An investigation on electro discharge micro-drilling of SiC-20% BN composite

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Abstract: SiC-20% BN composite is a newly developed material having potential applications in several engineering industries. Machining of such type of advanced ceramic composites by conventional methods is not only difficult to perform but it is also very costly. Electro discharge machining is seen as a potential process for such materials because it does not exert any mechanical force on tool and work piece and it is also independent of hardness of the work piece. In the present research the characteristic features of electro discharge micro-drilling of SiC-20% BN composite are studied through experimental investigation. The measured responses are material removal rate (MRR), tool wear rate (TWR) and relative electrode wear (REW). The optimal parameter settings for the responses are determined with the help of a statistical analysis. SEM micrographs of the holes were taken to illustrate the material removal mechanism of the ceramic composite. In the present research study it has been proved that EDM is a potentially successful technique for micro-hole drilling in this new generation composite.

Keywords: SiC-20BN; electrical discharge machining; EDM; micro hole; material removal rate; MRR; tool wear rate; TWR; relative electrode wear; REW.

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1 Introduction

Silicon carbide (SiC) has been considered as an important structural ceramic due to its excellent high temperature strength, good Young's modulus, high hardness, chemical inertness and relatively good oxidation resistance (Deason et al., 2005). Hence in recent years, it has been widely used in many fields, such as high-temperature structural applications in heat engines, heat exchangers, nozzles, space borne mirrors in the automotive and aerospace industries, precision bearings, cutting tools and seal parts in machinery industries and so on (Akira, 2008). In general, these engineering components have complex shapes and hence require machining of sintered SiC ceramics. However, it is difficult to machine sintered SiC ceramics due to their beneficial properties such as high rigidity and superior wear resistance, etc. Diamond tools are commonly used for machining of SiC ceramics, but the cost is very high due to the low removal rates, expensive diamond grinding wheels and tools (Gopal and Rao, 2002; Yin et al., 2004). In addition to that their thermal shock resistance is still insufficient for wider applications. Recently, a number of researchers have shown that the thermal shock resistance of ceramic materials such as alumina, SiC, silicon nitride and sialon can be significantly enhanced by the addition of boron nitride (BN) (Sinclair and Simmons, 1987). Valentine et al. (1986) found that the thermal shock resistance could be increased from 314°C for SiC to 526°C for SiC with 25% BN. In addition to that the thermal conductivity also increases by incorporation of BN into SiC. Therefore, these SiC-BN composites are generally designed for high temperature structural applications.

Electrical discharge machining (EDM) is a non-traditional machining process removing material by a succession of repeated electrical discharges between an electrode and a workpiece in a dielectric fluid and it has been employed to machine advanced engineering materials. However, ceramic composites are difficult to machine by EDM, as their electrical conductivity is low due to the electrical insulating property of the ceramic phase. Yan and Wang (1999, 2000) investigated the machining characteristics of Al_2O_3 composites using rotary electro discharge machining with tube electrode and found that peak current has the most significant effect on material removal rate (MMR). The feasibility of machining TiN-Si_3N_4 composites by micro-EDM method was investigated by Liu and Huang (2000, 2003) through incorporation of conducting toughening phases. It was reported that higher working voltage and current, as well as higher content of TiN resulted in greater MMR from the work piece material (Liu, 2003). The material removal mechanisms of ZrO_2-based, Si_3N_4-based and Al_2O_3-based ceramic materials, in addition to electrical conductive phases like TiN and TiCN, have been studied by Lauwers et al. (2004) with help of the analyses of the debris, the surface and sub-surface quality. It has been revealed that besides the typical EDM material removal mechanisms, such as melting, evaporation and spalling, other mechanisms such as oxidation and dissolution of the base material can also occur.

The present research exhibits the characteristic features of electro discharge machining of SiC-20% BN composite through Taguchi L_9 orthogonal array (Bagchi, 1993) based on experimental study. The measured responses are MMR, tool wear rate (TWR) and relative electrode wear (REW). The optimal parameter settings for the responses are determined with the help of the statistical analysis. Verification experiments have been carried out with the optimal parameter settings for each response factor.

2 Experimental details

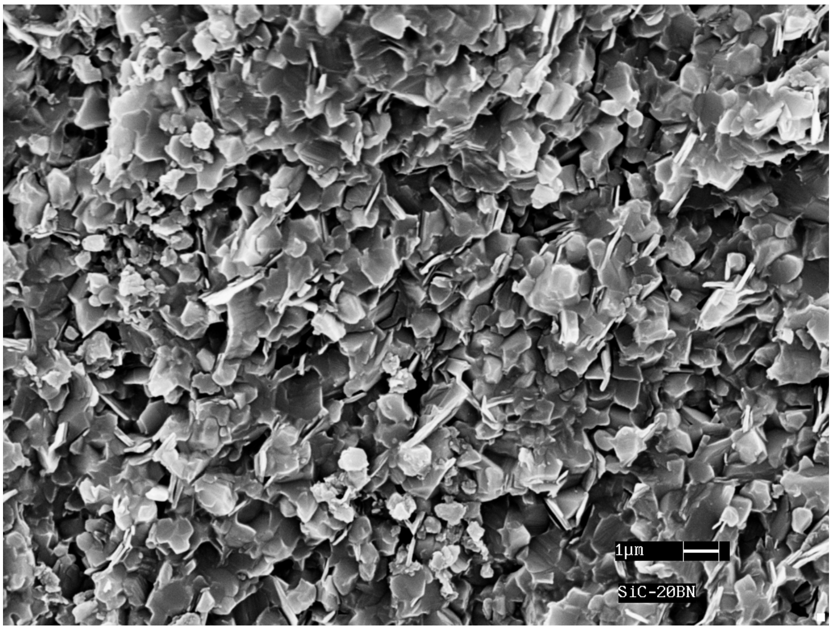
2.1 Experimental set up

An 'Electra' EMS 5535 R-50 ZNC, series 2000, die sinking EDM machine was used for the experiments. Copper was used as tool material. During machining, the polarity of the electrode was kept negative and that of the workpiece positive. A 'Mettler Toledo' digital weighing machine, type AG285, was used for measuring the weight of the workpiece and electrode before and after each machining operation for the purpose of calculating MRR, TWR and REW. A 'Mitutoyo' digimatic micrometer of type IP65 – No. 293-240, was used for measuring the thickness of the workpiece and the diameter of the tool before and after each machining operation. An 'Olympus' measuring microscope of type STM6; was used for measuring the diameters of the drilled holes after the machining operations. SEM photographs have been taken by a scanning electron microscope (maker Jeol Company, model no. JSM 6700F) along with the EDX analysis.

Table 1 Physical and mechanical properties of SiC-20BN composite

Material	*Density (gm/cc)*	*Yield stress (MPa)*	*Young's Modulus (GPa)*	*Micro hardness (HV_2)*
SiC-20BN	3.098	411.3 ± 29	245.2 ± 15.5	1,309 ± 51

Figure 1 Fracture surface of sintered SiC-BN composite with homogeneously distributed BN particles



2.2 Preparation of SiC-20BN composite

The starting powder used for the composites was commercially available SiC powder (carborundum universal). Ammonium biborate hydrate ($NH_4HB_4O_7$ $3H_2O$) was used as BN precursor due to its interior nitrogen source which would come out during its thermal decomposition. The BN content was adjusted to 20 vol% by adding the stoichiometric amount of ammonium biborate hydrate. The powders were mixed by attrition milling in an alumina container with alumina ball for 8 hrs using ethanol as a liquid medium. The milled powders were dried and were nitrided at 850 °C in NH_3 gas using a tube furnace for 15 hrs to obtain BN-SiC composites. The composite powders were reheated at 1,750°C in N_2 atmosphere for two hours to eliminate residual oxygen and improve crystallinity of BN. The composite powders were ball-milled with sintering aids (7 wt% Al_2O_3 and 3 wt% Y_2O_3) in ethanol for 20 hrs. The milled powders were dried and were placed in a graphite die for uniaxial hot pressing. Hot pressing was performed at 1860 °C for one hour under a pressure of 30 MPa under a nitrogen gas atmosphere. The measured physical and mechanical properties of the composite are listed in Table 1. Figure 1 shows the homogeneously distribution of BN in sintered SiC-BN composite. There is no agglomeration of BN observed.

2.3 Planning of experiments

The process parameters taken for consideration were pulse-on time, peak current, duty cycle and gap voltage, while the measured responses were MMR, electrode wear rate. Electrode wear ratio was calculated from the obtained data. Before finalising the levels of input factors, a number of trial experiments were carried out to study the behaviour of the material under various pulse-on time (T_{on}) and peak current (I_p). After some initial trial experimental runs, a satisfactory working range for the input parameters was established. The planning of experiment for the electro discharge machining of SiC-20BN composite was based on Taguchi L_9 orthogonal array. A total number of nine experiments have been performed along with three verification experiments. The input factors were peak current (I_p), pulse-on time (T_{on}), duty cycle (t) and gap voltage (V_g). Different levels of the input factors are shown in Table 2. The measured responses were MRR, TWR, REW was calculated as:

$$\frac{TWR}{MRR} \times 100\%$$

Verification experiments were carried out with the four optimal parameter settings for each response factors. The prediction error variance and confidence limits were calculated as indicated by Phadke (1989).

Table 2 Different levels of control parameters

Machining parameters	*Units*	*Level-1*	*Level-2*	*Level-3*
Peak current	Amp	1	3	5
Pulse-on time	μs	5	10	30
Duty cycle	%	36	53	66
Gap voltage	Volt	55	75	95

3 Analysis of experimental results

Taguchi L_9 orthogonal array is given in Table 3. A statistical analysis is carried out on each of the response factors. The analysis consists of calculation of signal to noise ratio value and analysis of variance (ANOVA) test for each response factor. The signal to noise ratios (S/N ratios) is calculated using the following equations [1, 2]. If the diminishing characteristic of response Y (i.e., TWR, REW) results in improved process performance, the formula will be:

$$S/N(\theta) = -10\log_{10}\left[\frac{\sum_{i=1}^{n} Y_i^2}{n}\right] \tag{1}$$

If the larger the characteristic Y (i.e., MRR), the better it is, then:

$$S/N(\theta) = -10\log_{10}\left[\frac{\sum_{i=1}^{n} \frac{1}{Y_i^2}}{n}\right] \tag{2}$$

where

n no. of replications.

Table 3 Taguchi L9 orthogonal array

Exp. no.	*Input factors*			
	Peak current (Ip) (Amp)	*Pulse on time (T_{on}) (μs)*	*Duty cycle (t) (%)*	*Gap voltage (V_g) (Volt)*
1	1	5	36	55
2	1	10	53	75
3	1	30	66	95
4	3	5	53	95
5	3	10	66	55
6	3	30	36	75
7	5	5	66	75
8	5	10	36	95
9	5	30	53	55

3.1 Influence of control parameters on MRR

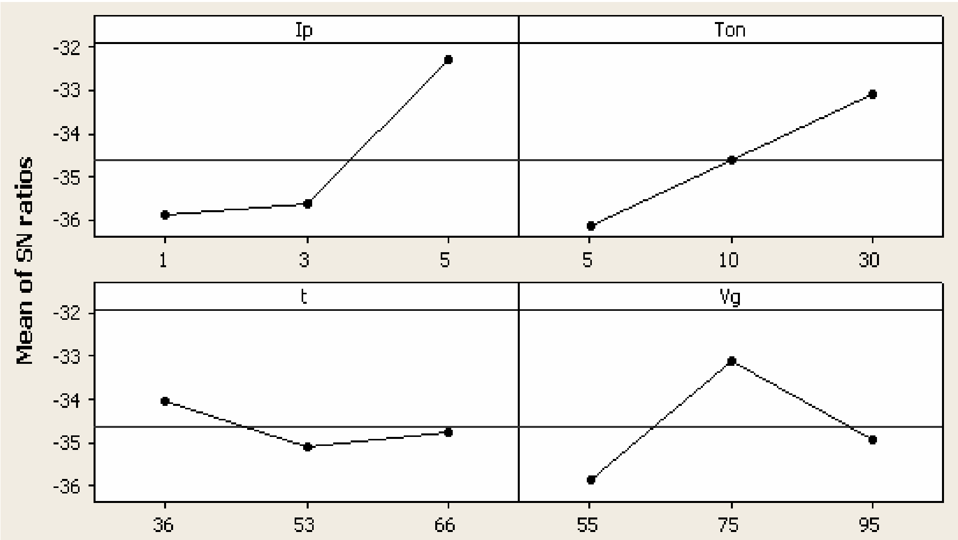
Table 4 represents the F-value and percentage contribution of different input factors on the responses as obtained by ANOVA. From Table 4, it is noticed that factor peak current (Ip), pulse on-time (T_{on}) and gap voltage (V_g) have the largest contribution, i.e., 47.27%, 26.95% and 22.47% respectively, for the MMR. Factor duty cycle (t) has much less contribution for MRR, 3.31%. Larger the contribution of a particular factor for a particular response, higher is the ability of that factor to influence the response. So peak current (Ip), pulse on-time (T_{on}) and gap voltage (Vg) have the maximum effect on MMR whereas duty cycle (t) have less effect on it.

Table 4 F-value and % contribution of different factors on responses as obtained by ANOVA

Input parameters	*Measured responses*					
	MRR		*TWR*		*REW*	
	F-value	*% Contribution*	*F-value*	*% Contribution*	*F-value*	*% Contribution*
Peak current(I_p)	14.27	47.27	8.29	26.91	8.18	64.04
Pulse on time (T_{on})	8.14	26.95	17.55	57.01	2.24	17.52
Duty cycle (t)	1	3.31	3.95	12.84	1.36	10.61
Gap voltage (V_g)	6.79	22.47	1	3.24	1	7.83

For MRR, the calculation of S/N ratio follows 'larger the better' model. S/N ratio graph for MRR has an increasing trend with increase of peak current (I_p) and pulse on-time (T_{on}) as depicted in Figure 2. So by increasing the peak current (I_p) and pulse on-time (T_{on}), high MRR can be achieved. With increase of gap voltage (V_g) at first the MRR increases and then it decreases. Duty cycle (t) have less significant effect on MRR. For higher peak current value and the pulse on-time, the spark energy is increased causing greater MMR. Increase in gap voltage causes greater speed of bombarding electron from the electrode to the workpiece, resulting in higher MMR. In Figure 2, the S/N ratio graph indicates that at low gap voltage (V_g), MRR is higher; it reaches an optimal value and then decreases with further increase of V_g. This phenomenon might be attributable to the transfer of energy during the discharging process. The low gap voltage may cause less melting and vaporisation from the surface of the workpiece, whereas the high gap voltage may cause an expansion of the plasma channel, thereby decreasing the energy density in the machining process. The material removal for the SiC phase is mainly due to chemical decomposition rather than melting and vaporisation. Sparking occurs between the particles of SiC and copper tool. But as BN is non-conductive, sparking does not take place between BN particles and those of copper tool. However, these BN particles are very fine and homogeneously distributed throughout the SiC matrix, therefore these BN particles are also decomposed along with SiC by thermal conduction. Another possibility is the case of agglomerated BN region (bigger size) where the BN is partially decomposed and it is removed by brittle fracture. It may also dislodge some material. Hence for BN phase, the material removal is due to thermal induced decomposition and in some cases by brittle fracture.

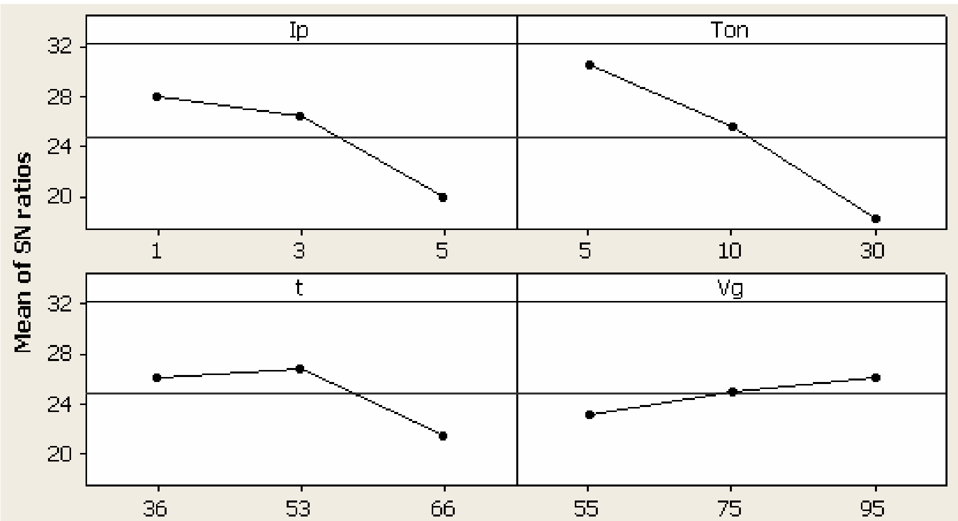
Figure 2 S/N ratio graph for MRR (see online version for colours)



3.2 *Effect of control parameters on TWR and REW*

Referring to Table 4, it is noticed that the factor pulse-on time (T_{on}) has the largest contribution to TWR, i.e., 57.01%. Factor peak current (I_p) has also some contribution for TWR, 26.91%. Factor duty cycle (t) has very less contribution, i.e., 12.84%. Factor gap voltage (V_g) has almost no influence on the total sum of squares, i.e., 3.24%. So pulse-on time (T_{on}) has the maximum effect on electrode wear rate and peak current (I_p) also has some influence on it whereas duty cycle (t) and gap voltage (V_g) have much less effect on TWR as evident from the S/N ratio graph (Figure 3).

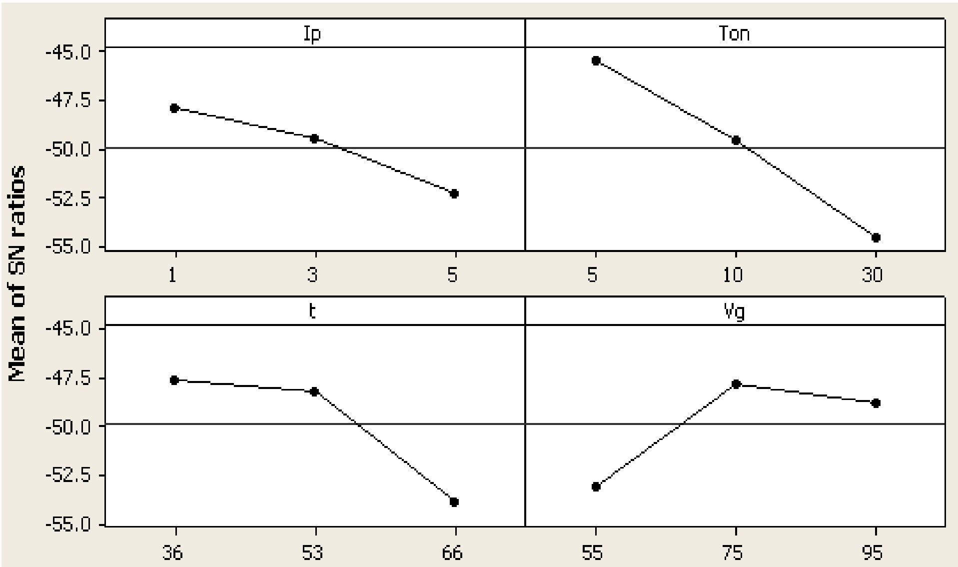
Figure 3 S/N ratio graph for TWR (see online version for colours)



For TWR, the calculation of S/N ratio follows 'smaller the better' model. From Figure 3, it is observed that S/N ratio graph for TWR has a decreasing trend with increase of peak current (Ip) and pulse-on time (Ton).

So by decreasing the pulse-on time (T_{on}) and peak current (I_p), lower TWR can be achieved. This phenomenon may be attributable to the tool electrode being made of copper which has a higher coefficient of thermal expansion than that of any other metal. Thus, the heat generated during machining was more; the rapid erosion of tool due to heat generation facilitated a reduction of tool material around the surface of the copper-made electrode for a higher pulse-on time. Duty cycle (t) and gap voltage (V_g) has less significant effect on TWR. The S/N ratio graph (Figure 4) for REW (following 'smaller the better' model) also in line with the observation for TWR. At higher V_g, MRR is high, while TWR is low; hence REW is low at higher gap voltage. Peak current and pulse-on time also have significant effect on REW with 64.04% and 17.52% contribution respectively. It is observed that at higher I_p and T_{on}, TWR is less; hence REW ratio comes to be lower at high value of I_p and T_{on}.

Figure 4 S/N ratio graph for electrode wear ratio (see online version for colours)



4 Verification experiments and analysis of Taguchi-based optimisation model

After determining the optimum conditions and predicting the response under these conditions, experiments were conducted with optimum parameter settings and the observed value of S/N ratio is compared with the predicted value. There are four optimum parameter settings corresponding to each of the three response factors. The combination of input factor levels, for the optimum settings, is given in Table 5.

Table 5 Optimal parameter settings of input factors

Physical requirement	*Optimal combinations*			
	I_p	T_{on}	t	V_g
Maximum MRR	5	30	36	75
Minimum TWR	1	5	53	95
Minimum REW	1	5	36	75

Using these optimum parameter settings, three verification experiments have been carried out. All response parameters corresponding to optimum parameter settings are calculated on the basis of Taguchi model and compared with the experimental results. The values of prediction error variance and the corresponding two-standard-deviation confidence limits (2σ) are shown in Table 6.

Table 6 Prediction error variance and 2σ limit

Verf. exp. for	*Exp. result*	*Model prediction*	$Error = \lvert (Exp.\,S/N - Pred.\,S/N) \rvert$	*Prediction error variance* (σ^2)	$\pm$ *2σ Limits*
Max. MRR	0.01478	0.01684	1.1351	1.81	2.69
Min. EWR	0.0071	0.0062	1.1146	7.61	5.52
Min. REW	123	122	0.8203	0.81	1.80

The experimental and predicted values represent the specific values for the particular response factor mentioned in Table 5 for which the corresponding verification experiment has been carried out. From Table 6, it has been observed that the prediction errors for MRR, TWR, REW are within the confidence limits, i.e., $\pm$ 2σ limits. Hence, it may be concluded that the Taguchi model is valid for EDM of SiC-20BN composite.

5 Analysis of SEM images of drilled holes

Figure 5 exhibits the SEM images of the drilled hole and its peripheral view at the level setting of experiment number 3 and experiment number 5 respectively. It has been observed that, some material is dislodged. This dislodgement of material is due to separation of BN particles from SiC phase.

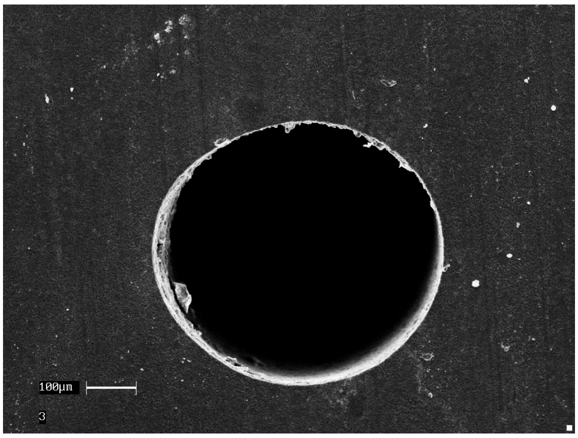
Due to spark discharge during electro discharge machining the SiC phase of SiC-20BN composite decomposes according to the following reaction:

$$SiC_{(s)} \rightarrow Si_{(g)} + C_{(s)}$$

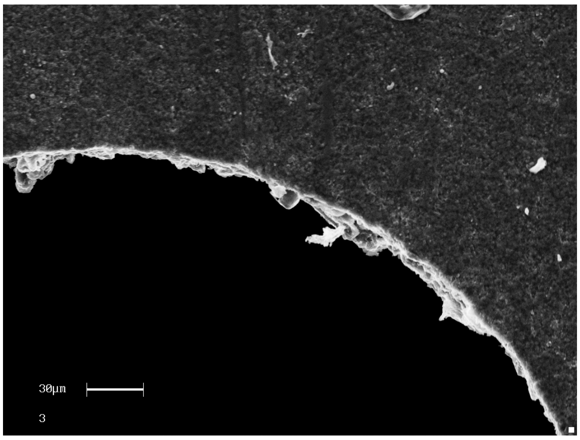
The carbon may then react further with the SiC and silicon gas to form other vapour species, such as SiC_2 and Si_2C. The BN phases also decompose according to the following reaction:

$$BN_{(s)} \rightarrow B_{(g)} + N_{(g)}$$

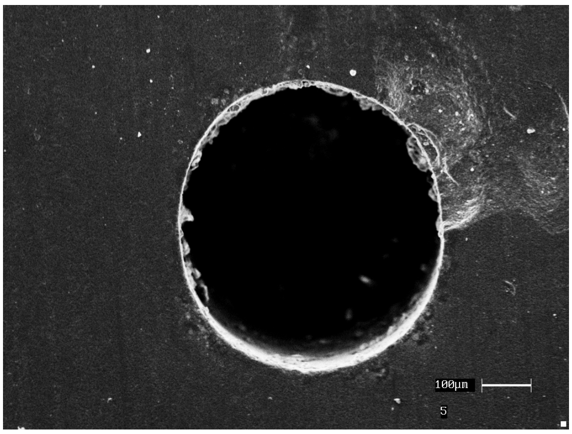
Figure 5 SEM view of the drilled hole and peripheral view of the hole machined [(a) and (b)] at the level setting of Exp. no. 3 and [(c) and (d)] at the level setting of Exp. no. 5



(a)

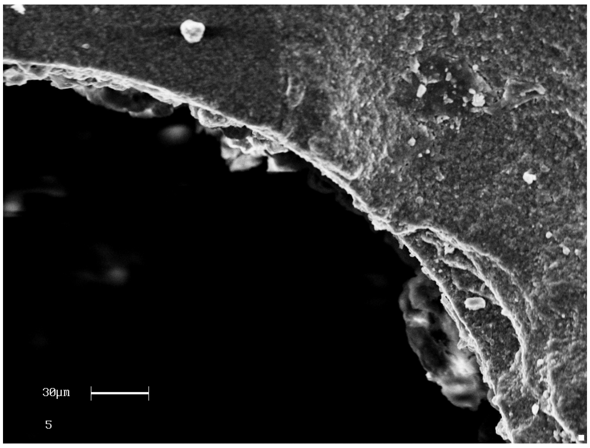


(b)



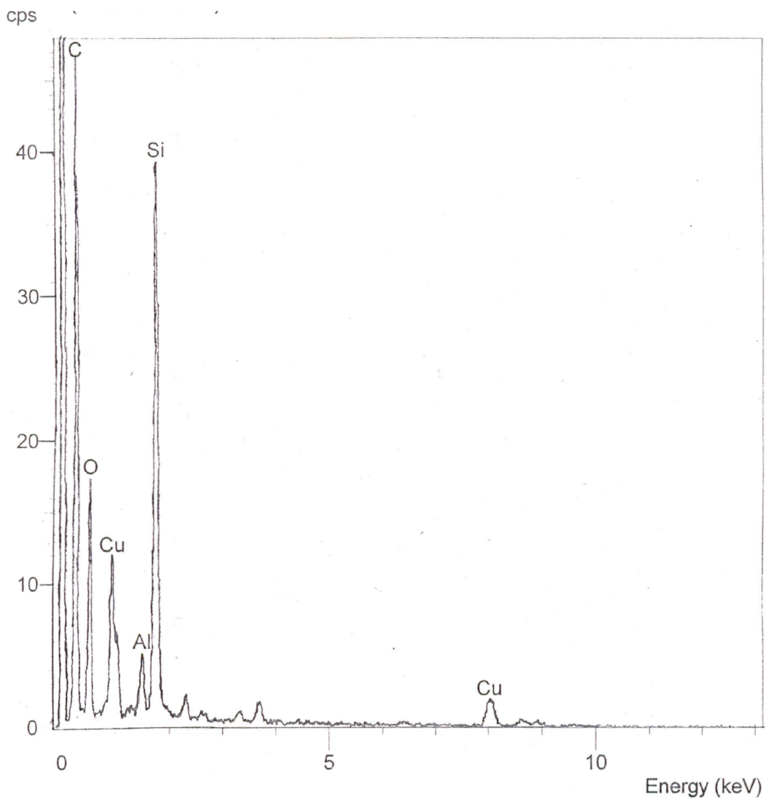
(c)

Figure 5 SEM view of the drilled hole and peripheral view of the hole machined [(a) and (b)] at the level setting of Exp. no. 3 and [(c) and (d)] at the level setting of Exp. no. 5 (continued)



(d)

Figure 6 EDX graph of the micro-hole generated on SiC-20BN C: carbon, O: oxygen, Al: aluminium, Si: silicon and Cu: copper



Electro discharge micro drilling (tool diameter of 0.5 mm) was conducted successfully in the present research study due to the chemical decomposition of SiC and BN phase. From the EDX analysis of the machined job, as shown in Figure 6, it has been found, the evidence of transfer of silicon, carbon and also some amount of copper from the tool electrode.

6 Conclusions

In the present research, electro discharge micro drilling of SiC-20BN ceramic composite has been carried out successfully. From the analysis of experimental results, it is observed that the MRR is mainly affected by peak current, pulse-on time and gap voltage. Duty cycle has least effect on it. MRR increases with increase in peak current and pulse-on time, while with increase in gap voltage, it reaches up to a maximum limit and then decreases. From the analysis of TWR data, it is observed that pulse-on time and peak current are the most important process parameters. The effect of duty cycle is less on TWR and gap voltage has almost no effect on it. TWR decreases with increase in pulse-on time and peak current. With increase in duty cycle, TWR at first increases and then decreases.

REW also decreases with increase in peak current, pulse-on time and duty cycle. With increase in gap voltage, at first it has an increasing and then decreasing trend. The optimum parameter setting for each response parameter has been decided using Taguchi technique and then verification experiments were conducted for each optimum parameter setting to check the validity of the proposed model. From the verification experiment it is observed that the prediction accuracy of the proposed model is quite good and hence the model is acceptable. Besides, SEM micrographs of the holes confirm the fact that BN particles are removed from matrix by brittle fracture during EDM in case of agglomeration of BN.

The verification experiments prove that the proposed additive model is adequate. The levels of parameters at verification experiments are optimum parameter settings for the corresponding response factors. From the present research study it is obvious that EDM is a potentially successful technique for micro-hole drilling in this new generation composite. The proposed guideline is extremely useful for optimum electro-discharge machining of this promising material in modern manufacturing industries.

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