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Application of electrical discharge machining for machining of semi-conductor materials

M. Zohoor* **and A.R. Hosseinali Beigi**

Faculty of Mechanical Engineering, K.N. Toosi University of Technology, Pardis Street, Mollasadra Ave., Vanak Square, Tehran, P.O. Box 19395-1999, Iran.

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Surface-roughness;
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Abstract. In recent years, the research work in material science has encouraged the development of advanced ceramic materials. Boron carbide has many applications in industries for manufacturing of products such as water jet nozzle and abrasive particles. In this paper several experimental tests have been conducted to study the effect of process parameters in machining of boron carbide "B4C" by using the electrical discharge machining process "EDM". The effect of voltage variation, current intensity, on-pulse and off-pulse durations on surface roughness (Ra) and Material Removal Rate (MRR) were studied simultaneously by utilizing the Design Of Experiment (DOE) technique. This research work indicated that the "EDM" process can be used to machine semi-conductor materials such as "B4C" successfully. In addition, it was found that, the quantity of material removal rate and the quality of workpart surface roughness could be affected by the variations of these process parameters. Finally, the experimental results obtained were compared with the published results reported by other scientist, and a good agreement was found between them.

1. Introduction

Non-conventional machining such as ultrasonic, laser beam and Electro-Discharge Machining (EDM) have several advantages over conventional methods for machining of novel materials such as B4C. These materials are used in aerospace and defense industries, automotive engineering, biological and nuclear fields [1]. EDM is an advanced technique that is usually used for machining very hard conductor materials which their machining is difficult or sometimes impossible by traditional methods. In this process, there is no direct contact between work-piece and tool (electrode). However, stiffness and hardness of work-piece have no effect on material removal rate [2,3].

Puertas and Luis [4] have studied the application of "EDM" for machining "WC-CO", "B4C" and "SiC" ceramics. They reported the effect of current intensity and on-pulse on machining the above ceramics. Riaz et al. [5] have examined the effect of current intensity, on-pulse, off-pulse and flushing pressure on surface roughness and material removal rate in "EDM" process, using "Al-Sicp-B4cp" and "Al-Sicp-Glass". Lee and Li [6] studied some "EDM" parameters such as voltage, type of electrode and electrode polarity in machining of tungsten carbide. They found that copper is the best electrode. Her and Weng [7] considered the effect of off-pulse, voltage, electrode polarity and the electrode rotating speed on surface roughness in semi-conductor "BaTiO3". They reported that the best smoothness is obtained when off-pulse is 1200 μs, voltage is 30 volts and electrode speed is 100 rpm. Lin

*. *Corresponding author. Tel.: +98 21 84063223; Fax: +98 21 88674748*
E-mail addresses: mzohoor@kntu.ac.ir and mehdizohoor@gmail.com (M. Zohoor)

et al. [8] have studied the electrical discharge energy in "EDM" and examined the machining and bending resistance of tungsten carbide. They concluded that by increasing the electrical discharge energy, the surface roughness and surface cracks of the work-part would be increased. Senthilkumar and Reddy [9] studied about electro discharge machining of steel and the effect of electrode material on Metal Removal Rate (MRR) and Tool Removal Rate (TRR). Results showed that copper composite with 40% boron carbide reinforcement exhibited better Metal Removal Rate (MRR) and Tool Removal Rate (TRR) compared to conventional copper electrode. Kibria et al. [10] investigated the effect of dielectric on micro-EDM characteristics such as Material Removal Rate (MRR), Tool Wear Rate (TWR), Overcut (OC), taperness and Machining Time (MT) during micro-machining of Ti-6Al-4V. The results showed that MRR and taperness were improved and TWR was reduced employing B4C powder than pure dielectric.

The main drawback of "EDM" for machining ceramic materials is the high electrical resistivity which usually lies between 100 and 300 Ωcm. To overcome this problem, electrical resistivity of ceramic material should be decreased by adding a conductor element to it [11]. Boron carbide (B4C) is a semi-conductor ceramic material. It is one of the hardest materials known, ranking third behind diamond and cubic boron nitride. It is the hardest material produced in tonnage quantities and originally was discovered in mid 19th century. Boron carbide is used to produce abrasive materials and make water jet nozzles. By increasing the temperature, the heat conduction of boron carbide is decreased, therefore, boron carbide shows low resistance to thermal shock [12,13].

In this paper several experimental test have been conducted to investigate the effect of process parameters in machining of "B4C" by using "EDM". The effect of voltage variation, current intensity, on-pulse and off-pulse durations on surface roughness and material removal rate were studied by using "DOE" full factorial technique. To verify this research work, the experimental results obtained were compared with the published results reported by Puertas and Luis [4] and a good agreement was found between them.

2. Experimental setup

In order to perform experimental tests, a setup for "EDM" process was designed. In this study, a Pishrane TehranEkram spark machine model 404H with iso-frequency and iso-pulse generator by a maximum current intensity equal to 50 amps was used. Also for measuring workpart surface roughness, a Mahr roughness tester model M300-RD18 was utilized. A cylindrical copper electrode with 6 mm in diameter with (8/93gr/cm^3) density was applied and gasoline was utilized as dielectric liquid. As the machining of boron carbide is performed at high spark and flash, spray flashing at the same time is not appropriate, because it leads to creation of flaming at the tool and workpiece; therefore, the workpart was submerged in a dielectric liquid.

3. Experimental work

3.1. Workpart specifications

To study the effect of process parameters in "EDM" process, boron carbide "B4C" was selected as a semiconductor material. The dimensions of workpart used in EDM process was 50 mm × 50 mm × 5 mm. B4C has excellent properties, such as low wear coefficient (2×10^{-14} m^2 N^{-1}), high melting point (2540°C), high hardness (30 GPa) [14], low density (2.50 g/cm^3) [15], high module of elasticity (450 GPa), high thermal conductivity (29 W/m.k), and high electrical conductivity ($2.6\times10^3\Omega^{-1}$.m^{-1}) [5].

3.2. Input data

To do the experimental work, four factors (parameters) have been used as variables in the EDM processes, which are input voltage, current intensity, on-pulse time and off-pulse time. Several experimental investigations were performed to find the optimum values for minimum and maximum quantities of process variables for machining of B4C. The ranges of variations for parameters are indicated in Table 1.

Quantities of the four parameters with respect to two levels with center points are given in Table 2.

Table 1. Arrangement of input data for experimental tests according to four factors.

Factors	Factor quantities		Unit
	Min.	Max.	
Voltage "V"	80	250	(V)
Current intensity "I"	0.5	10	(Amp.)
On-pulse "T_{on}"	8	15	(μs)
Off-pulse "T_{off}"	75	450	(μs)

Table 2. Input data for experimental tests according to "MINITAB" level classifications.

Factors	Level 1	Center point	Level 2	Unit
	-1	0	1	
Voltage "V"	80	110	250	(V)
Current intensity "I"	0.5	5	10	(Amp.)
On-pulse "T_{on}"	8	10	15	(μs)
Off-pulse "T_{off}"	75	225	450	(μs)

Table 3. Experimental results corresponding to matrix created by "MINITAB" software.

Test number	Input data				Output results		
	Voltage (v)	On-pulse (μs)	Current intensity (Amp.)	0ff-pulse (μs)	Surface roughness (μm)	Machining time (s)	Material removal rate mm^3/min
1	80	8	0.5	75	7.15	952	0.178
2	250	8	0.5	75	7.25	785	0.216
3	80	15	0.5	75	6.98	936	0.181
4	250	15	0.5	75	7.50	683	0.248
5	80	8	10	75	6.75	985	0.172
6	250	8	10	75	6.91	892	0.190
7	80	15	10	75	6.84	916	0.185
8	250	15	10	75	7.26	737	0.230
9	80	8	0.5	450	6.95	942	0.180
10	250	8	0.5	450	7.16	788	0.215
11	80	15	0.5	450	6.71	991	0.171
12	250	15	0.5	450	7.40	689	0.246
13	80	8	10	450	6.77	952	0.178
14	250	8	10	450	6.91	883	0.192
15	80	15	10	450	6.75	963	0.176
16	250	15	10	450	7.30	740	0.229
17	110	10	5	225	6.98	847	0.200
18	110	10	5	225	7.07	870	0.197
19	110	10	5	225	7.05	839	0.202
20	110	10	5	225	7.00	852	0.199

3.3. Output results

In this research work, the surface finish quantities were measured and material removal rate was calculated after each experiment. The results for 20 experimental tests presented in the forms of tables and diagrams are as follows:

1. The surface finish was measured in the form of average roughness (Ra) and recorded by a Mahr roughness tester model M300-RD18 as enumerated in Table 3.
2. Different methods were used for calculating material removal rates. In this study, the material removal rates was calculated by measuring the volume of removed material "B4C" and machining time. For each test, selected depth of tool in workpart was 0.1 mm, and it was fixed for each test. Machining time for each test was measured by machine timer.

Using the above mentioned information, the material removal volume from workpart was calculated by:

$$\text{MRR} = \frac{\frac{\pi . d^2}{4} \times h}{T} \text{mm}^3/\text{s}, \quad (1)$$

where $d = 0.6$ mm is the tool diameter; $h = 0.1$ mm is the depth of tool in workpart, and T is the machining time in seconds.

4. Design of experiments

With respect to the four process parameters (Table 1), it was very difficult to show the effect of all factors on output results simultaneously. According to the theory of probability and using the design of experiment for two levels with four factors (2^4), the number of experiments which could be carried out was 16 [16]. In order to increase the accuracy of the output results, four additional center points were added to the previous tests which causes that the number of experiments raised to 20.

Experimental test layout with input data and output results for 20 experiments using B4C as test material and EDM as a metal cutting process is shown in Table 3.

5. Results of analysis

5.1. Verification of results

To verify the accuracy of results obtained in this research work, the results reported by Puertas and

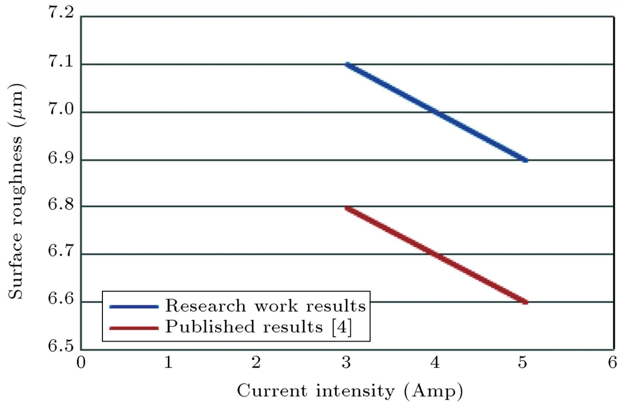

Figure 1. Surface roughness (μm) versus current intensity (Amp.).

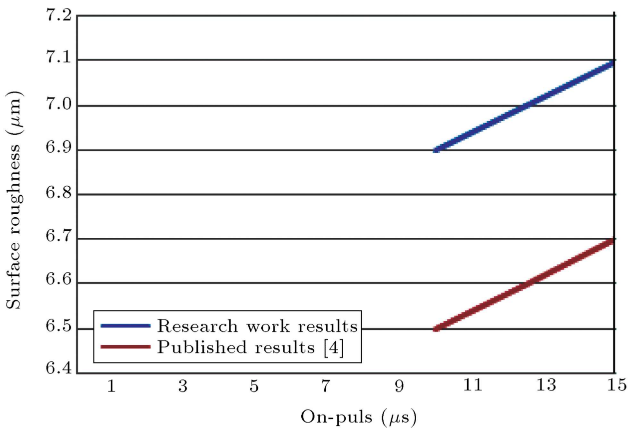

Figure 2. Surface roughness (μm) versus on-pulse time (μs).

Luis [4] have been compared with the corresponding results of this research work as follows.

In Figures 1 and 2, the effect of process parameters, such as current intensity and on-pulse duration, on the surface roughness are demonstrated, respectively.

By comparing the results provided by Puertas and Luis [4], and the results obtained in this article, as shown in Figures 1 and 2, it can be found that the surface roughness is directly proportional to the on-pulse time and current intensity. In both figures, the slope of curves is the same, so there is a strong agreement between the results obtained in this article and the results published by Puertas and Luis [4].

5.2. Surface roughness "Ra"

Variation of surface roughness versus of current intensity and off-pulse time is demonstrated in Figure 3. It was found that, by increasing the current intensity and off-pulse time, surface roughness is decreased linearly. According to Figure 3, slope of the left curve is sharper than the right curve.

In metal cutting by EDM, it can be concluded that in machining semi-conductor materials, the surface roughness is indirectly proportional to the current intensity, whereas, for the conductor materials, the surface roughness is directly proportional to the current intensity.

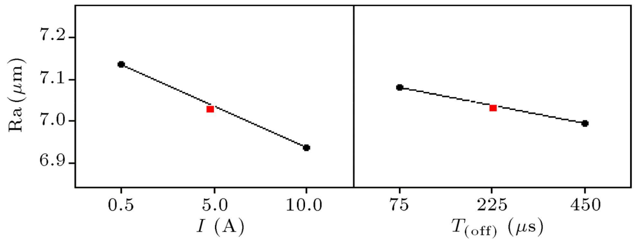

Figure 3. Surface roughness versus current intensity and off-pulse time.

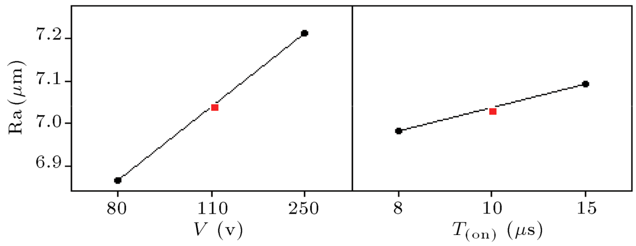

Figure 4. Surface roughness versus voltage and on-pulse time.

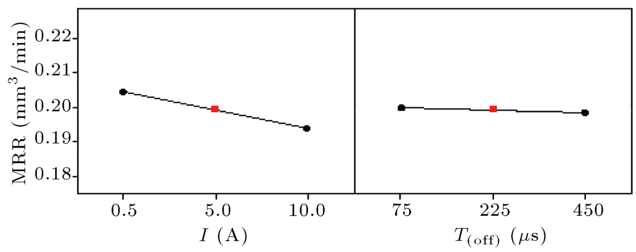

Figure 5. Material removal rate versus current intensity and off-pulse time.

Variation of surface roughness versus voltage and on-pulse time is depicted in Figure 4. It was considered that, by increasing the voltage and on-pulse time, surface roughness is increased linearly. According to Figure 4, slope of the left curve is sharper than the right curve.

5.3. Material Removal Rate (MRR)

Variation of material removal rate versus current intensity and off-pulse time is indicated in Figure 5. It was realized that, by increasing the current intensity, material removal rate is decreased linearly. But, by increasing the off-pulse time, the material removal rate remains constant throughout the process.

In application of EDM, it can be concluded that in machining semi-conductor materials, the material removal rate is indirectly proportional to current intensity. Whereas, in machining the conductor materials, material removal rate is directly proportional to the current intensity. This phenomenon is because of the fact that the electrical resistance of semi-conductor

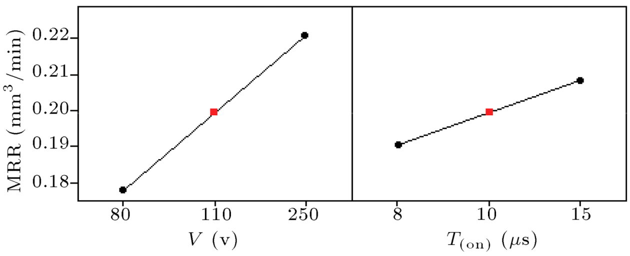

Figure 6. Material removal rate versus voltage and on-pulse time.

materials is higher than conductor one. The maximum current intensity which can be used for machining B4C is 10 amperes. If the current intensity rises to a higher specific value, the workpart would breakdown.

Variation of material removal rate versus voltage and on-pulse time is depicted in Figure 6. It was noted that, by increasing the voltage and on-pulse time, material removal rate is increased linearly. According to Figure 6, slope of the left curve is sharper than the right curve. With increasing on-pulse time to a higher specific value, the workpart would breakdown.

6. Conclusion

In this paper, several experimental tests have been conducted to study the effect of process parameters in machining of boron carbide "B4C" by using the electrical discharge machining method "EDM". The effects of voltage variation, current intensity, on-pulse and off-pulse durations on surface roughness (Ra) and Material Removal Rate (MRR) were studied and the following important points were concluded:

1. The results of this research work indicated that the "EDM" process can be used to machine semi-conductor materials such as "B4C" successfully.
2. It was found that the quantity of material removal rate and the quality of workpart surface roughness could be affected by the variation of process parameters such as: voltage, current intensity, on-pulse and off-pulse durations.
3. The experimental results obtained here, were compared with the published results reported by Puertas and Luis [4] and a good agreement was found between them.
4. In machining semi-conductor materials, the surface roughness is indirectly proportional to current intensity, whereas for the conductor materials, the surface roughness is directly proportional to the current intensity.
5. It was noticed that by increasing the voltage and on-pulse time, surface roughness is increased linearly.
6. In machining semi-conductor materials, the material removal rate is indirectly proportional to current intensity. This is while for the conductor materials, material removal rate is directly proportional to the current intensity. This phenomenon is because of the higher electrical resistance of semi-conductor materials compared to conductor one. The maximum current intensity which can be used for machining B4C is 10 amperes. If the current intensity rises to a higher specific value, the workpart would breakdown.
7. It was noted that by increasing the voltage and on-pulse time, material removal rate is increased linearly. With increasing on-pulse time to a higher specific value, the workpart would breakdown.

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Biographies

Mehdi Zohoor has been teaching and conducting research in Manufacturing and Mechanical Engineering as a full time University Faculty Member (Associate Professor), working in the Faculty of Mechanical Engineering at the K. N. Toosi University of Technology in Tehran, since 1993. He is also a part-time University Faculty Member working in the Department of Mechanical and Aerospace Engineering at the University of IAU, Science and Research Branch in Tehran, since 2003.

After graduating and obtaining a B.E. degree from the Bangalore University in India, he joined Tebed Textile Co., and worked as a Technical Manager and Vice Factory Manager for five years. Finally, he went to England and attended postgraduate courses in Machine Tool and Manufacturing Technology, and Manufacturing and Mechanical Engineering, respectively. Then, an MSc degree and a PhD degree were awarded to him by the Birmingham University. He has published numerous articles in scientific national, ISC and ISI Journals, and is the author of several papers in many national and international conferences.

He is the author of many books, and is the Chief Director of the Office of International Scientific Cooperation at the K. N. Toosi University of Technology. He is also a founding member of Society of Manufacturing Engineering of Iran.

Ali Reza Hosseinali Beigi was born in Rafsanjan, Iran, in 1985. He received a BSc degree in Manufacturing Engineering in 2008. An MSc degree was awarded to him by the K. N. Toosi University of Technology in 2011. He is interested to do research work in Machinability of Materials.