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An experimental investigation of wire electrical discharge machining of hot-pressed boron carbide

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Abstract

The present work discusses the experimental study on wire-cut electric discharge machining of hot-pressed boron carbide. The effects of machining parameters, such as pulse on time (TON), peak current (IP), flushing pressure (FP) and spark voltage on material removal rate (MRR) and surface roughness (R_a) of the material, have been evaluated. These parameters are found to have an effect on the surface integrity of boron carbide machined samples. Wear rate of brass wire increases with rise in input energy in machining of hot-pressed boron carbide. The surfaces of machined samples were examined using scanning electron microscopy (SEM). The influence of machining parameters on mechanism of MRR and R_a was described. It was demonstrated that higher TON and peak current deteriorate the surface finish of boron carbide samples and result in the formation of large craters, debris and micro cracks. The generation of spherical particles was noticed and it was attributed to surface tension of molten material. Macro-ridges were also observed on the surface due to protrusion of molten material at higher discharge energy levels.

Keywords: Hot-pressed boron carbide; MRR; R_a; Wire electrical discharge machining

1. Introduction

Wire electrical discharge machining (WEDM) of hot-pressed boron carbide is considered in this work. Hot-pressed boron carbide possesses superior hardness, high Young's modulus and low density. Due to the excellent properties, it is a promising material as personnel body armour. This material is used to fabricatea variety of armourpanels to provide ballistic protection against different threats. This material cannot be processed by conventional metal cutting techniques like turning and milling due to its high hardness and strength levels [1,2]. Wire electrical discharge machining a type of unconventional machining process, is employed to accomplish the objective. WEDM plays significant role in cutting the electrically conductive materials to produce intricate profiles and complex shapes. The material removal takes place due to melting and evaporation of workpiece because of the heat produced by discharges. The wire traverse is regulated by numerically controlled system to accomplish the desired accuracy of components.

The most significant performance measures of WEDM are material removal rate (MRR) and surface roughness (R_a) of workpiece. Spark gap voltage, discharge current, pulse on-time, pulse off-time and dielectric flushing conditions are the machining parameters that influence the performance measures. Tosun et al. [1] investigated the effect of WEDM machining parameters on performance characteristics, i.e MRR, kerf width and R_a. An optimum combination of process parameters was derived for large MRR and small R_a by using analysis of variance (ANOVA). Poros et al. [2] made an attempt to develop a model to correlate the thermal properties of material and the efficiency of machining. Buckingham pi theorem was employed to establish the relationship between the variables used in the study. Tzeng et al. [3] studied the influences of cutting speed, depth of cut and feed rate on

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surface roughness using the Taguchi technique and grey relational analysis. In this study, an orthogonal array was applied to plan the experiments for optimizing the cutting operations with multiple response measures. Chiang et al. [4] carried out grey relational analysis to optimize the wire-EDM process with multiresponse characteristics such as MRR and R_a. The optimum process parameters were selected from the response graph obtained by grey relational grade. Kumar et al. [5] employed a grey relational methodology to optimize the input parameters of EDM, i.e., duty factor, pulse on-time and peak current to maximize MRR. The optimum process parameters were validated by confirmation experiments. Wang et al. [6] explored the possibility of removing a recast layer using etching by means of EDM. An L9 orthogonal array was selected to design the experiments for attaining the optimum process parameters. Somasekhar et al. [7] presented the modelling and optimization of micro-EDM using back propagation and genetic algorithms. The neural network model has been established and simulated using MATLAB. Lin et al. [8] attempted to improve the multiple response characteristics using Taguchi technique with grey relational analysis by optimizing the process parameters of EDM. Patel et al. [9] developed a surface roughness prediction model for electric discharge machining of Al_2O_3/SiC/TiC ceramic composite. This model optimized the machining variables to obtain high surface quality. Lin et al. [10] studied the effects of EDM parameters on material removal rate, electrode wear rate and surface roughness for ceramics (Al_2O_3+ 30% VolTiC). Machining parameters have been optimized for each performance measure by using Taguchi method.

The purpose of the present study is to examine the effects of machining parameters on material removal rate (MRR) and surface roughness (R_a) of hot-pressed boron carbide. The material removal rate (MRR) can be considered as the degree of production whereas surface roughness (R_a) represents the measure of surface quality. Based on the literature survey, several pilot experiments have been performed to select the process parameters influencing on performance characteristics. The chosen machining variables are pulse on-time, pulse off-time, peak current and spark voltage. The Taguchi technique is a dominant experimental planning tool that uses an efficient and orderly approach for obtaining the optimum process variables. An appropriate design of experiments (DOE) is selected to perform more precise and accurate experiments. In the present research, an L16 Taguchi standard orthogonal array was selected for the design of experiments [11]. Confirmation experiments were then conducted based on the Taguchi analysis. The surfaces of machined samples were examined using scanning electron microscopy (SEM). The influences of machining parameters on mechanism of MRR and R_a were described.

2. Experimental details

2.1. Material and methods

The experiments were performed using a CNC ULTRACUT WEDM (maker: Electronica Machine Tools Ltd). The wire cut electric discharge machine consists of a machine tool, a CNC pulse generator and a dielectric fluid supply unit. The tool consists of a main worktable, an auxiliary table and a wire drive mechanism [12]. CuZn37 brass wire with 0.25 mm in diameter was employed in the present trials. Wire travels through the workpiece from upper and lower wire guides. In wire-cut EDM process the spark is generated between continuous travelling wire and workpiece. Hot-pressed boron carbide blocks (100 mm × 100 mm × 5 mm thickness) were used. The strength of the material is 410 GPa, its hardness is 31 GPa, and the Young's modulus is 460 GPa. Machining performance was evaluated by MRR and SR.

The MRR was determined by equation

$$MRR(\mathrm{mm}^3/\mathrm{min}) = V_c \times b \times h \tag{1}$$

where V_c is the cutting rate; b is width of the cut; and h is the depth of the job (mm).

The surface roughness, usually expressed as R_a value in microns, was obtained by Taylor Hobson Surtronic 25 roughness checker.

2.2. Taguchi method: planning of experiments

To study the effects of machining parameters on the performance characteristics (MRR and R_a) under the optimal machining parameters, a specifically designed experimental procedure is required [13–16]. Based on the preliminary investigations, the input parameters chosen were pulse on-time (TON), peak current (IP) and spark voltage (SV). The working range of input parameters and the levels taken are shown in Table 1.

In this study, the Taguchi method, a powerful tool for parameter design of performance characteristics, was used to optimize the machining parameters for maximum metal removal rate, maximum gap current and minimum surface roughness in WEDM [1]. Two major tools used in this method are (i) S/N (signal/noise) ratio to measure the quality and (ii) orthogonal array to accommodate many factors affecting simultaneously to evaluate the machining performances. According to Taguchi quality design concept, an L16 orthogonal array table with 16 rows was chosen for the experiments (Table 2). The experimental observations are further transformed into a signal-to-noise (S/N) ratio by using ANOVA.

The analysis of variance (ANOVA) of S/N data (Tables 3(a) and 3(b)) is carried out to identify the significant variables and quantify their effects on the response characteristics. In the present study, all designs, plots and analysis were carried out using Minitab statistical software. There are several S/N ratios

Table 1
Input process parameters and their levels.

Parameters	Level 1	Level 2	Level 3	Level 4
TON/μs	0.65	0.7	0.75	0.8
IP/A	12	14	16	18
SV/V	10	15	20	25

Table 2
Experimental design using L16 orthogonal array.

Expt. No	TON	IP	SV	MRR/ $(mm^3 \cdot min^{-1})$	R_a/μm
1	0.65	12	10	0.182	1.76
2	0.65	14	15	0.269	1.94
3	0.65	16	20	0.316	2.61
4	0.65	18	25	0.435	2.85
5	0.70	12	15	0.279	1.98
6	0.70	14	10	0.315	2.12
7	0.70	16	25	0.427	2.81
8	0.70	18	20	0.528	2.93
9	0.75	12	20	0.296	2.09
10	0.75	14	25	0.328	2.34
11	0.75	16	10	0.493	3.09
12	0.75	18	15	0.542	3.57
13	0.80	12	25	0.475	3.34
14	0.80	14	20	0.538	3.61
15	0.80	16	15	0.557	3.68
16	0.80	18	10	0.576	3.76

Table 3
(a). Analysis of variance for MRR.

Source	DF	Seq SS	Adj MS	F	P
TON	3	59.62	19.884	13.63	0.004
IP	3	57.98	19.328	13.25	0.005
SV	3	3.644	1.215	0.83	0.523
Residual error	6	8.754	1.459		
Total	15	130.033			

Table 3
(b). Analysis of Variance for Surface roughness.

Source	DF	Seq SS	Adj MS	F	P
TON	3	38.463	12.82	17.05	0.002
IP	3	29.26	9.753	12.97	0.005
SV	3	1.465	0.488	0.65	0.612
Residual error	6	4.513	0.752		
Total	15	73.701			

available depending on the type of characteristics. The characteristic of which higher value represents better machining performance, such as MRR, is called 'higher is better, HB'. Inversely, the characteristic of which lower value represents better machining performance, such as surface roughness, is called 'lower is better, LB". Therefore, "HB" for the MRR and "LB'' for the R_a were selected for obtaining the optimum machining performance characteristics [17–23]. The confirmation test [19] is an essential step for validating the conclusions drawn from DOE with experimental results. The response characteristics of significant variables are shown in Table 4.

3. Results and discussion

Fig. 1 shows the effect of peak current on MRR for various values of TON of 0.65 μs, 0.7 μs, 0.75 μs and 0.8 μs. It can be seen from Fig. 2 that the MRR value tends to increase with the higher TON and peak current levels. MRR is directly proportional to the power supplied during TON. It is observed that the TON and peak current have strong effects on MRR. It is suggested to apply TON of 0.8μs and peak current of 18 A, respectively, for achieving maximum MRR. At low input power, a small amount of thermal energy is produced, and a significant portion of thermal energy is absorbed by the surroundings. This keeps available energy less. But the rise in input power generates an intense discharge, which impacts the surface of the workpiece and causes more molten material to be driven out of the crater. Flushing pressure (FP) has a significant influence on MRR. Higher MRR can be achieved by supplying dielectric fluid at low velocity in the spark gap. This enhances an improvement in efficiency and thus increases MRR. Higher FP hinders the creation of ionized bridges across the gap, which would reduce spark energy and diminish MRR.

Increase in TON from 0.65 to 0.8 μs resulted in the formation of larger craters on the machined surface. This is reason for the increase in R_a with input power and TON. It is recommended to use TON of 0.65μs and IP of 12 A, respectively, for obtaining minimum R_a. The thermal power generates the high temperatures and causes the melting and vaporization of the material. Figs. 3 and 4 demonstrate R_a in function of the parameters of TON and peak current. The data indicates that R_a decreases by decreasing TON and peak current values. The influence of spark voltage on response characteristics is shown in Fig. 5, for TON of 0.85 μs, TON of 32 μsec and peak current of 16 A. The influence of spark voltage on surface roughness (R_a) is illustrated in Fig. 6. The plot exhibits a trend of increase from 1.26 to 2.35 μm. MRR is found to increase with spark voltage up to certain range and then it decreases at higher spark voltage due to widening of discharge gap. Fig. 3 depicts the effect of spark voltage on R_a. The R_a enhances with the raise in TON. With longer period of spark duration, the number of discharges increases, resulting in the wider craters. Hence, the surface finish will be rougher. When spark gap voltage is increased, the discharge gap gets widened, resulting in better surface accuracy due to stable machining. The influence of wire tension is not very significant.

The surfaces of machined samples were examined using scanning electron microscope (SEM). It is observed from SEM micrographs (Figs. 7 and 8) that the machined surfaces contain spherical modules, craters, pochmarks and microcracks. The

Table 4
Results of the confirmation experiments.

Performance responses	Optimum set of parameters	Predicted confidence intervals at 95% confidence interval	Actual value
Material removal rate/$(mm^3 \cdot min^{-1})$	TON (4), IP (4) and SV (1)	$0.562 < \mu_{CR} < 0.581$	0.578
Surface roughness/μm	TON (1),IP (1) and SV (1)	$1.63 < \mu_{CR} < 1.84$	1.53

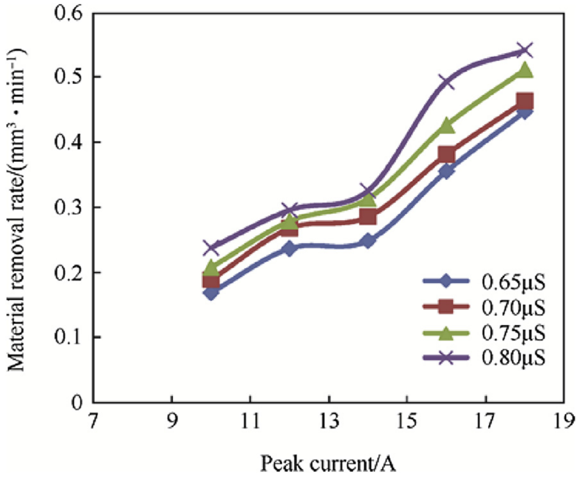

Fig. 1. Effect of peak current on Material removal rate.

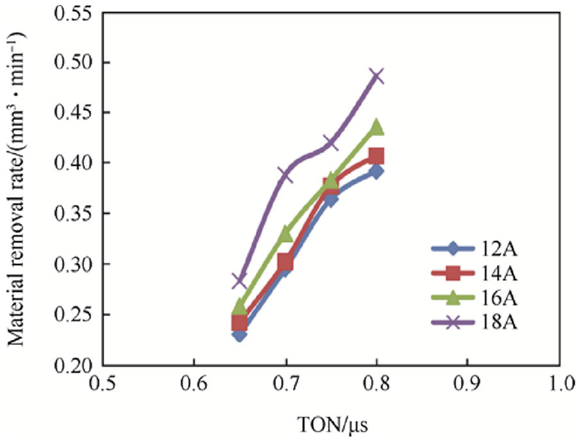

Fig. 2. Effect of pulse on time on Material removal rate.

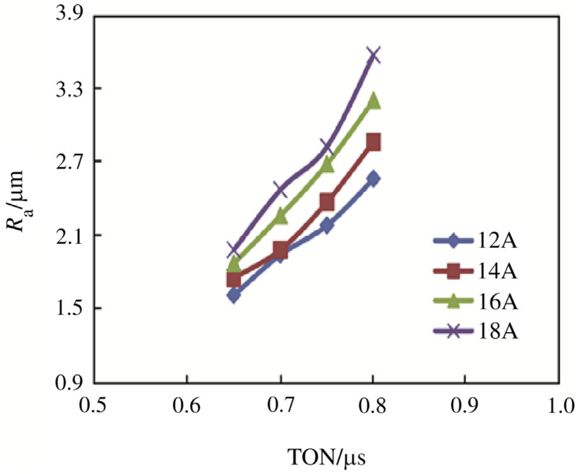

Fig. 4. Effect of pulse on time on surface roughness.

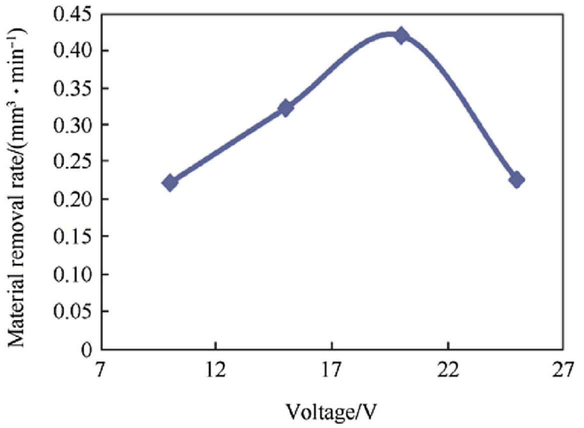

Fig. 5. Effect of voltage on material removal rate.

TON (0.8 μs) and peak current (18 A) were observed as the most significant parameters affecting the surface properties. The increase in TON resulted in the formation of craters on the surface. These craters were developed due to a succession of sparks. Small portion of the melted material generated by the electric discharge was removed by the dielectric fluid (Fig. 11). The generation of spherical particles was noticed and it was attributed to the surface tension of molten material. Macro-ridges were also observed on the surface due to the protrusion of molten material (Fig. 10). Fig. 4 demonstrates that fewer numbers of craters were formed at peak current (12 A) and TON (0.65 μs). Due to low peak current and TON,

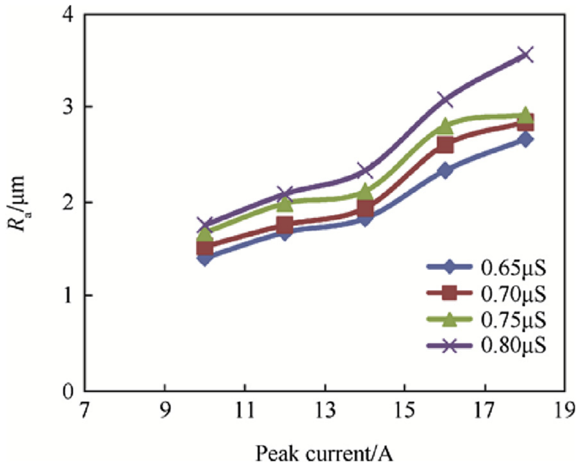

Fig. 3. Effect of peak current on surface roughness.

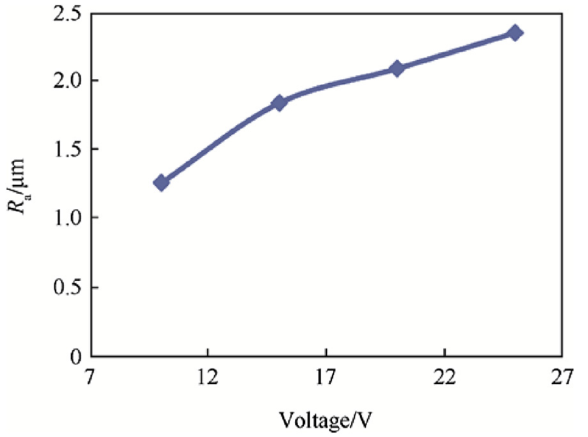

Fig. 6. Effect of voltage on surface roughness.

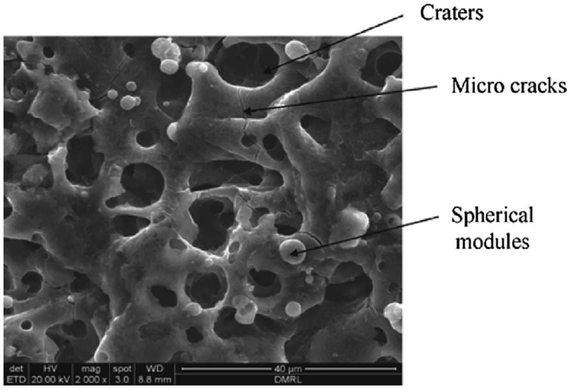

Fig. 7. SEM micrographs observed at TON = 0.8 μs and peak current = 18 A.

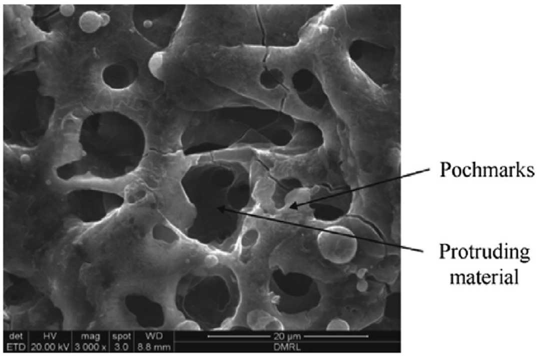

Fig. 8. SEM micrographs observed at TON = 0.8 μs and peak current = 18 A.

the machined surface is bombarded with fewer energy sparks. The crack formation is mainly attributed to the fast heating and cooling of the machined surface by dielectric fluid. The uneven heating and cooling caused the development of stresses, which leads to crack formation (Fig. 9). At a large current, a stronger discharge generates more heat energy. By virtue of the size of workpiece, some amount of heat is absorbed by it. The remaining portion of energy is accumulated at the wire, resulting in higher wear rate. This leads to frequent wire breakages. The wire breakage occurs due to the reduction of tensile strength of the brass wire through thermal softening. It is observed that the third levels of TON, peak current and spark voltage provide a maximum value of MRR. It demonstrates that the first levels of TON, peak current and spark voltage result in the minimum value of surface roughness.

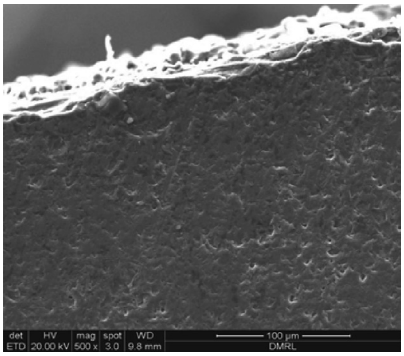

Fig. 10. SEM micrographs observed at higher TON = 0.8 μs and peak current = 18 A.

4. Conclusions

The significance of machining variables of WEDM on MRR and R_a of hot-pressed boron carbide has been studied. The effects of machining variables on the mechanism of MRR and surface roughness have been assessed by using scanning electron microscope. The conclusions are as follows:

1) It was demonstrated that higher TON and peak current deteriorated the surface finishes of boron carbide samples and resulted in the formation of large craters, debris and micro cracks.
2) The high discharge energy caused more frequent melting explosion, leading to the formation of a deep crater on the machined surface.
3) The residuals of spherical nodules in free or compound form were observed near the heat affected zone. These spherical nodules were formed due to discharge heat and rapid quenching.
4) Wear rate of brass wire increases with increase in input energy, leading to wire breakage.

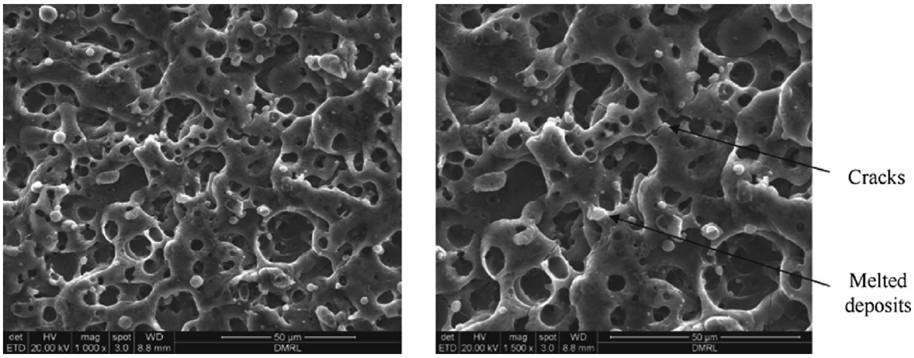

Fig. 9. SEM micrographs observed at TON = 0.7 μs and peak current = 16 A.

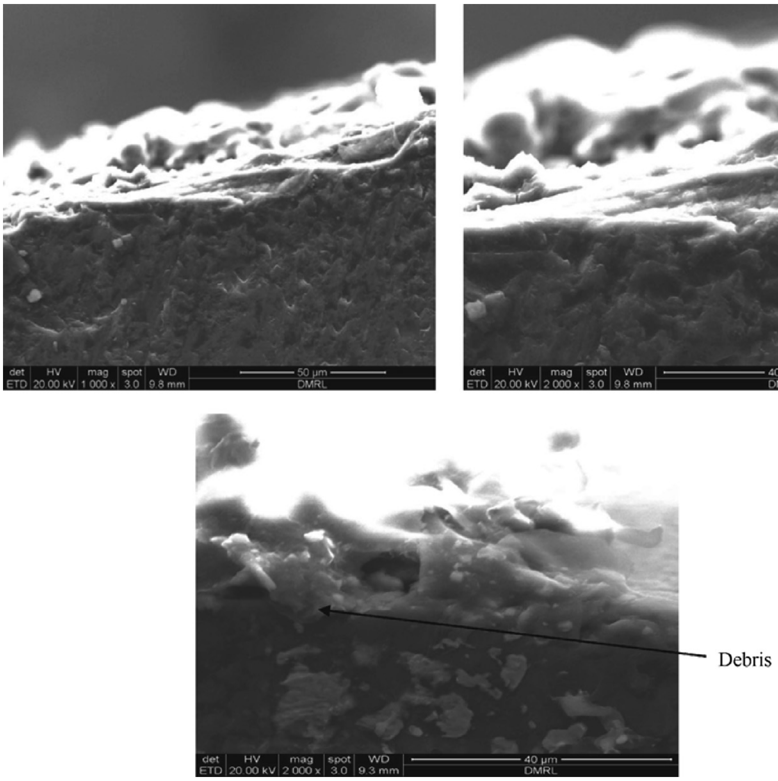

Fig. 11. SEM micrographs observed at higher TON = 0.75 µs and peak current = 16 A.

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