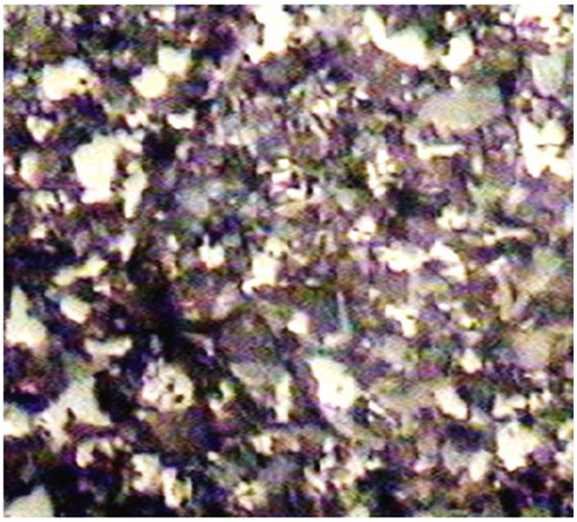

Fig. 4 The optical micrograph of Al_2O_3-SiC_w-TiC composite

observed that the surface becomes corrosion and abrasion resistant due to surface modification (Furutania et al. 2001; Kansal et al. 2007b; Kumar and Batra 2009, 2012; Kumar et al. 2009). The surface modification was due to inclusion of powder, debris and hydrocarbon present in dielectric medium (Chow et al. 2008; Kumar and Batra 2012; Kumar et al. 2009). The SEM analysis revealed presence of surface defects like shallow overlapping of recast, re-solidified circular shapes, deep craters, pock marks, debris and globules (Chow et al. 2008; Han et al. 2007; Peças and Henriques 2008; Wong et al. 1998; Yeo et al. 2007).

PMEDG of conductive ceramic materials

The powder mixed electric discharge grinding (PMEDG) process has not been explored so far. The work done by authors (Satyarthi and Pandey 2012) compared effects of different powders such as graphite, silicon oxide and silicon carbide in PMEDG at constant powder concentration and varying other input parameters. It was found that the MRR achieved by PMEDG was 2 to 13 times higher than EDG processing while using silicon carbide (SiC) and graphite powders, whereas 2 to 7 times higher with silicon oxide (SiO). The surface roughness obtained by EDG process was lower than PMEDG. The formation of surface and subsurface damages was not evident. The results for silicon carbide and graphite powders were found interesting, which led to explore effects of powder concentration and its interactions with other process parameters while PMEDG processing of Al_2O_3–SiC_w–TiC ceramic.

Methods

Experimental procedure and analysis of experimental data

The powder mixed electric discharge grinding (PMEDG) experiments were conducted on the setup designed and developed in the laboratory as shown in Fig. 1. The EDM head assembly of "Electronica leader ZNC" die-sinking EDM machine was attached with the developed setup mounted with servo motor to get desired rotational motion of the grinding wheel, as shown in Fig. 2. The setup has been facilitated with servo motors mounted on the EDM bed to get desired linear motion. These servo motors were connected to a dedicated system through role-based collaboration (RBC) break out box and ACR processor-based 4 axis motion controller. Aries view software was used for ACR processor-based 4 axis motion controller. A separate dielectric tank with the provision of controlled dielectric flow was used, to avoid mixing of conductive phase powder with the fresh dielectric stored in the dielectric tank of the EDM facility. The dielectric medium used for all of the experiments was kerosene.

Details of workpiece

The electrically conductive Al_2O_3-SiC_w-TiC ceramic composite supplied by Industrial Ceramic Technology was selected as workpiece. The processing steps used by supplier of ceramic composite are shown in Fig. 3. In Table 1 the physical and mechanical properties of the Al_2O_3-SiC_w-TiC ceramic composite have been summarized. The optical micrograph of Al_2O_3-SiC_w-TiC composite has been shown in Fig. 4. The size of the workpiece selected suitably was a square of 20×20 mm^2

Table 2 PMEDG process factors and ranges

Process factors	Symbol	Levels				
		Lowest	Low	Center	High	Highest
		−2	−1	0	+1	+2
Powder concentration (g/L)	P_c	8	16	24	32	40
Duty-ratio (%)	D_c	0.24	0.40	0.56	0.72	0.88
Pulse on time (μs)	T_{on}	100	200	300	400	500
Table speed (m/min)	V_t	0.030	0.045	0.060	0.075	0.090
Wheel speed (m/min)	V_w	0.79	1.57	2.36	3.14	3.93

Table 3 Grinding wheel specifications, dressing and other parameters used in experiments

Grinding wheel specification		Parameters kept constant during PMEDG processing	
Wheel diameter	100 mm	Polarity	Negative
Wheel bonding	Bronze	Gap voltage	70 V
Abrasive grit size	#800 mesh	Discharge current	4 A
Wheel thickness	20 mm	Dielectric	Kerosene
Parameters for wheel dressing			
Pulse peak current	6 A	Duty ratio	0.56
Pulse on time	200 μs	Wheel speed	3.93 m/min

Table 4 Measured responses corresponding to each experimental run

S. No.	P_c (g/L)	D_c (%)	T_{on} (μs)	V_t (m/min)	V_w (m/min)	MRR (mg/min)	R_a (μm)
1	24	0.56	500	0.060	2.3550	21.26	0.4893
2	16	0.40	200	0.045	3.1400	12.04	0.4067
3	24	0.24	300	0.060	2.3550	15.89	0.2659
4	24	0.56	100	0.060	2.3550	12.17	0.2578
5	16	0.40	400	0.075	3.1400	15.43	0.6441
6	32	0.40	200	0.075	3.1400	16.48	0.5396
7	24	0.56	300	0.060	2.3550	21.39	0.4939
8	24	0.56	300	0.060	2.3550	21.68	0.4886
9	24	0.56	300	0.060	2.3550	19.23	0.5085
10	32	0.72	200	0.045	3.1400	17.45	0.3141
11	24	0.88	300	0.060	2.3550	28.43	0.5277
12	24	0.56	300	0.060	2.3550	21.25	0.4922
13	24	0.56	300	0.060	2.3550	18.76	0.4873
14	16	0.72	400	0.075	1.5700	13.78	1.3706
15	40	0.56	300	0.060	2.3550	32.41	0.1873
16	16	0.72	200	0.045	1.5700	13.92	0.9133
17	24	0.56	300	0.060	3.9250	21.31	0.7466
18	32	0.40	400	0.045	3.1400	25.22	0.3243
19	32	0.72	400	0.045	1.5700	24.25	0.2943
20	24	0.56	300	0.060	2.3550	18.81	0.4984
21	8	0.56	300	0.060	2.3550	11.47	0.1677
22	16	0.72	200	0.075	3.1400	18.35	0.4919
23	32	0.72	400	0.075	3.1400	48.24	0.2522
24	24	0.56	300	0.090	2.3550	28.53	0.5784
25	32	0.40	200	0.045	1.5700	16.62	0.3905
26	24	0.56	300	0.060	0.7850	14.98	0.9711
27	16	0.40	400	0.045	1.5700	13.13	0.3999
28	32	0.40	400	0.075	1.5700	21.88	0.5775
29	24	0.56	300	0.030	2.3550	17.21	0.3889
30	16	0.40	200	0.075	1.5700	13.45	0.3214
31	16	0.72	400	0.045	3.1400	18.82	0.7038
32	32	0.72	200	0.075	1.5700	32.89	0.2807

Table 5 Analysis of Variance for MRR after dropping insignificant factors and interactions

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	10	0.0016964	0.0016964	0.0001696	37.862	0.000000
Residual error	21	0.0000941	0.0000941	0.0000045		
Lack-of-Fit	16	0.0000844	0.0000844	0.0000053	2.733	0.135556
Pure error	5	0.0000097	0.0000097	0.0000019		
Total	31	0.0017905				

DF Degree of freedom, *SS* Sum of squares, *MS* Mean square
R-Sq = 94.75%; R-Sq(pred) = 87.74%; R-Sq(adj) = 92.24%
$F > F_{0.01,10,21}$
$F_{lack\ of\ fit} < F_{0.01,16,21}$
Model is not adequate ($F_{0.01,10,21} = 3.37$)
Lack of fit is insignificant ($F_{0.01,16,21} = 3.03$)

having uniform thickness of 5 mm. The workpiece was grounded by diamond grinding wheel of 200 mesh, to achieve uniform average surface roughness in the range of 0.28 to 0.30 μm before experimentation.

Selection of process parameters

It is evident from the literature presented in section 1, that the PMEDG process is governed by numerous process parameters. Pilot experiments were carried out by one variable at a time approach to determine the range of process parameters on the present setup. The selected process factors and range has been given in Table 2. The choice of the conductive phase powder was based on preliminary experimentation for better MRR and surface integrity. The preliminary experimentation was performed with SiC, SiO_2 and graphite powders as described in section 1.2. It was observed that the SiC powder gave maximum MRR with acceptable surface integrity. Therefore, the SiC power was used in this work to study PMEDG process characteristics in detail. Patel et al. (2009a, 2009b) reported the gap voltage to be an insignificant factor for MRR of Al_2O_3–SiC_w–TiC, as it is used to maintain the inter-electrode gap by servo control. The study of influence of process parameters on EDG of Al_2O_3–SiC_w–TiC by the authors of this paper has shown insignificant contribution of discharge current in the selected range therefore the discharge current and gap voltage were kept constant in this study. Table 3 shows the grinding wheel specification, wheel dressing parameters and parameters which were kept constant during PMEDG process. The dressing of the wheel was carried out at the beginning of experimentation. The machining time of 20 min was suitably decided for all the experiments.

Experimental design

The half factorial central composite rotatable design (CCRD) was considered in present work since it requires fewer numbers of experiments to describe the influence of input process parameters on the response than full factorial CCRD. Powder concentration, Duty ratio, pulse on time, table speed and wheel speed were selected as process factors as given in Table 2. The measurements of surface roughness of machined surface were carried out on “Talysurf 6, Rank Taylor Hobson, England”. A traverse length of 2 mm with a cutoff evaluation length of 0.8 mm was selected. The weight measurement was carried out on “METTLER TOLEDO AB265-S/FACT” weighing machine with least count of 0.01 mg. The weight loss of material was taken as the average of 5 readings to minimize errors. The experimentally obtained MRR and SR values are given in Table 4. The extent of surface damages was characterized by Scanning Electron Microscope (SEM) EVO 50.

Data analysis

The analysis of variance (ANOVA) has been conducted to check the adequacy of the model and understand the significance of process factors and interactions. The ANOVA table for MRR after dropping insignificant terms and interactions has been presented in Table 5. The value of R^2 is 94.75% which shows that regression model provides strong correlation among process factors and interactions at $\alpha = 0.01$. The model is adequate and the lack of fit is insignificant. The regression equation for MRR has been given by Eq. (1).

Table 6 Analysis of Variance for SR after dropping insignificant factors and interactions

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	15	1.85864	1.85864	0.097823	1151.09	0.000000
Residual error	16	0.0000000	0.0000000	0.0000000		
Lack-of-Fit	11	0.0000000	0.0000000	0.0000000	1.69	0.291328
Pure Error	5	0.0000000	0.0000000	0.0000000		
Total	31	1.85966				

DF Degree of freedom, *SS* Sum of squares, *MS* Mean square
R-Sq = 99.95%; R-Sq(pred) = 99.38%; R-Sq(adj) = 99.86%
$F > F_{0.01,15,16}$
$F_{lack\ of\ fit} < F_{0.01,11,16}$
Model is adequate ($F_{0.01,15,16} = 3.41$)
Lack of fit is insignificant ($F_{0.01,11,16} = 3.69$)

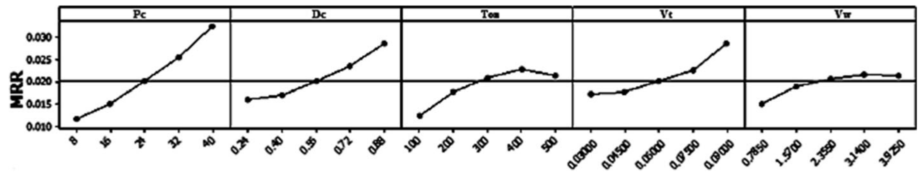

Fig. 5 Main effect plot for MRR

$$\mathbf{MRR} = 0.0954 - 0.002\mathbf{P}_c - 0.00617\mathbf{D}_c - 0.000126\mathbf{T}_{on} - 48.1\mathbf{V}_t - 0.009.5\mathbf{V}_w + 0.000124\mathbf{P}_c\mathbf{D}_c + 0.000003\mathbf{P}_c\mathbf{T}_{on} + 1.03\mathbf{P}_c\mathbf{V}_t + 4.82\mathbf{D}_c\mathbf{V}_t + 0.00056\mathbf{D}_c\mathbf{V}_w + 0.000038\mathbf{T}_{on}\mathbf{V}_w \quad (1)$$

$$\mathbf{R_a} = 1.84 + 0.065\mathbf{P_c} + 0.49\mathbf{D_c} + 0.00109\mathbf{T_{on}} - 0.28\mathbf{V_w} - 0.0000979\mathbf{P_c^2} - 0.0661\mathbf{D_c^2} - 0.00000322\mathbf{T_{on}^2} - 0.0000283\mathbf{V_t^2} + 0.15\mathbf{V_w^2} - 0.00937\mathbf{P_c}\mathbf{D_c} - 0.000083\mathbf{P_c}\mathbf{T_{on}} - 3.04\ \mathbf{P_c}\mathbf{V_t} + 0.00643\mathbf{V_w}\mathbf{P_c} + 0.000104\mathbf{D_c}\mathbf{T_{on}} - 51.79\mathbf{D_c}\mathbf{V_t} - 0.05\mathbf{D_c}\mathbf{V_w} + 3.73\mathbf{T_{on}}\mathbf{V_t} - 0.000449\mathbf{T_{on}}\mathbf{V_w} - 125.16\mathbf{V_t}\mathbf{V_w} \quad (2)$$

The ANOVA table for surface roughness (SR) after dropping insignificant terms and interactions has been presented in Table 6. Table shows that the value of R^2 is 99.95% representing strong correlation between process factors and interactions at significance level of $\alpha = 0.01$. The model is adequate and the lack of fit is insignificant. The regression equation for SR (R_a) may be given by Eq. (2). Further, due to experimental error and noise present in the system, the value of estimated parameters and the responses like MRR and R_a, are subjected to uncertainty. Therefore, the confidence interval was calculated to estimate the precision of MRR and R_a and is given by Eq. (3).

$$\Delta\mathbf{Y} = \mathbf{t}_{\left(\frac{\alpha}{2},\ \ \mathbf{DF}\right)}\sqrt{\mathbf{V_e}} \quad (3)$$

Results and discussion

This section includes detailed discussion on the outcome of data analysis with respect to the material removal rate (MRR), surface roughness (SR) and surface integrity during the powder mixed electric discharge grinding (PMEDG) of Al_2O_3–SiC_w–TiC ceramic composite. The effects and percentage contributions of significant process factors and its interactions have also been presented and discussed in this section. The response surfaces have been presented and the trends are explained in order to have a feel of associated process physics of MR and surface generation in PMEDG process.

Material removal rate

The main effect plot and the percentage contribution of various process factors and interactions with respect to MRR have been shown in Figs. 5 and 6 respectively. It can be seen from Fig. 5 that all input process factors selected for study affects the PMEDG process significantly. The powder serves as a bridge for the ions imposed due to ionization of dielectric. The conductive phase powder also reduces the insulating strength of the dielectric fluid, and creates several parallel paths of ion transfer. The high temperature produced due to EDM action thermally softens the work material in the grinding zone in addition to partial melting and vaporization. The bridging effect caused by inclusion of conductive phase powders in the dielectric medium promotes disintegration of spark into several increments (Chow et al. 2008; Chow et al. 2000). The inclusion of powder in recast layer (surface modification) makes it weak which may be easily removed by grinding action of the grits (Chow et al. 2008; Kumar and Batra 2012; Kumar et al. 2009). Therefore, the increase in powder concentration increases the MRR. The increase in Duty ratio results in reduced pulse off time, which shows that the sparking takes place after small interval of time, which also promoted increase in discharge energy, resulting in increased MRR. Discharge energy is a function of discharge current, discharge voltage and pulse on time. Therefore increase in pulse on time increased the discharge energy which resulted in increased MRR upto 400 μs. Further increase in discharge energy promotes wheel loading due to which the material removed by

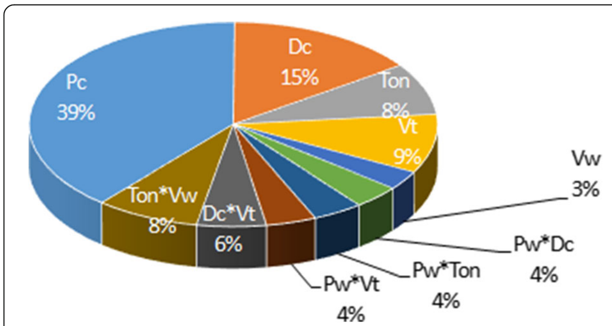

Fig. 6 Percentage contributions of process factors and interactions on MRR

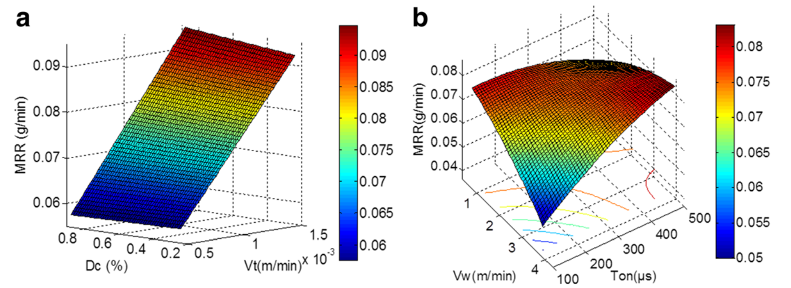

Fig. 7 Response surface plots of process factor's interactions on MRR. **a** Interactions of Duty ration and table speed. **b** Interactions of pulse on time and wheel speed

grits is seized, resulting in decreased MRR. The increase in table speed raises the feed rate hence the amount of softened work material availability per unit time is also increased which is swept by abrasives, which promotes increase in MRR with the increased table speed. The increase in wheel speed raises the number of active grits per unit time resulting in increased MRR (Satyarthi and Pandey 2013b). The interaction terms having contribution of less than 5% (Fig. 6) are considered to be insignificant, but these cannot be excluded from the statistical model as exclusion of these terms results in inadequacy of the model and significant lack of fit. The response surfaces showing the effect of significant interaction terms (>5%) affecting MRR have been presented in Figs. 7 and 8. Figures 7a and 8a-b shows the interaction of Duty ratio and table speed. The small increase in Duty ratio increases the MRR as the spark interval is decreased. The increase in table speed increases the MRR, due to the increased feed rate that is availability of more material for abrasion per unit time. The increase in table also promotes ductile mode grinding which is dominated by the number of active grits (Xie and Lu 2011). Figs. 7b and 8c-d shows the interaction of pulse on time and wheel speed. From Fig. 8c it is clear that at low wheel speeds upto 1.57 m/min the MRR is reduced with the increase in the pulse on time, but for wheel speed beyond 1.57 m/min the MRR increases with the increase in pulse on time. Which shows that the EDG

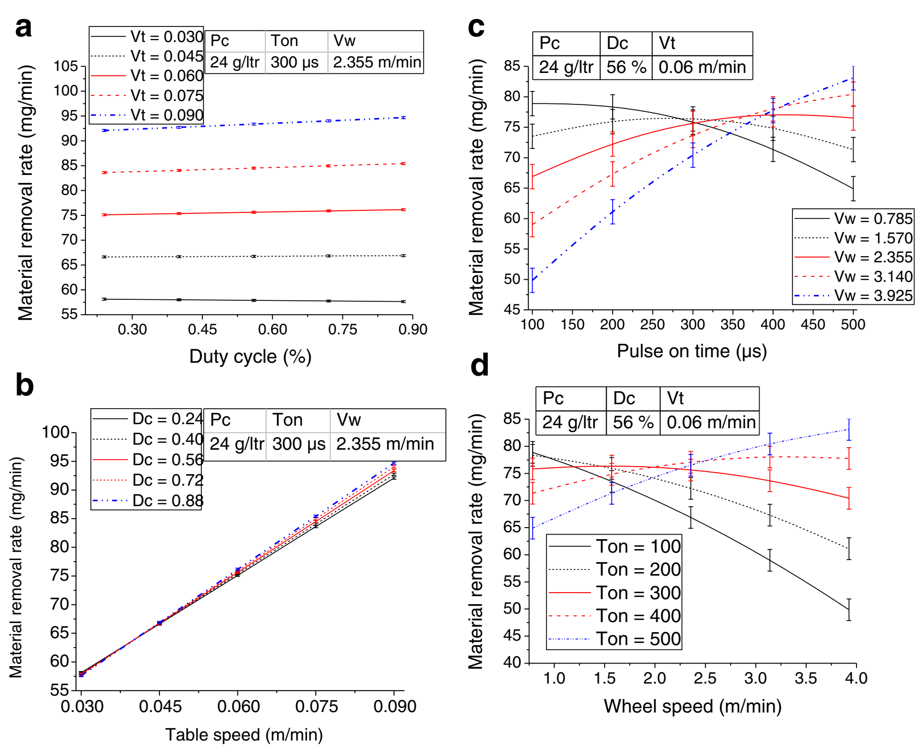

Fig. 8 Line plots conceived with respect to response surface plots. **a-d** Material removal rate (mg/min)

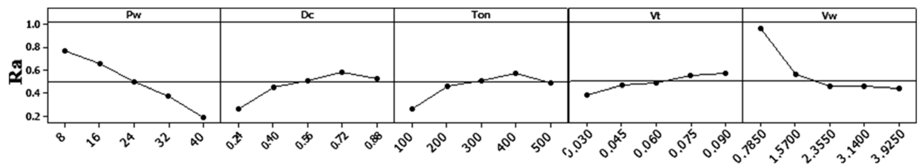

Fig. 9 Main effect plot for surface roughness

action is prominent and in agreement to the findings of Satyarthi and Pandey (2013b). The MRR first reduces with the increase in wheel speed upto certain limit and thereafter further increase in wheel speed increases the MRR (Satyarthi and Pandey 2013b). From Fig. 8d it could be seen that the increase in wheel speed reduces the MRR for pulse on time less than 300 μs, whereas for pulse on time greater than 300 μs, the MRR is increased. The reduction in MRR with the increase in wheel speed at low pulse on time may be due to low discharge energy, as at low discharge energies the grinding action is prominent (Satyarthi and Pandey 2013b). Whereas, the increase in wheel speed at increased pulse on time supports the EDG action and results in increased MRR (Satyarthi and Pandey 2013b).

Surface roughness

The main effect plot and the percentage contribution of various process factors and interactions with respect to surface roughness (SR) have been shown in Figs. 9 and 10 respectively. It can be seen from Fig. 9 that all of the input process factors affect the PMEDG process significantly. The increase in Duty ratio, pulse on time and table speed increases the SR. The increase in Duty ratio and pulse on time upto 72% and 400 μs respectively increases the SR, thereafter further increase results in decreased SR. The increased SR may be attributed to the formation of bigger size craters due to increased discharge energy and grain dislodgement due to increased feed rate. Whereas, the increase in powder concentration and wheel speed reduces the SR. The increase in powder concentration supports disintegration of spark into several branches which as a results forms small sized overlapping craters and results in reduced SR. The increase in wheel speed raises the number of active grits per unit time, which as a result sweeps more material from the work surface resulting in reduced SR. It is quite evident that the increase in wheel speed upto certain limit reduces the SR, but further increase in wheel speed do not contribute significantly, which may be due to the wheel loading. The interaction terms having contributions less than 5% (Fig. 10) are considered to be insignificant, but these cannot be excluded from the model as exclusion of these terms results in inadequacy of the model and significant lack of fit.

The response surfaces showing the effect of significant interaction terms (>5%) affecting SR have been presented in Figs. 11 and 12. Figures 11a and 12a-b show the interaction of powder concentration and Duty ratio. The increased Duty ratio reduces the spark interval and promotes overlapping of the small craters formed, resulting in reduced SR. The increase in powder concentration increases the SR, which may be due to disintegration of the spark and hence formation of more number of craters per pulse, however this phenomenon is dominated by the main effect of powder concentration; and therefore overall effect is reduction in SR. Figures 11b and 12c-d show the interaction of wheel speed

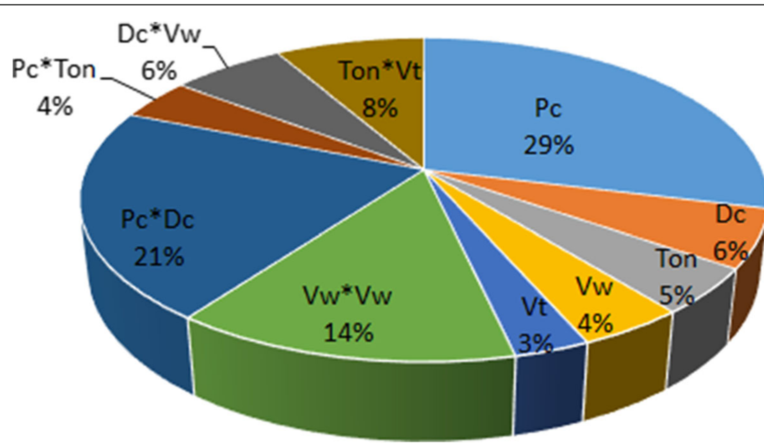

Fig. 10 Percentage contributions of process factors and interactions on surface roughness

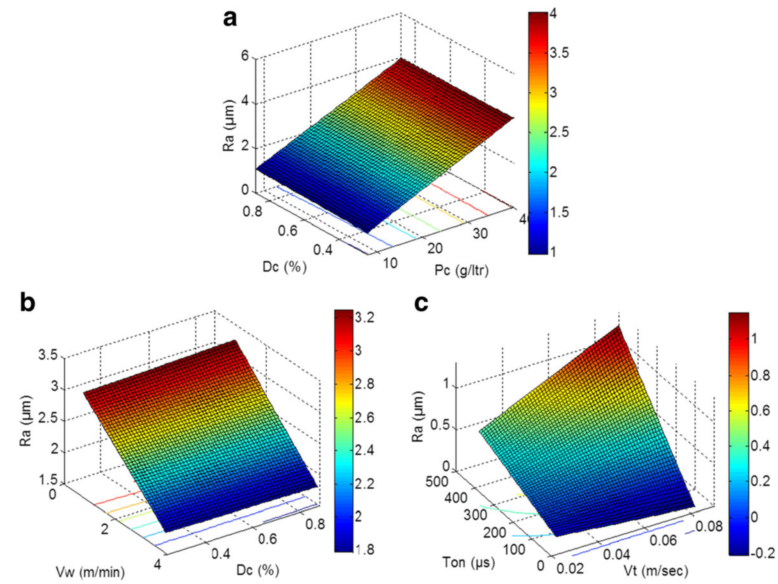

Fig. 11 Response surface plots of process factor's interactions on surface roughness. **a** Interactions of Duty ratio and powder concentrations. **b** Interactions of wheel speed and Duty ratio. **c** Interactions of pulse on time and table speed

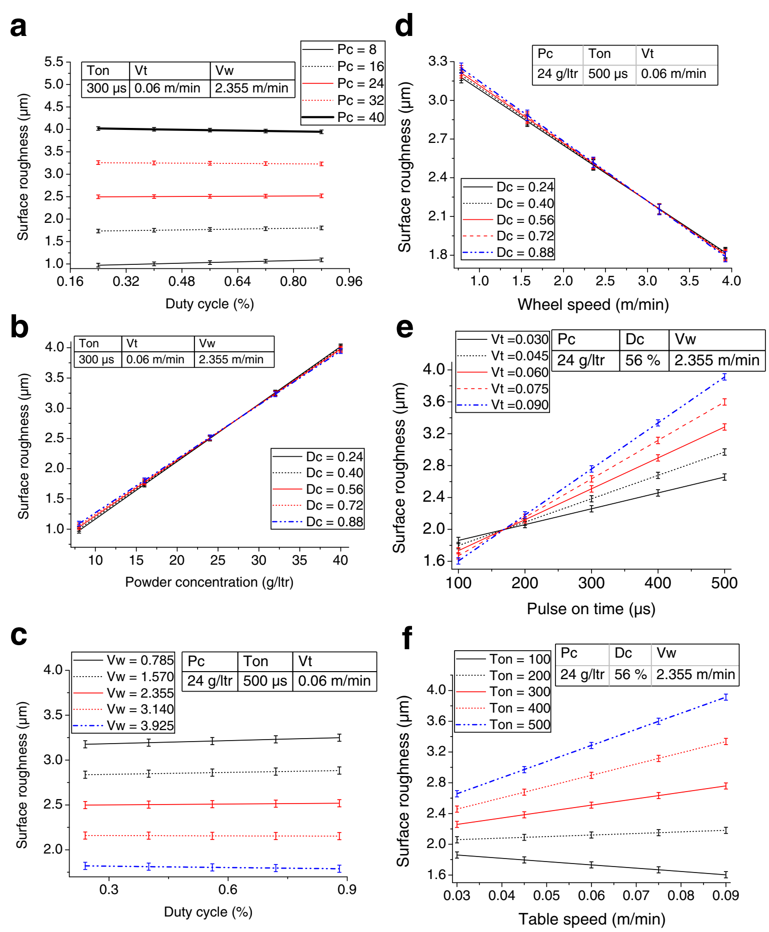

Fig. 12 Line plots conceived with respect to response surface plots. **a**-**f** Surface roughness (µm)

Table 7 Optimum process parameters

PMEDG Response	P_w (g/ltr)	D_C (%)	T_{on} (µs)	V_t (m/min)	V_w (m/min)	Calculated optimum	Experimental value
MRR_{max}	40	0.88	500	0.090	3.93	49.26 (mg/min)	49.69 (mg/min)
Ra_{min}	08	0.56	300	0.060	2.36	0.1679 (µm)	0.1677 (µm)

and Duty ratio. The effect of increased Duty ratio has been discussed for Fig. 12a. From Fig. 12d it may be noticed that the increase in wheel speed results in reduced SR, which may be due to the increased number of abrasives available per unit time supporting even distribution/sweeping of work material as well as recast prior to the solidification. Figures 11c and 12e-f shows the interaction of pulse on time and table speed. The increase in pulse on time results in the increased SR, which may be due to formation of bigger craters promoted by increased discharge energy and dislodgement of constituting elements of ceramic material by thermal loading. From Fig. 12f it may be seen that the increase in table speed results in reduced SR for low pulse on time (<200 µs), whereas for increased pulse on time the SR increases with the increase in table speed. The reason for the reduced SR for low pulse on time may be attributed to the low discharge energy promoting grinding action prominently (Satyarthi and Pandey 2013b). Whereas, at increased discharge energy the EDG/EDM action becomes prominent (Satyarthi and Pandey 2013b) and results in increased SR.

Process optimization

In the present work an attempt has been made to estimate the processing conditions for the highest possible MRR and the lowest possible SR. To achieve this, optimization of Eqs. (1) and (2) has been done by a standard MATLAB 2011a function, *fmincon* (Bacchewar et al. 2007), which can handle optimization problems of

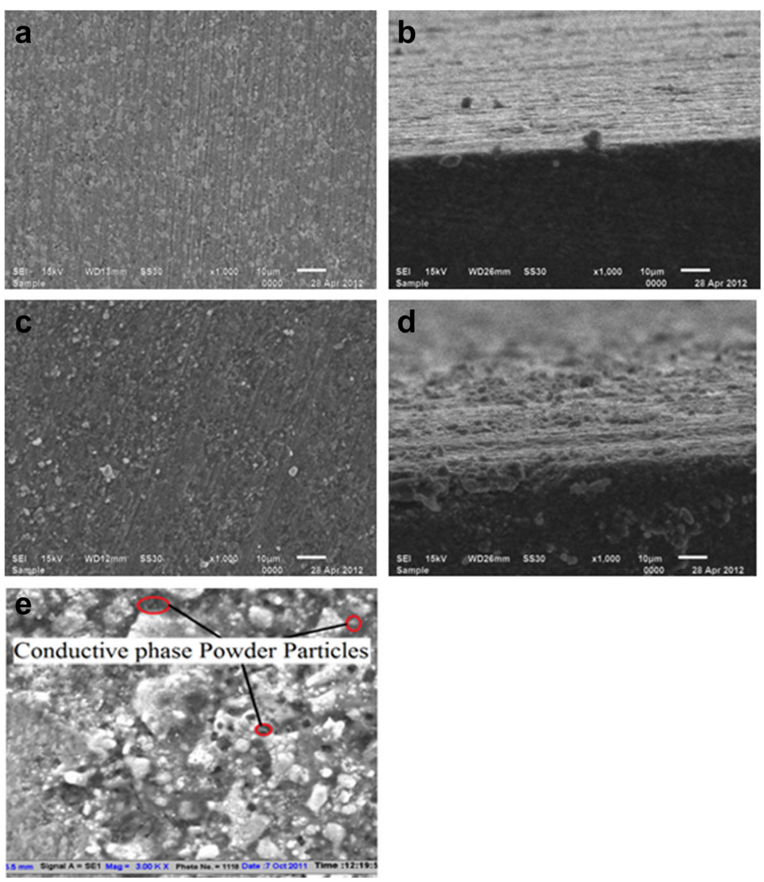

Fig. 13 SEM micrographs showing effect of PMEDG at various input process parameters. **a**-**b** P_w-08, DC-0.56, T_{on}-300 V_t-0.06, V_w-2.355. **c**-**d** P_w-40, DC-0.56, T_{on}-300 V_t-0.06, V_w-2.355. **e** SEMmicrograph showing presence of SiC powder particles after PMEDG of alumina ceramic

the nonlinear nature. The obtained results has been validated by conducting experiment and are presented in Table 7.

Surface integrity

The outcome of data analysis and its discussion in previous sections revealed that the PMEDG process is governed prominently by powder concentration, discharge energy and grinding action. The discharge energy is a function of discharge voltage, discharge current and pulse on time/Duty ratio. The increase in discharge current and pulse on time increases the discharge energy. The amount of discharge energy transferred from tool to workpiece is disintegrated into several increments due to conductive phase powders present in the dielectric medium and simultaneous grinding action supports the removal/sweeping of the recast prior to its solidification. Figure 13a-b shows the scanning electron micrographs obtained when workpiece was acted with low discharge energies, and the EDG action remained prominent (softened material was removed by the melting and abrasion). The soft recast material being swept along the work surface resulted in good surface finish as shown in Fig. 13b. The high MRR with considerably low surface roughness may be attributed to the grinding action of abrasives on the softened material and/or recast layer. Figure 13c-d shows the effect of increased powder concentration. The increased powder concentration increased disintegration of discharges. This led to the formation of more number of craters per discharge. The craters so formed were partially filled by molten material/recast. The grinding action in the case was unable to remove the complete molten material due increase in the inter-electrode gap (Chow et al. 2008; Chow et al. 2000; Kansal et al. 2007b), which seized the grinding action, hence a huge re-solidified layer was deposited on the surface, giving very rough surface. The surface characterization of these samples indicated the presence of small pit marks, grinding marks and deposited recast layer.

Further, The MRR obtained by PMEDG process was found to be 3 to 10 times higher than the EDG (Satyarthi and Pandey 2016). It was found that the SR obtained by PMEDG was 2 – 4 times higher than EDG but lower than EDM process (Satyarthi and Pandey 2012, 2013a).

Conclusions

In the present work PMEDG processing of Al_2O_3–SiC_w–TiC has been successfully performed on the developed EDG setup. The results indicated that the selected input parameters and its interactions significantly influenced the MRR. The addition of powders in the dielectric significantly improved the MRR. The highest MRR obtained by PMEDG was 49.69 mg/min. The defects induced by EDM and conventional diamond grinding processes like heat affected zone, surface and subsurface cracks were not observed on PMEDG processed surfaces. The surface produced by PMEDG was obtained free from defects like surface/subsurface cracks, heat affected zone and micro-pores although recast layer and big size craters were found on the surface in certain processing conditions. It has been established that the PMEDG process is a better option for processing extremely hard, brittle and fragile Al_2O_3–SiC_w–TiC ceramic material as preliminary operation before applying EDG process to achieve increased MRR.

Highlights

- The machining of Al_2O_3–SiC_w–TiC ceramic has been successfully performed on the developed PMEDG setup.
- The MRR obtained by PMEDG process was found to be 3 to 10 times higher than the EDG and the highest MRR obtained was 49.26 mg/min.
- The surface roughness achieved by PMEDG was 2 to 4 times higher than EDG.
- PMEDG process may be used before EDG process to obtain high MRR.
- The defects induced by EDM and conventional diamond grinding processes were not observed on PMEDG processed surfaces.

Authors' contributions

The present work is an attempt to fill the research gap in the field of Powder mixed EDG, which has not been witnessed (attempted) so far in my knowledge. The following are the key observations noticed by the author's. The machining of Al_2O_3–SiC_w–TiC ceramic has been successfully performed on the developed PMEDG setup. The MRR obtained by PMEDG process was found to be 3 to 10 times higher than the EDG (as compared with published work of author's) and the highest MRR obtained was 49.26 mg/min. The surface roughness achieved by PMEDG was 2 to 4 times higher than EDG (as compared with published work of author's). PMEDG process may be used before EDG process to obtain high MRR. The defects induced by EDM and conventional diamond grinding processes were not observed on PMEDG processed surfaces (as compared with published work of author's). Both authors read and approved the final manuscript.

Competing interests

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