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Performance of cryogenically treated Cu and CuCrZr electrodes in an EDM process

A. Çetin[1], G. Çakır[2], K. Aslantaş[3], N. Uçak[4]*, A. Çiçek[4]

[1]*Sakarya Vocational School of Higher Education, Sakarya University, Sakarya, Turkey*
[2]*Cumayeri Vocational School of Higher Education, Düzce University, Düzce, Turkey*
[3]*Faculty of Technology, Department of Mechanical Engineering, Afyon Kocatepe University, Afyonkarahisar, Turkey*
[4]*Faculty of Engineering and Natural Sciences, Department of Mechanical Engineering, Ankara Yıldırım Beyazıt University, Turkey*

Abstract

In this study, the effects of cryogenic treatment (CT) on the performance of CuCrZr alloy and Cu electrodes in electro discharge machining (EDM) of AISI P20 tool steel were investigated experimentally. For this purpose, a group of electrodes were cryogenically treated at –140 °C for 30 min and then tempered at 175 °C for 1 h. The tool performance was evaluated in terms of electrode wear rate (EWR), material removal rate (MRR), and average surface roughness (*Ra*) of machined surfaces. The EDM tests were conducted at pulse currents of 4, 8, 12, and 16 A and pulse durations of 25 and 50 μs. Experimental results showed that treated electrodes were less worn than the untreated ones and the *Ra* values of machined surfaces decreased when cryo-treated electrodes were used. Also, it was observed that pulse current is the most effective parameter in the EDM process.

Key words: electro discharge machining (EDM), cryogenic treatment, wear rate, copper alloy

1. Introduction

Conventional cutting processes frequently are inadequate to machine difficult-to-cut materials. In addition to difficult-to-cut materials, more complex geometries, tighter tolerances, and higher surface quality are required in some industries such as aircraft, automotive, cutting tool, and mold making [1]. Therefore, new manufacturing methods called nontraditional manufacturing processes have been developed in past several decades. Unlike traditional methods, in nontraditional manufacturing methods, mechanical, thermal, chemical, electrical energies or their combinations are used instead of a cutting tool. One of these methods is EDM widely used in many industrial areas. In EDM, the material removal occurs between electrode and workpiece by using precisely controlled electric sparks within the dielectric liquid [2]. In an EDM process, there is no limitation on strength and hardness of the material. This nontraditional manufacturing process can be applied to all of the electrically conductive engineering materials [3]. Due to lots of advantages in machining of a variety of high strength and very complex components which are impossible to machine with traditional methods, EDM is a popular research topic for many researchers. To enhance its performance characteristics, EDM process needs improving in terms of better MRR, lesser EWR and improved surface quality [4]. Since EWR directly affects dimensional accuracy [5] and the manufacturing costs, an electrode is one of the most important components used in an EDM process [6] to improve process quality and to reduce machining costs. CT is a type of heat treatment processes implemented to improve tool performance and workpiece quality. It has various advantages such as providing more wear resistant cutting tools, the decrease in residual stresses and the retained austenite content, better fatigue strength, hardness, and thermal and electrical conductivity (EC) [7–9]. It has lots of applications in physics, chemistry, biology, medicine, and engineering [10]. There are some research works conducted to find its effects on an EDM process in the literature. Mathai et al. [11] studied the effects of CT on electrode materials during EDM. They reported that wear rate of electrodes re-

*Corresponding author: tel.: +90 312 324 15 55; fax: +90 312 324 15 05; e-mail address: nucak@ybu.edu.tr

Table 1. Chemical composition and some properties of electrode materials (wt.%)

Material		CuCrZr			Cu
Chemical composition	Elements	Cr	Zr	Cu	Cu
		1.00	0.10	Balance	100

Table 2. Chemical composition of AISI P20 steel (wt.%)

C	Si	Mn	Cr	Mo	Ni	S	Fe
0.40	0.25	1.5	1.90	0.2	1.0	0.001	Balance

Table 3. Materials and EDM parameters

Workpiece material	AISI P20 tool steel
Electrode materials	CuCrZr and Cu
Dielectric fluid	Petrofer dielectricum 358 mineral based oil
Pulse current (A)	4, 8, 12, 16
Pulse-on time (μs)	25, 50
Pulse-off time (μs)	2.5, 5
Duty factor (%)	90.9
Machining time (min)	20

duced after CT and comparatively less influence of CT on MRR and *Ra* was observed. Sundaram et al. [12] investigated the effects of cold treatment at –101 °C and CT at –185 °C on copper electrodes in EDM of beryllium-copper alloy workpieces. According to test results, it was found that CT considerably enhanced MRR, but did not affect EWR significantly. In another study [13], wear properties of cryogenically treated copper, brass, and graphite electrodes in EDM of En-31 were investigated. Results of the experimental study showed that cryogenically treated copper electrode had 18 % better MRR performance and 31 % lesser EWR than the untreated one.

Any improvement in mechanical and physical properties of electrode materials plays a crucial role in enhancing the performance of an EDM process. Although some studies on surface integrity, modeling, MRR, and EWR have been reported in the literature [14-16], there is no study on a performance evaluation of untreated and cryo-treated Cu and CuCrZr electrodes. Also, as is reported in the literature survey, CT has positive effects on electrode and workpiece materials such as better MRR, EWR, and surface quality. One of the objectives of this study is to evaluate performances of treated and untreated CuCrZr and Cu electrodes in terms of EWR, MRR, and *Ra* in EDM of AISI P20 tool steel. The other is an investigation of the influence of different process parameters on an EDM process.

2. Materials and method

2.1. Test materials

CuCrZr and Cu are used as tool materials in the experimental study. Chemical compositions of CuCrZr and Cu electrodes are given in Table 1. The diameter of both electrodes is 10 mm. To observe the effects of CT, the electrodes were divided into two groups as treated and untreated electrodes. The former group of electrodes were cryogenically treated at –140 °C for 30 min and then tempered at 175 °C for 1 h. AISI P20 tool steel commonly used for plastic injection molds and tooling and casting dies was selected as workpiece material. The chemical composition of AISI P20 tool steel is shown in Table 2.

2.2. EDM tests

A King ZNC K3200 model EDM machine was used for the experimental studies. The EDM tests were conducted at pulse currents of 4, 8, 12, and 16 A and pulse durations of 25 μs and 50 μs. Other machining parameters were kept constant for all tests. Experimental conditions are given in Table 3. Petrofer dielectricum 358 mineral based oil was used as the dielectric fluid. To obtain accurate values, the EDM experiments for each combination of machining conditions were repeated three times, and their mean value was accepted as a test result. Each machining test was performed for 20 min for both treated and untreated electrodes.

2.3. Measurements of performance characteristics

Due to the nature of EDM process, EC plays an important role in terms of efficiency of an EDM process. For this purpose, ECs of CuCrZr and Cu electrodes were measured using an SIGMATEST D2.068 device. Mean value of four EC measurements were accepted as a value of EC. Also, prior the EDM experiments, the hardness values of treated and untreated electrodes were measured using an HMV-2 Shimadzu Vickers hardness tester. The load of 1 kg was applied for 8 s to electrode materials for the hardness test. Five readings were taken from electrode specimens, and their mean value was accepted as a hardness value. The roughness values of the machined surfaces for each machining condition were measured using an NANOVEA 3D optical profilometer, and the *Ra* values were accepted as a mean value of three different measurements. EWR and MRR values for both Cu and CuCrZr electrodes were found by considering mass losses after an EDM process. To calculate the wear rates of electrodes and MRRs of workpieces, the specimens were weighed before (MBT – Mass Before Testing) and after (MAT – Mass After Testing) the EDM process using an analytical balance with 250 g maximum capacity and 0.0001 g accuracy. EWR and MRR were calculated using following equation:

$$\mathrm{EWR} = (\mathrm{MTB}_{\mathrm{electrode}} - \mathrm{MAT}_{\mathrm{electrode}})/t\ (\mathrm{g\ min^{-1}}), \quad (1)$$

$$\mathrm{MRR} = (\mathrm{MTB}_{\mathrm{workpiece}} - \mathrm{MAT}_{\mathrm{workpiece}})/t\ (\mathrm{g\ min^{-1}}), \quad (2)$$

where t is machining time.

3. Results and discussion

3.1. Electrical conductivity

Figure 1 shows the EC values of treated and untreated CuCrZr and Cu electrodes. It was found that ECs of CuCrZr electrodes increased from 44.16 to 45.46 m ohm^{-1} mm^{-2} after CT. EC values of treated CuCrZr electrodes increased by approximately 3 % in comparison to untreated ones. Considering copper alloys, this case can be explained by the improved homogeneity of the crystal structure, dissolving gaps and dislocations of alloying elements with CT. Thus, the microstructure after CT had more intense structure and EC value improved [17, 18]. Yildiz et al. [17] found similar results for EC values of cryogenically treated beryllium-copper alloys. On the other hand, CT did not significantly affect the EC values of Cu electrodes. EC values for untreated and treated Cu electrodes

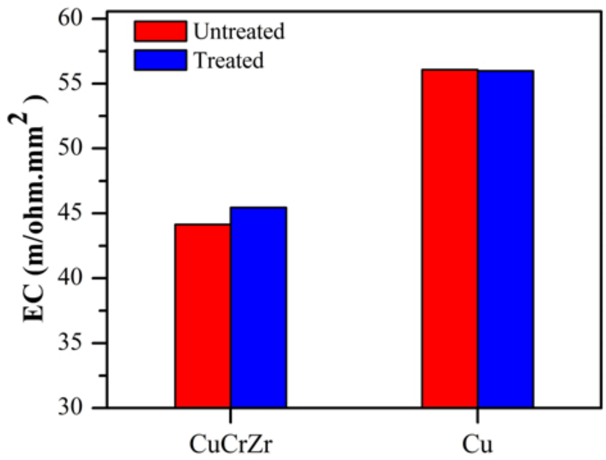


Fig. 1. EC values of the electrodes.

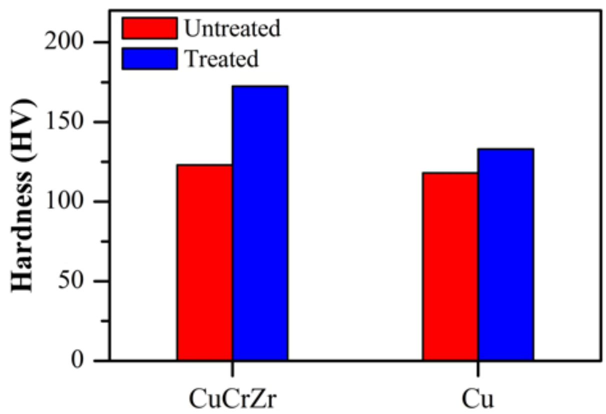


Fig. 2. Hardness values of the electrodes.

were measured as 56.08 and 55.99 m ohm^{-1} mm^{-2}, respectively. As can be seen from Fig. 1, the EC values of both treated and untreated Cu electrodes are higher than those of CuCrZr electrodes. This case was associated with negative effects of alloying elements (Cr and Zr) within CuCrZr electrode materials on EC.

3.2. Hardness

Figure 2 shows the hardness values of Cu and CuCrZr electrodes before/after cryogenic treatment. It can be said from Fig. 2 that CT affected the hardness values of both electrodes. According to hardness measurements, the hardness values of CuCrZr and Cu electrodes increased by about 40 % and 13 % after CT, respectively. CT leads to a finer grained, denser and more homogeneous structure [11]. Therefore, the hardness values of both electrode materials increase. Another remarkable point in Fig. 2 is that CT is more effective on CuCrZr specimen (40 %) than pure Cu specimen (13 %) in terms of an increase in hardness.

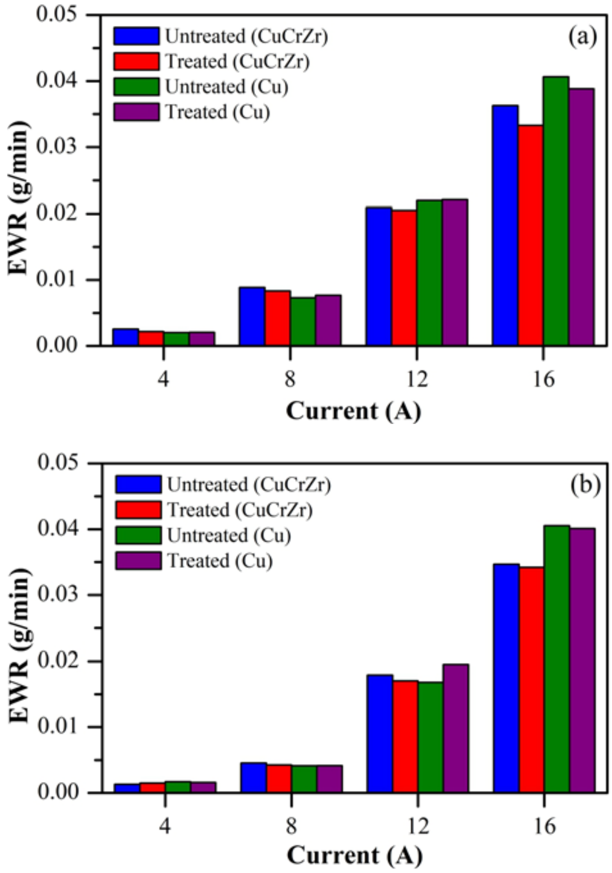


Fig. 3. EWR values versus at a) 25 μs and b) 50 μs pulse duration.

This case can be attributed to the improved structural compactness of copper alloys after CT [17, 18]. When compared hardness values of Cu and CuCrZr specimens, the hardness value of CuCrZr specimen is higher than that of Cu specimen due to chromium and zirconium alloying elements with higher hardness values.

3.3. Electrode wear rate

Figure 3 shows the experimental results for EWR. As shown in Fig. 3, treated CuCrZr electrodes were less worn than untreated ones by about 8 and 0.3 % at 25 and 50 μs, respectively. The maximum improvement in wear rate of CuCrZr electrodes after CT is 15.2 % at 4 A and 25 μs. Therefore, the effect of CT on EWR is considerable. Because electric current directly affects the efficiency of an EDM process, a higher EC value provides more efficient machining. As mentioned earlier, CT increased the EC and hardness values of the CuCrZr electrodes. Besides, thermal conductivity, one of the most important parameters to increase the efficiency of an EDM process, increases with increasing EC according to Wiedmann-Franz-Lorenz law. An increase in thermal conductivity leads to lesser local temperature and thus, lesser tool wear [19, 20]. Therefore, when considering the effect of CT on EC of CuCrZr electrode, it can be said that CT decreased the wear rate of CuCrZr electrodes due to their increasing electrical and thermal conductivity. Also, it is thought that a significant increase in hardness of CuCrZr electrodes after CT improved tool wear of treated CuCrZr electrodes. However, CT did not affect the performance of Cu electrodes significantly (averagely 0.6 and 2 % increase in EWR at 25 and 50 μs, respectively) regarding electrode wear. The maximum improvement (7.33 %) in EWR for Cu electrodes was obtained at 4 A and 50 μs. This improvement in the EWR of the Cu electrode can be attributed to short holding times at cryogenic temperatures. Considering the studies about the performance of cryogenically treated copper electrodes in literature, it can be said that CT time affects the EWR value significantly. According to test results of Mathai et al. [11], electrodes cryogenically treated for 12 hours exhibited superior performance in terms of EWR to ones treated for 24 h in EDM of AISI 304 stainless steel. Besides, Sundaram et al. [12] reported that the effect of CT on tool wear was marginal in EDM of beryllium-copper using cryogenically treated copper electrodes. Also, as shown in Fig. 3, EWR substantially increased with increasing pulse current for two types of electrodes. The EWR increased by averagely 19 times and 21 times from 4 to 16 A for CuCrZr and Cu electrodes, respectively. This case is associated with the energy of pulse increases at higher discharge currents. High discharge current values generate large amounts of heat, and this leads to melting and evaporating of a larger amount of material both electrode and workpiece [21, 22]. Thus, increasing pulse current results in an increase in EWR values. Figure 4 shows SEM images of worn electrodes after an EDM process at 4 and 16 A, respectively. An increase in pulse duration led to a decrease in EWR. From 25 to 50 μs at the same currents, EWR decreased by 27 % for the CuCrZr electrode and by 21 % for the Cu electrode. This can be explained by the fact that an increase in the pulse duration leads to an increase in the diameter of the discharge column. Consequently, it causes a reduction in the energy density of the electrical discharge on the discharge spots and electrode wear [6]. Similar results have also been obtained in some experimental research works [6, 11, 17].

3.4. Material Removal Rate (MRR)

MRR values at different currents and pulse durations are shown in Fig. 5. When compared to untreated CuCrZr electrodes, MRR of treated CuCrZr electrodes decreased by about 6 and 2 % at 25 and 50 μs, respectively. CT provides better electrical and thermal conductivity to electrode materials, which re-

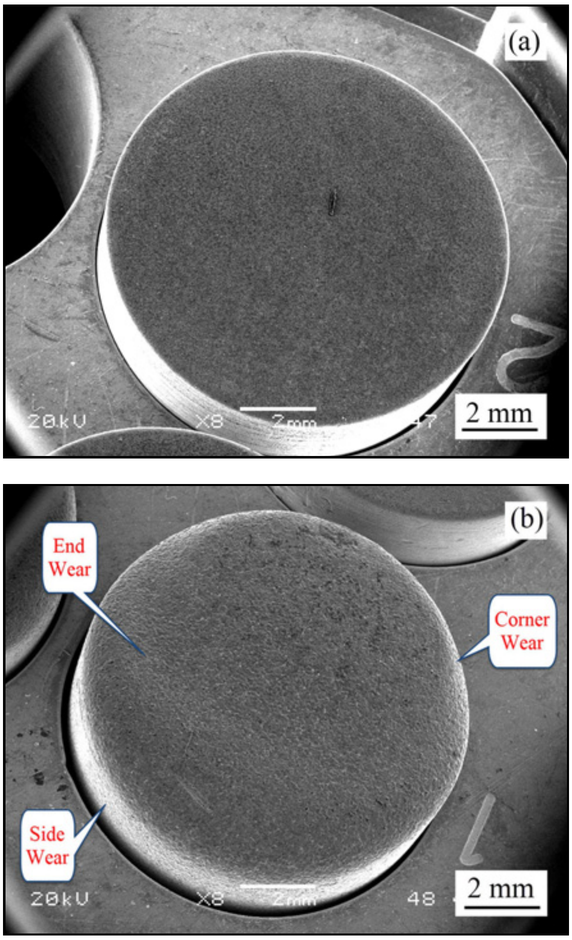


Fig. 4. The SEM images of electrodes at a) 4 A, b) 16 A.

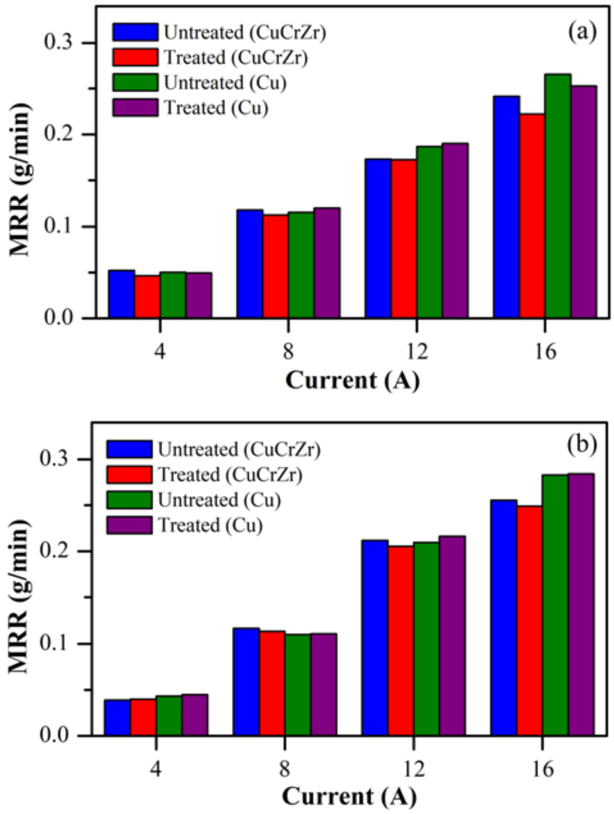


Fig. 5. MRR values at a) 25 µs and b) 50 µs pulse duration.

duces bulk electrical heating, so there is less excessive melting of the tool and the workpiece and therefore resulting lesser MRR [11, 19]. Besides, the maximum improvement in MRR with CuCrZr electrodes after CT is 11.2 % at 4 A and 25 µs. On the other hand, MRR of treated Cu electrodes did not change significantly (averagely 0.06 and 2 % increase in MRR at 25 and 50 µs, respectively) with CT. This result could be related to the almost same EC values of treated and untreated Cu electrodes. The maximum improvement in MRR value for Cu electrodes, 4.8 %, was obtained at 16 A and 25 µs. Both treated and untreated Cu electrodes exhibited better performance in terms of MRR than CuCrZr electrodes for both at 25 and 50 µs in average. Besides, the MRR values of CuCrZr electrodes did not change significantly from 25 to 50 µs (increased by averagely 2 %), while MRR values of Cu electrodes decreased by about 20 % with increasing pulse duration. The reason could be that with high pulse-on duration, the workpiece is melted more and needs longer pulse-off time to remove melted particles. However, if pulse-off time is too short (as 2.5 and 5 µs in this study), the dielectric liquid cannot remove melted part of the workpiece, due to lack of sufficient time, so it remains in the spark gap, thus, resulting in decreasing MRR [23]. Another reason can also be associated with constant duty factor. Since the discharge delay is less in lower pulse-on times when compared with large pulse-on times, thus a number of pulses is higher for shorter pulse durations [17]. Also, the MRR increased from 4 to 16 A by about 456 and 482 % for CuCrZr and Cu electrodes, respectively. Increasing current increases spark energy, thus the volume of the craters increases and as a result, MRR value is higher at high currents [23].

3.5. Surface roughness

Figure 6 shows *Ra* measurement results. Although the *Ra* values of surfaces machined with untreated CuCrZr electrodes are better than treated ones in certain conditions, it was observed that machined surfaces with treated CuCrZr electrodes have averagely 1.1 and 1.4 times better surface quality at 25 and 50 µs, respectively. Also, the lowest *Ra* value decreased from 4.75 to 3.29 µm with CT, was obtained for machined surfaces with treated CuCrZr electrode at 4 A and 25 µs. CT enhanced surface quality of workpiece up to 30.7 % for treated CuCrZr electrode.

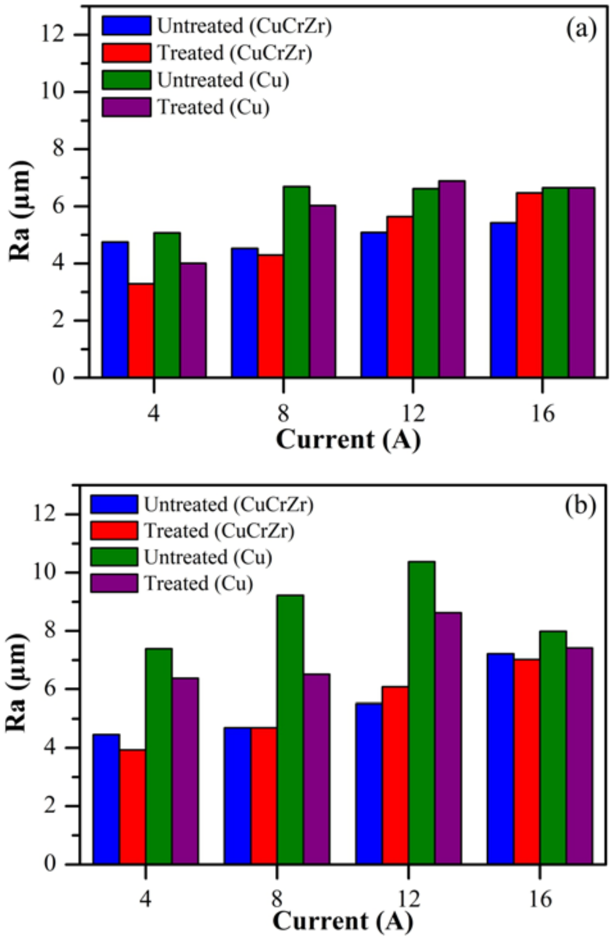


Fig. 6. *Ra* values at a) 25 µs and b) 50 µs pulse duration.

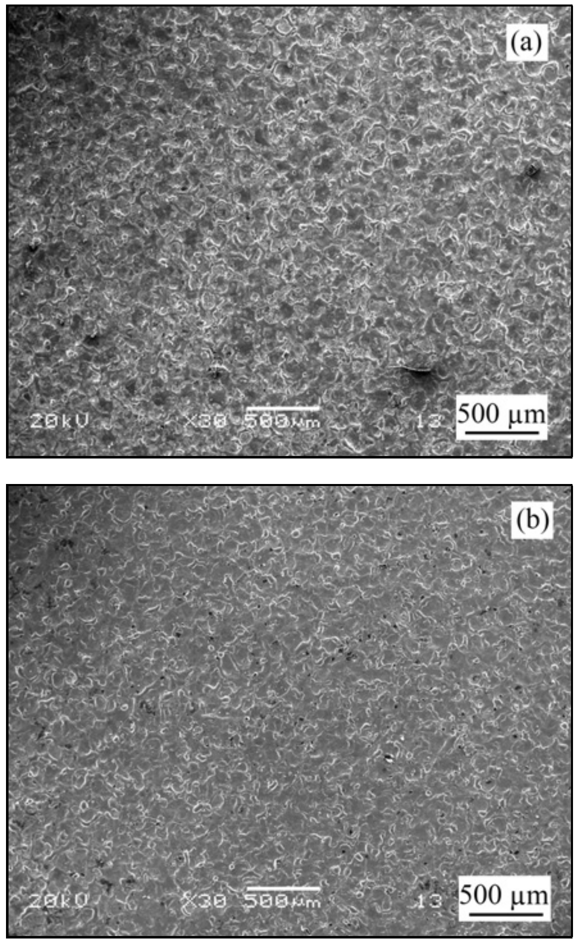


Fig. 7. The workpiece surfaces machined by a) untreated, b) treated CuCrZr electrodes.

Figure 7 indicates 30× magnified SEM images of machined surfaces with untreated and treated CuCrZr electrodes at 4 A and 25 µs, respectively. The remarkable points in these figures are that the craters on the surface machined by untreated CuCrZr electrode are larger and deeper in comparison to treated CuCrZr electrode. This case shows positive effects of CT on surface quality in the EDM process.

On the other hand, when the *Ra* values of machined surfaces with treated and untreated Cu electrodes were examined, it was observed that CT significantly improved the *Ra* values for almost all machining conditions. According to test results, surfaces machined with treated Cu electrodes have averagely 7 and 17 % better surface quality than untreated ones at 25 and 50 µs, respectively. The maximum improvement in *Ra* of the workpiece after CT is 29.4 % at 8 A and 50 µs. Figure 8 shows the 3D topographic maps of machined workpiece surfaces with treated and untreated Cu electrodes under this working condition. It also is obvious from the Fig. 8 that the craters are relatively larger and deeper on surface machined by untreated Cu electrode than treated one.

According to test results, both treated and untreated CuCrZr electrodes exhibited better performance in terms of *Ra* than Cu electrodes for all machining conditions. The *Ra* value increased averagely by 63 and 30 % from 4 to 16 A for CuCrZr and Cu electrodes, respectively. Figure 9 shows topographies of surfaces machined by untreated CuCrZr electrodes at a constant pulse duration (50 µs) and different currents. As can be seen from Fig. 9, with an increase in current from 4 to 16 A, the deeper craters form and this case deteriorates the surface quality of workpiece material. Also, from 25 to 50 µs pulse duration at the same currents, *Ra* increased by 10 % for the CuCrZr electrode and 33 % for the Cu electrode. Figure 10 shows the topographies of surface machined with untreated CuCrZr electrodes at different pulse durations and a constant current (12 A). As well known, an EDM process forms craters on a workpiece surface due to the sparks, and it is clear that smaller crater dimensions result in better surface quality. Thus, it is thought that an increase in the pulse current and pulse duration decreases surface quality [22, 24].

Temperatures in an EDM process range between

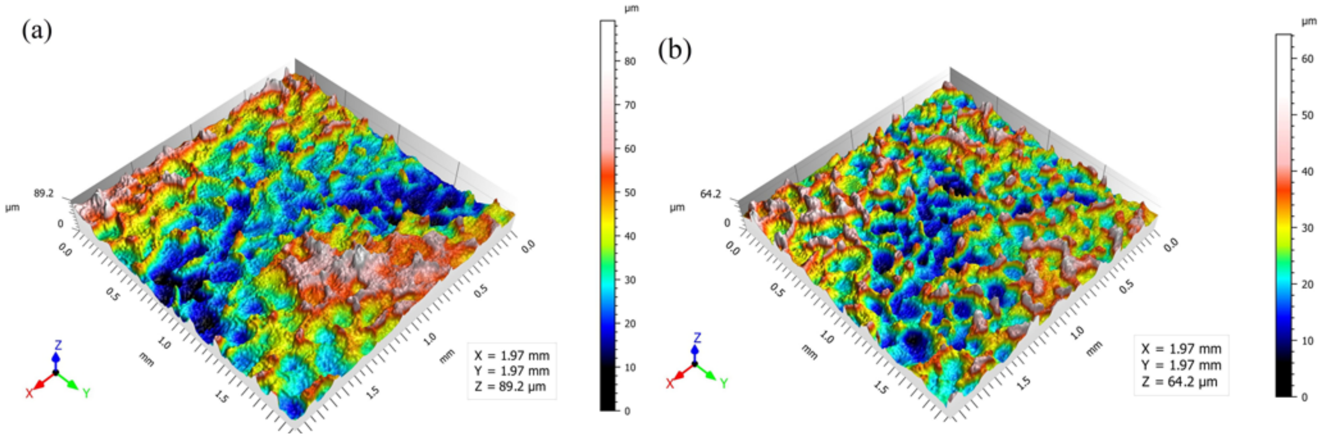


Fig. 8. 3D Topography of surfaces machined by a) untreated, b) treated Cu electrodes.

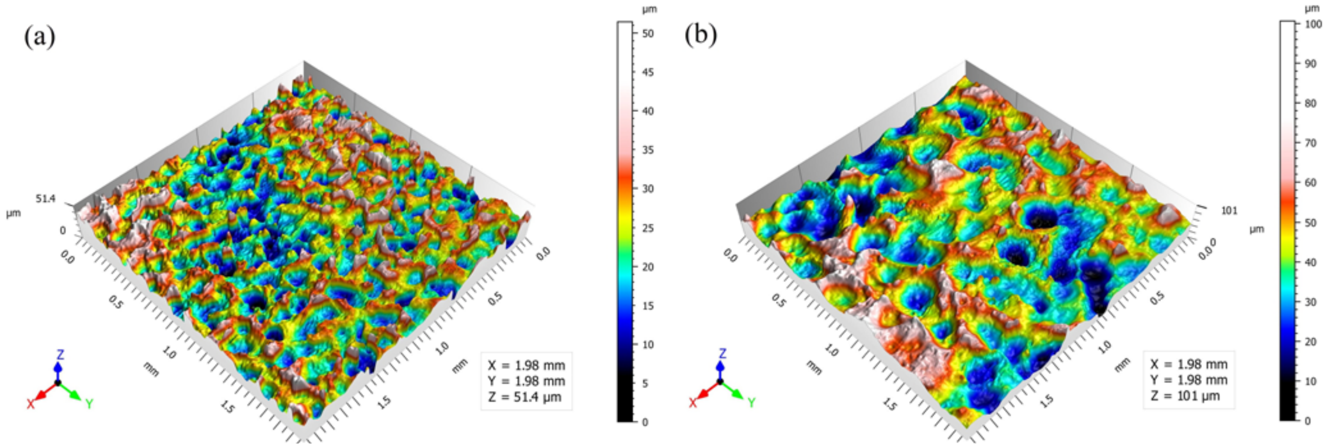


Fig. 9. 3D Topography of surfaces machined at a) 4 A, b) 16 A.

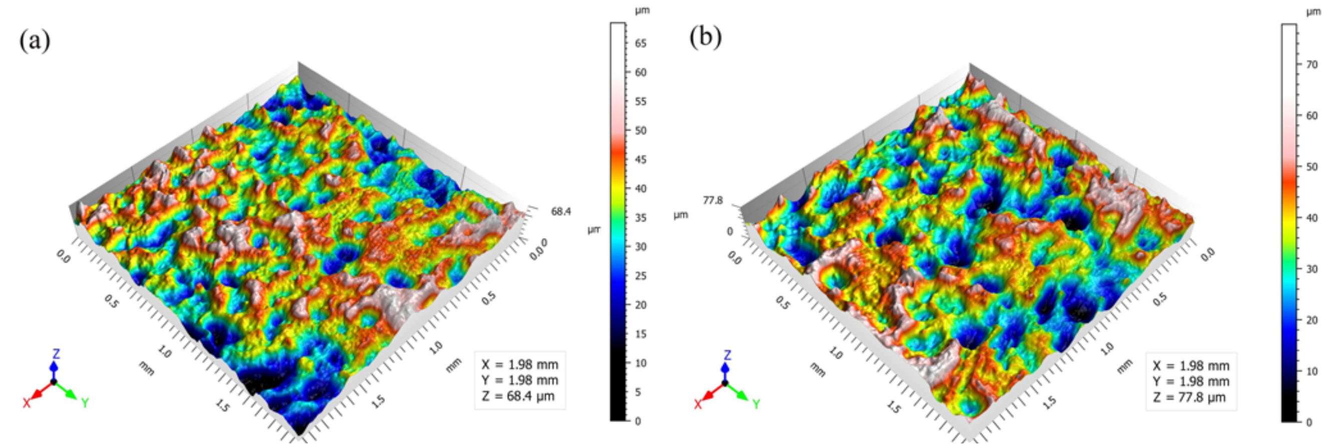
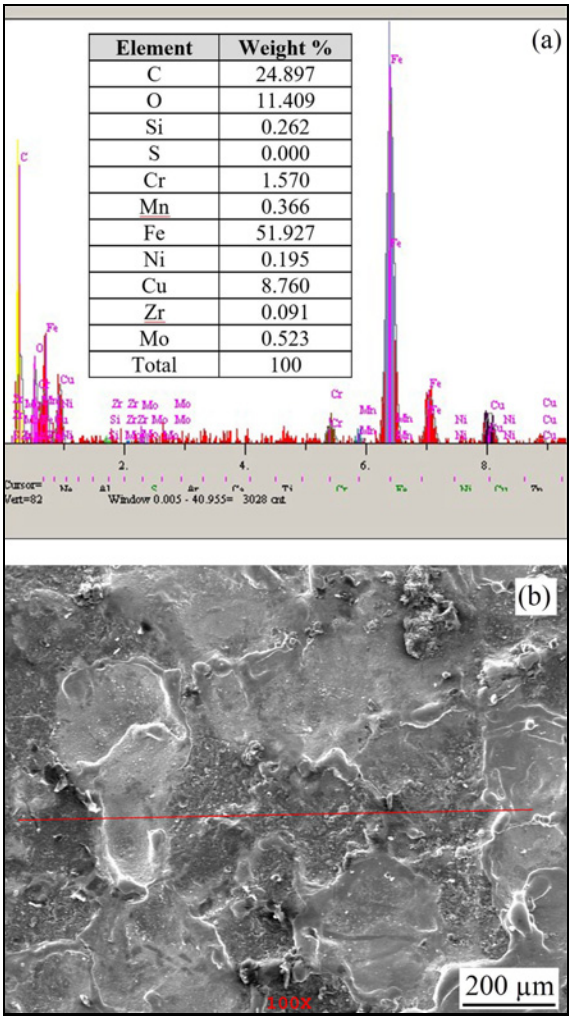


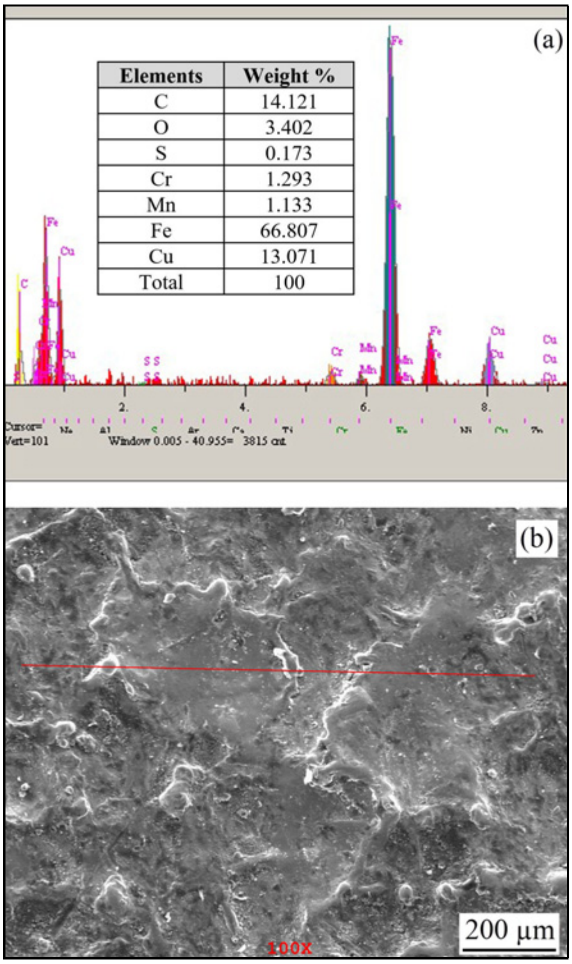
Fig. 10. 3D Topography of surfaces machined at a) 25 µs, b) 50 µs.

8000 and 12000 ℃ when electrode and workpiece generate thermal energy [4, 25]. This leads to melting and evaporating of materials from workpiece and electrode. At these high temperatures, adhesions occur between workpiece and electrode and affect the performance of EDM process [26]. Because of that, EDX analysis was carried out to determine the adhesions on the machined surfaces of the workpiece. EDX analyses and SEM pictures of surfaces machined by CuCrZr and Cu electrodes are shown in Figs. 11 and 12, respectively. Accordingly, the presence of Cu, Cr, and Zr elements found within both electrode mate-



Element	Weight %
C	24.897
O	11.409
Si	0.262
S	0.000
Cr	1.570
Mn	0.366
Fe	51.927
Ni	0.195
Cu	8.760
Zr	0.091
Mo	0.523
Total	100

Fig. 11. a) EDX analysis of surface machined by CuCrZr electrode at 16 A and 50 µs, b) its SEM picture.



Elements	Weight %
C	14.121
O	3.402
S	0.173
Cr	1.293
Mn	1.133
Fe	66.807
Cu	13.071
Total	100

Fig. 12. a) EDX analysis of surface machined by Cu electrode at 16 A and 50 µs, b) its SEM picture.

rials confirms the adhesion to the workpiece material. High carbon content (24.897 and 14.121 %) within the workpiece material can be attributed to burning of dielectric fluid during EDM process.

Figure 13 also shows the EDX analysis of numbered five points of Cu and CuCrZr electrodes used in the EDM processes. According to Fig. 13a, it can be said that light gray areas represent the adhesions from workpiece material on Cu electrode and dark areas represent heat affected zones on the electrode. When examining EDX analysis of light gray areas in Fig. 13b, it is observed that main impurity elements found in chemical compositions of these points are C and Fe. The presence of high Fe content, as well as carbon content, is good evidence for material transfer from workpiece material to electrodes during an EDM process. Also, it is thought that high carbon content on electrode surfaces could come from the dielectric fluid and workpiece material [27].

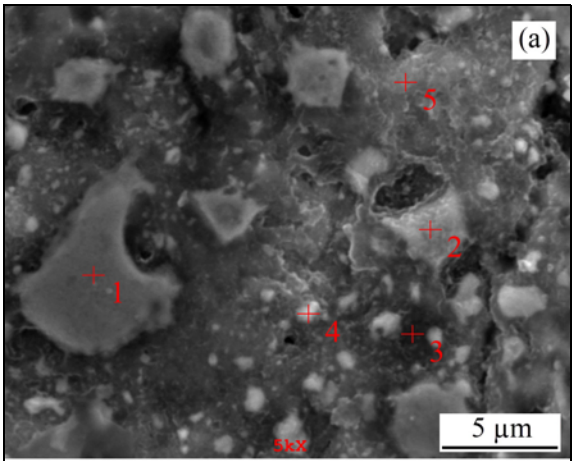
4. Conclusions

In this experimental study, the effects of CT on EDM of AISI P20 tool steel with CuCrZr and Cu electrodes were investigated at different working conditions. The findings of this study are as follows:

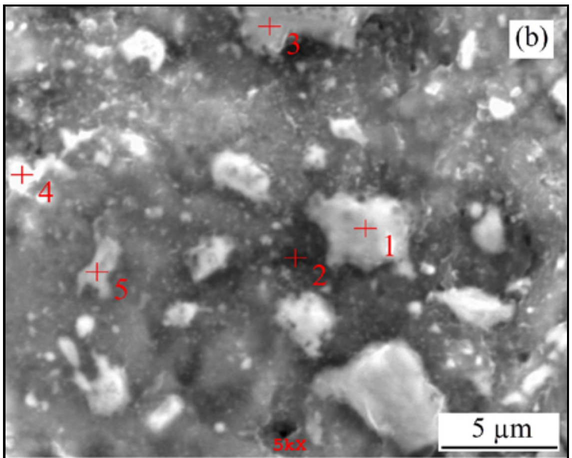
– There were observed some beneficial effects of CT on EC and hardness of both electrodes due to a more homogeneous, denser and fine grained structure after CT.

– In general, EWR and *Ra* values were lower in the EDM processes in which cryo-treated electrodes were used. According to test results, CT was more effective on EWR of CuCrZr electrodes than that of Cu electrodes. This can be associated with increased hardness and EC values of CuCrZr electrodes after CT. Also, a significant improvement in surface quality with treated Cu electrodes is observed with CT.

– CT led to the decrease in MRR of CuCrZr electrodes, while MRR values of Cu electrodes increased slightly. CT provided better electrical and thermal



Points	Elements					
	Weight %					
	C	O	Cr	Fe	Cu	Total
1	15.263	0.000	3.780	78.744	2.212	100
2	23.581	0.000	2.554	70.442	3.443	100
3	36.174	1.521	0.106	12.388	49.812	100
4	32.943	1.727	1.520	54.333	9.477	100
5	19.840	0.773	1.103	67.196	11.088	100



Points	Elements					
	Weight %					
	C	Cr	Fe	Cu	Zr	Total
1	9.049	3.350	84.341	2.801	0.459	100
2	43.368	0.915	22.809	32.587	0.321	100
3	10.645	2.088	82.962	4.047	0.257	100
4	19.226	1.318	58.854	20.385	0.218	100
5	28.828	2.181	41.441	27.254	0.295	100

Fig. 13. EDX analysis of a) Cu and b) CuCrZr electrodes.

conductivity to CuCrZr, which reduces bulk electrical heating, so there is less excessive melting of the tool and the workpiece and therefore resulting lesser MRR.

– An increase in discharge current caused a dramatic increase in EWR, MRR, and *Ra* values for both electrodes. This can be explained by the fact that higher discharge current values led to the formation of deeper and larger craters.

– A variation of pulse duration from 25 to 50 µs affected both electrodes performance significantly. In general, EWR and MRR decreased while *Ra* increased.

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