中國機械工程學刊第四十三卷第四期第 355~362 頁(民國一百一十一年)
Journal of the Chinese Society of Mechanical Engineers, Vol.43, No.4, pp.355~362 (2022)

Surface Roughness Performance of Cu Electrode on Hardened AISI 4140 Steels in EDM Process

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Keywords: Surface roughness, AISI 4140, EDM, Cu electrode, machinability.

ABSTRACT

Electrical Discharge Machining (EDM) is widely used unusual manufacturing methods due to the fact that requirement of cutting, brittle, hard and complex geometry. In this context, high-alloy and hardened steels used as mold material which is desired wearing resistance from the materials. The desired long-life criteria can also be achieved in many steel materials by cooling process. In this experimental study, surface roughness performance of Cu electrode in EDM process of hardened AISI 4140 steels was investigated. Discharge current, pulse duration, waiting period were determined as EDM processing parameters and two separate experiments were carried out on materials with different heat treatment processes. As a result of the experimental study, the surface roughness values were measured on machined workpiece surfaces and average surface roughness values were determined. It has been observed that the EDM processing parameters have variable effects on the surface roughness in heat treated workpieces. The results also show that EDM processing becomes more difficult and the surface quality decreases when AISI 4140 materials, which are cooled for a certain period of time, are subjected to tempering heat treatment.

INTRODUCTION

Electrical Discharge Machining (EDM) is a machining method, defined as melting of very small frequency electric arcs occurring between workpiece surface and electrode. Also, this method is preferred widely because of there is not contact between the workpiece and tool. During machining does not occur deformation and shear force. This method is used especially in the automotive and aerospace sector by reason of high hardness materials can be processed easily (Kam and Seremet, 2021; Kam and Saruhan, 2021). Thus, the strength of the steel material does not effect on the machining performance. AISI 4140 steel material, which is widely used and its machinability is important for the automotive industry, various machinery equipment, and engine parts (Kam, 2016; Adin and Okumus, 2021; Kam 2021). Thermal conductivity of a workpiece can also affect its response to machining. It is observed that workpiece material with low thermal conductivity could absorb less heat during machining, leading to lower material removal rate (MRR). The materials that are difficult to process with traditional manufacturing methods can be processed with the EDM method, resulting in especially cost savings (Mohd et al., 2007). Today, although this method is widely used in manufacturing, factors such as low machining speed, low amount of MRR, the necessity of conducting materials to be processed and the formation of rough surfaces restrict the use of this method. High temperatures occurring during the processing of hard materials in traditional manufacturing methods cause cutting tool wear, affecting the product surface quality and increasing the number of cutting tools used, thereby increasing processing costs. In the machinability of high hardness materials, quality can be increased production costs and reduced by using non-traditional manufacturing methods. In EDM method, copper, brass, aluminum and graphite materials with electrical conductivity are used as electrodes (Anjum et al., 2017; Jamwal et al., 2018).

In this method, the most important machining process parameters affecting the surface quality are; workpiece material, discharge current, pulse on time, electrode material, pulse off time, electrode size and type. In the studies in the literature, experimental studies were carried out by choosing fixed parameters

Paper Received Apr., 2022. Revised May, 2022, Accepted May, 2022, Author for Correspondence: A. İpekçi

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in general (Mohd et al., 2007; Anjum et al., 2017; Jamwal et al., 2018; Kumari et al., 2018). In the studies in the literature, surface roughness of workpiece, processing speed of the workpiece and the electrode wear were investigated after the EDM process. In general studies, it is aimed that determining the most suitable machining parameters for the workpiece and the electrodes used. Many studies indicate that the use of lower machining parameters will result in better surface quality. It is stated that especially the discharge current (less than 10 A) and pulse on time (50 - 100 μs) are effective on surface roughness (Torres et al., 2015; Chakraborty; 2015). In order to complete manufacturing process in a short time, it is aimed to have a high metal removal rate and a lower electrode wear volume. Electrodes that wear less in the machining process provide better dimensional accuracy. In addition, the use of high discharge current increases the amount of material removed per unit time in operations. This increases the electrode wear volume by approximately 50% (Singh et al., 2016).

In this content; Cryogenic treatment is performed to improve the mechanical properties of alloyed steel materials (Kam, 2016). It is applied in two types as Shallow and Deep Cryogenic Treatment process. There are many studies on improvement for mechanical properties in the literature. It was determined that cryogenic cooling significantly affects the mechanical properties for AISI 4140 steel on the process parameters. The low holding times (less than 48 hours) in the cryogenic treatment process have a positive effect on many mechanical properties, especially wear. It has been observed that industrial cryogenic treatment (short holding time) has a lower effect on mechanical properties compared to general cryogenic treatment (holding time longer than 48 hours) (Kam, 2016; Kam and Saruhan, 2018; Kam and Saruhan, 2019; Kam et al., 2022; Kam and Saruhan, 2016; Kam et al., 2016). The cryogenic process was generally applied to the electrode in studies. As a result of these studies, pulse duration and discharge current were determined as the most effective parameters. It is reported that there is a 20% decreasing in the wear rate of electrode with the cryogenic cooling process (Hadad et al., 2018; Kumar and Kumar, 2015; Kumar and Kumar 2014; Srivastava and Pandey, 2012).

Experimental and optimization studies were carried out on different cryogenically treated electrodes. Electrodes made of different materials (Copper, Titanium alloy, Inconel 718, AISI D2 and AISI D3) were used in these studies. Electrode wear, MRR and surface roughness were taken as criteria in all studies. As a result of these studies, cryogenic treatment of the electrode; electrode wear, MRR, and surface roughness were observed to improve between 20% and 30% (Hui et al., 2016; Abdulkareem et al., 2009; Kumar, 2015; Mohanty et al., 2017; Kumar et al., 2012, Sundaram et al., 2009; Sharma et al., 2015). For wire EDM process, wire materials were cryogenically treated and Taguchi optimization was applied for effective parameters. An increase of approximately 10% in MRR (material removal rate) was observed as a result of cryogenic therapy (Kapoor et al., 2012). Cryogenic process was applied for micro EDM application. As the effective parameters, the pulse duration is specified by the discharge current. As a result, MRR increased by 58% and mean surface roughness decreased by 29% (Manivannan et al., 2018).

In the present study, surface roughness performance of Cu electrode in EDM process of heat treated AISI 4140 steels was examined experimentally. The reason for choosing this material is that it is often preferred in mold parts due to its cost and prevalence. Mold parts are often produced using EDM machining due to geometrical difficulties. Considering the studies in the literature, it has been observed that only one cryogenic cooling process is applied to AISI 4140 material. However, the holding time of the cryogenic process and the subsequent tempering process have effects on the mechanical properties and machinability of the material. These processes are frequently applied within companies in applications. Therefore, it has been observed that no studies have been conducted on the effects of different holding times in EDM process of different cryogenic treated and tempered AISI 4140 steel workpieces. Therefore, in this study, different cooling times and tempering processes were applied and their effects on EDM process were observed.

MATERIAL AND METHOD

In this study, workpieces machined from AISI 4140 steel material with Ø 26x10 mm dimensions, 8.9 g/cm^3 density, and 30x30 mm square copper electrode were used. In the EDM process, pure copper electrode was used since the electrode was desired to have high electrical conductivity. Pure copper is tried to be purified from nature by reduction. Pure copper alloys can be reduced in three basic methods as electrolytic copper, phosphorous copper and oxygen-free copper.

Electrolytic copper is a material that contains a maximum of 0.03% oxygen and has high electrical conductivity.

The chemical component of AISI 4140 material is given in Table 1.

The experimental setup in which is performed at room temperature using King brand ZNC-K / 3200 EDM bench given in Figure 1. AISI 4140 steel workpiece used in the study is shown as electrode (copper) and dielectric liquid.

Table 1. Chemical components of AISI 4140.

Element	Composition (%)
C	0.39
Si	0.27
Mn	0.74
P	0.008
S	0.01
Cr	1.06
Mo	0.2
Al	0.03

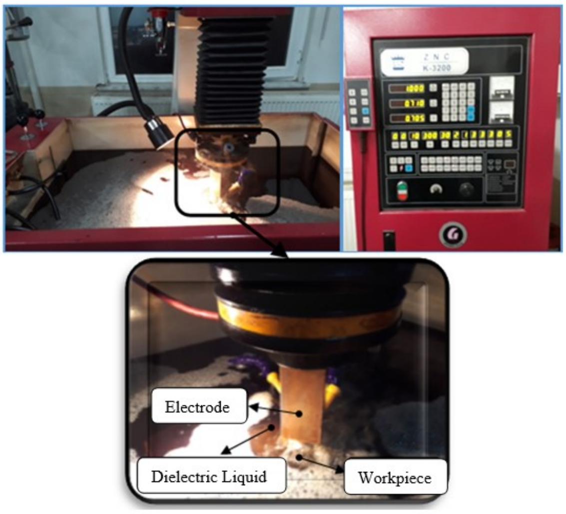

Fig. 1. Experimental setup.

EDM processing parameters of experimental study are given in Table 2. These parameters were specified as discharge current (10 and 20 amperes), pulse on time (100 µs) and pulse off time (10, and 30 µs) and experiments are performed on different deep cryogenic treated workpieces. The most commonly used parameters in the literature and manufacturing have been selected. Preliminary tests were carried out in order to choose very low or very high values and not to obtain unsatisfactory results. The heat treatment processes applied to the materials used in the experiments are given in Table 3.

Table 2. EDM processing parameters.

Process Parameters	Experiment 1	Experiment 2
Pulse on Time (Ton) (µs)	100	100
Pulse off Time (Toff) (µs)	10	30
Discharge Current (A)	20	10

Table 3. Heat treatment process.

Work piece Code	Applied Heat Treatments
W1	Raw material
W2	Conventional heat treatment
W3	Conventional heat treatment and cryogenic treated with 12 hours
W4	Conventional heat treatment and cryogenic treated with 24 hours
W5	Conventional heat treatment and cryogenic treated with 36 hours
W6	Conventional heat treatment and cryogenic treated with 48 hours
W7	Conventional heat treatment, cryogenic treated with 12 hours and tempered
W8	Conventional heat treatment, cryogenic treated with 24 hours and tempered
W9	Conventional heat treatment, cryogenic treated with 36 hours and tempered
W10	Conventional heat treatment, cryogenic treated with 48 hours and tempered

As given in the Table 3, conventional heat treatment process is applied to raw material work-pieces, after which deep cryogenic treatment process is applied with different holding times (12 to 48 hours) and finally tempering applied as last heat treatment process.

Raw material workpieces is used without heat treatment. As shown in the Figure 2, the workpieces are firstly hardened to approximately 500 hardness Vickers hardness value by applying conventional heat treatment. Conventional heat treated workpieces; after that, workpieces hardened in the oven by heating to 420 °C for 30 minutes, austenitizing process at 850 °C for 30 minutes and tempering at 320 °C for 2 hours. After these processes, workpieces was made ready as a conventional heat-treated workpiece. Other workpieces after the conventional heat treatment process were applied to deep cryogenic (cooling) treatment at -140 °C temperature for 12, 24, 36 and 48 hours. Then, workpieces with deep cryogenic treated were applied tempering at 200 °C by 2 hours.

Vickers hardness measurements were carried out for each test sample with a Metkon brand Duroline-M model hardness testing device before the materials were subjected to EDM process after heat treatment. In obtain to optimum measurements, all measurements repeated three times and the average of the results was taken.

After EDM processes, surface images are taken with the help of an optical microscope to give an image of the surface forms of the samples. Surface scanning is performed with a 3D optical profilometer to examine the morphological state of the machined surfaces. In this scan, a topographic measurement of a 5 mm region in the lateral direction of 0.1 µm and a height sensitivity of 0.02 µm was performed.

A dino-lite brand digital camera is used as a camera to take optical microscope images. This camera has a resolution of 5 MP resolution with a numerical f aperture of 0.05 – 0.3. It has 200x magnification and 8 micron sensitivity.

Mahr - Marsurf PS 10 model surface roughness measuring device used for surface roughness measurements for EDM machined surfaces. The dimensions are in LC ISO - 16610 - 21 standard and the measurement distance is 4.8 mm. The tip radius of the measuring needle is 5 µm. In order to avoid errors for surface roughness values, measurements were taken three times from the EDM machined surfaces and averaged surface roughness values are formed.

RESULTS AND DISCUSSION

In Figure 2, the changes in Vickers hardness values of the samples machined from AISI 4140 steel, which has been conventional heat treatment, deep cryogenic treatment with different holding times and tempered, are given.

When we look at the micro hardness values, the highest values are respectively W5, W6, W9, W10, W8, W7, W4, W3, W2 and W1. The reason for the highest hardness values in the samples of deep cryogenic treatment was attributed to formation of a more brittle structure as a result of the austenite phase, which has a soft structure in internal structure of AISI 4140 steel, with the deep cryogenic treatment (Zhirafar, 2005; Kam and Saruhan 2018; Kam and Saruhan 2019; Kam et al., 2022; Kam and Saruhan 2016).

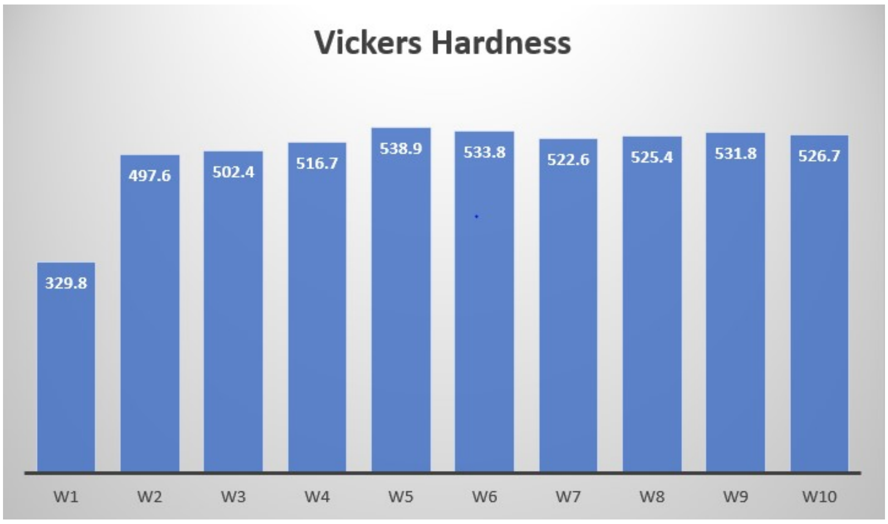

Fig. 2. Changes of average hardness by heat treatment in samples.

The images of the surfaces formed after the EDM process of the tempered AISI 4140 steel samples are given in Figure 3. Fig. 3 shows that surface roughness values increase, the porous structure remaining on the surface after the EDM process grows. In other words, there is a relationship between pore size and surface roughness values. The mechanism of the EDM process is related to electrochemical properties such as thermal and electrical conductivity, high thermal resistance (Kam et al., 2016; Akincioglu, 2019; Akincioglu, 2021; Akincioglu et al., 2016). For this reason, it is understood that there are certain differences in each experiment that the parameters in Experiment 2 give better results on EDM processing when surface roughness measurements and surface images are processed after EDM process. This difference reduced the surface roughness by approximately 20%. Here, when the effective factor is lower discharge current and pulse off time is slightly higher, balanced cooling is achieved and surface quality is increased. On the relationship of EDM process with cryogenic treatment, it can be said that it improves the porous surface structure in general.

The averaged surface roughness values are obtained as a result of Experiment 1 and 2 as given in Table 4 and Table 5. When we examine the surface images with the lowest surface roughness values are obtained, shows that surface porosity has more homogeneity in W4, W8 and W10 processes in AISI 4140 steel workpieces. In this context, this change in the machinability and conductivity of the cryogenic treatment is related to the surface roughness obtained after the EDM process. This change may be due to the diffusion property of carbon atoms at low temperatures and this relates electrical conductivity. Deep cryogenic treatment process may be due to increase in toughness, hardness, wear resistance, and improvement in especially electrical and thermal properties of AISI 4140 steel workpieces.

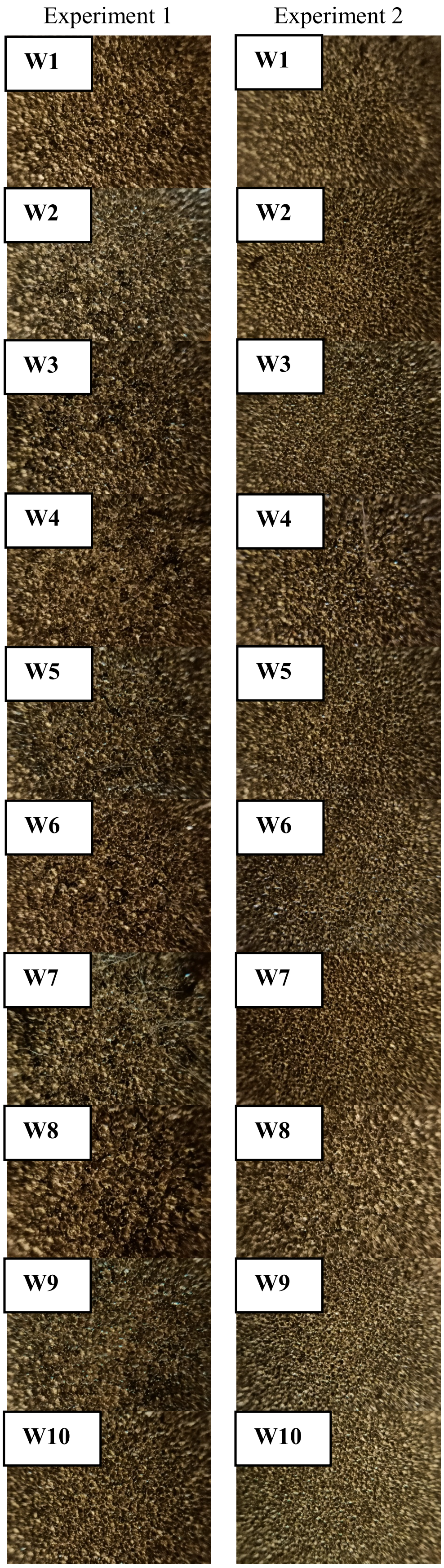

Fig. 3. Surface images after EDM process.

Table 4. Surface roughness values for Experiment 1.

Workpiece No	Averaged Ra (μm)	Averaged Rz (μm)
1	10.037	51.942
2	12.115	66.812
3	10.621	55.616
4	11.103	54.885
5	10.355	52.192
6	11.720	64.495
7	10.458	52.639
8	8.729	44.476
9	11.593	57.137
10	9.197	45.611

According to the experimental data that was given in Table 4, the lowest surface roughness was observed in W8 and W10. The heat treatments corresponding to these workpieces were observed to be conventional heat treatment, cryogenic treated with 12 hours - tempered and conventional heat treatment, cryogenic treated with 24 hours - tempered. When conventional heat treatment and cryogenic treatment and conventional heat treatment, cryogenic treatment and annealing process are examined, it is observed that the cryogenic holding time has the maximum effect on surface roughness in 24 hours, the effect decreases when the holding time is 36 hours, and the surface roughness decreases again when the holding time is 48 hours.

Table 5. Surface roughness values for Experiment 2.

Workpiece No	Averaged Ra (μm)	Averaged Rz (μm)
1	8.781	48.483
2	8.570	46.888
3	8.998	48.943
4	8.102	41.766
5	10.777	52.675
6	10.307	53.029
7	9.678	46.069
8	8.197	43.144
9	9.053	49.444
10	9.302	48.636

When Table 5 is examibed, the lowest surface roughness values were observed in W4 and W8. The heat treatments corresponding to these workpieces were observed to be conventional heat treatment and cryogenic treated with 24 hours and conventional heat treatment, cryogenic treated with 24 hours and tempered. For conventional heat treatment and cryogenic treatment and conventional heat treatment, cryogenic treated and tempered samples, the holding time required to obtain the optimum surface quality is 24 hours, and the surface quality decreases as you go above or below this value.

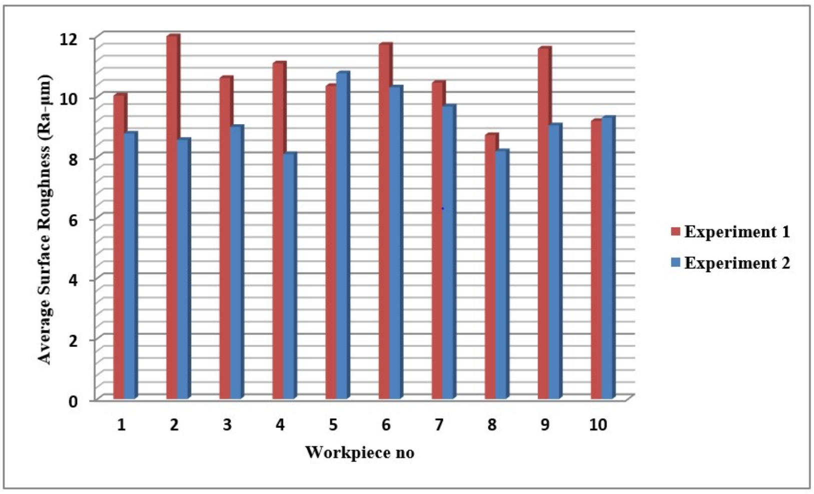

Fig. 4. Comparison graphic of average surface roughness values.

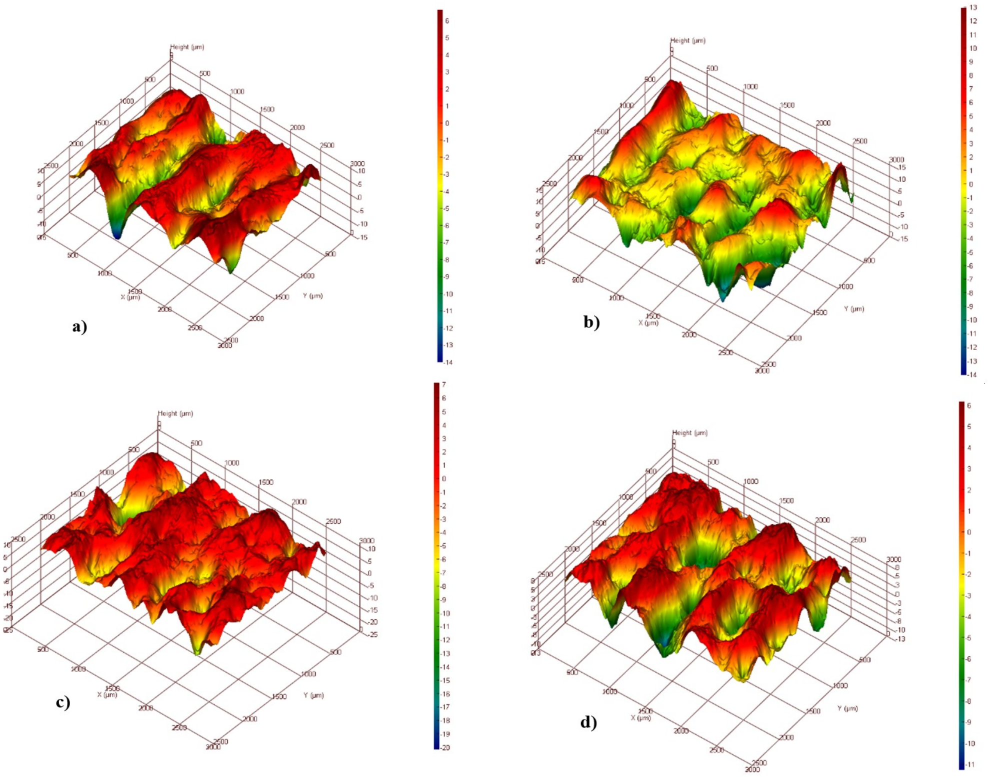

Fig. 5. Comparison graphic of optical profilometer views of EDM machined surfaces: a) Experiment 1 – W8, b) Experiment 1 – W10, c) Experiment 2 – W4, d) Experiment 2 – W8

Compared to Experiment 1 and Experiment 2, improvement in the lowest surface roughness values acquired by increasing holding time and decreasing the current observed that the lowest surface roughness values derived in conventional heat treatment, cryogenic treated with 24 hours and tempered process. In this case, only low surface roughness can achieved in Conventional heat treatment, cryogenic treated and tempered process in Experiment 1, while low surface roughness can obtained in conventional heat treatment and cryogenic treated process in Experiment 2.

Average surface roughness values were given as comparison graphic in Figure 4. This comparison graphics show that increasing holding time and decreasing discharge current has positive effect on surface quality on conventional heat treatment, cryogenic treated and conventional heat treatment, cryogenic treated - tempered workpieces with EDM process. The surface quality obtained with the tempering process after conventional heat treatment and cryogenic treated process in Experiment 1 can also be achieved without the need for tempering after conventional heat treatment and cryogenic treated process in Experiment 2.

When Figure 5 is examined, it is observed from the green color that the recesses deepen in item b). In the c) option, since the red and yellow colors are intense, the surface distribution is low and the depth distribution is balanced. In a) and d) options, green colors that deepen regionally indicate that larger pores are obtained.

CONCLUSIONS

In this experimental study, In this experimental study, surface roughness performance of cu electrode on heat treated AISI 4140 steels by EDM method was investigated. Eventually, surface roughness and micro-hardness of the workpieces was measured, surface morphologies and surface images of machined workpieces were comparatively analyzed.

Conventional heat treatment and cryogenic treated process has positive influence on surface roughness of workpieces EDM machined.

The surface morphology of the conventional heat treatment and cryogenic treated workpieces were better than that of conventional heat treatment and cryogenic treated - tempered workpieces.

Surface morphologies and surface images of machined workpieces with the lowest surface roughness values are obtained, shows that surface porosity has more homogeneity in W4, W8 and W6, W10 processes in AISI 4140 steel workpieces.

The lowest surface roughness values are obtained, that thermal and electrical properties have more improved in W4, W8 and W10 processes in steel workpieces. This change in the machinability and conductivity of the cryogenic treatment is related to the surface roughness obtained after EDM process.

The lowest surface roughness values and balanced depth distribution, EDM processing parameters as, discharge current (10 amperes), pulse duration (100 µs), waiting period (30 µs) were obtained cryogenic treatment with 24 hours holding time.

In the present study, it may be useful to apply different tempering temperatures and holding times to fully observe the effect of the tempering process on conventional heat treatment and cryogenic treated workpieces.

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NOMENCLATURE

Cu	copper
C	carbon
Si	silicium
Mn	manganese
P	phosphore
S	sulphur
Cr	chromium
Mo	molybdenum
Al	aluminium
MP	megapixel