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The Effects of Cold and Cryogenic Treatments on the Machinability of Beryllium-Copper Alloy in Electro Discharge Machining

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Abstract
In this study, beryllium-copper alloy was subjected to around -150° F for cold treatment and to around -300° F for cryogenic treatment and the effects of these cold and cryogenic treatments on the machinability of beryllium-copper workpieces in electro discharge machining have been investigated. Experimental results showed about 20-30 % increase in material removal rate of cold and cryogenic treated workipeces. Variations in electrode wear rate, surface roughness and average white layer thickness were found to be marginal.

Keywords:
Be-Cu Alloy, Cryogenic Treatment, EDM

1 INTRODUCTION

Advanced engineering materials often pose machinability challenges for traditional processes such as turning and milling. Nontraditional processes like electro discharge machining (EDM); due to their unique mechanism of material removal are useful alternatives in such cases [1]. Conversion of electrical energy to thermal energy through repeated occurrence of sparks between the tool and the workpiece in EDM results in the material removal from workpiece as well as tool by melting and evaporation. Numerous studies on the improvement of EDM performance have identified major process parameters such as electrical parameters (voltage, current, pulse on/off time, polarity etc.), flushing (pressure, flushing direction and method) and material characteristics (electrode, work-piece, dielectric). However, the effects of cryogenics on EDM performance have not yet been adequately explored. Limited literature available on this topic indicate the potential for the application of cryogenics for the improvement of several processes such as turning [2, 3], milling [4], drilling [5] and EDM [6, 7]. In these studies, cryogenic temperatures have been used for treatment of cutting tools or cooling purposes. In an earlier study, it was reported that material removal rate of EDM process was improved by employing cryogenically treated copper electrodes [6]. Another study [7] showed a reduction in electrode wear and surface roughness by application of cryogenic cooling on copper electrodes during EDM of titanium alloy workpiece. Improvements in traditional machining processes by cryogenic treatment are attributed to the increased hardness and wear resistance of cutting tools after the treatment processes. In addition, it has been reported that electrical and thermal properties of the materials are also improved by cryogenic treatment and better electrical properties are also essential for workpiece materials in EDM. All of the related literature suggest that in general either cryogenic cooling or cryogenic treatment improve the mechanical, electrical and thermal properties of subjected materials. Since the effects of mechanical properties do not have primary importance in EDM, it is interesting to conduct experimental study to determine the net effects of cryogenic treatment of beryllium-copper (Be-Cu) alloy workpiece materials on EDM performance. Be-Cu alloys are known as high-reliability engineered materials and they have been used in different kind of applications such as automotive, aerospace, electronics, electromechanical, computer, telecommunications and medical industries because of their high fatigue strength and hardness, excellent wear and corrosion resistance and non-magnetic characteristics. As a microstructure property, copper and beryllium form a uniform, homogeneous liquid solution. Beryllium become integral part of the copper crystal and the face-centered-cubic structure of copper are usually maintained. Atoms of beryllium replace copper in the same lattice positions, forming a substitutional solid solution. Be-Cu alloys have been used for all kind of flat and helical springs, switch gear part, control valves and diaphragms and vibrator arms. It has also been used for plastics extrusion dies and certain machine jigs where combination of impact strength and high electrical conductivity was of importance [8]. However, there are some problems in machining of Be-Cu alloys in traditional machining processes [9]. Its high strength becomes a serious problem in terms of surface integrity and tool wear [10]. Additionally, beryllium and its compounds can be harmful because of their toxic properties [8]. Electrical discharge machining of Be-Cu alloy can be performed safely and effectively because of its good thermal and electrical properties. In this study, cold treatment was applied to the Be-Cu alloy workpieces in addition to cryogenic treatment and their machinability performance was examined in terms of material removal rate, electrode wear ratio, surface roughness and white layer thickness formation in EDM of mesoscale holes. Electrical conductivity investigations were also performed for the experimental materials. Important aspects of cryogenics and cold/cryogenic treatment processes are provided in the following section. Details of the experimental work, results/discussion and conclusion are presented subsequently.

2 COLD AND CRYOGENIC TREATMENTS

Cryogenics is a branch of low-temperature physics concerned with the effects of very low temperatures less than about 123°K (-150°C) and it extends down to absolute zero -273°C (-459°F). Historically, the development of cryogenic science occurred primarily in the years from 1900 to 1950 with liquefaction technology for cryogens. Applications of cryogenics in industry vary from space research to food handling. The effects of cryogenic temperatures on properties of materials have been examined extensively in terms of mechanical, thermal and electrical properties. It is reported for several engineering materials that mechanical properties such as the yield strength, tensile strength, fatigue strength, impact strength, hardness and elastic modulus increase as the temperature decrease [11]. Another study reports that the thermal conductivity decreases as the temperature is lowered for certain alloys such as titanium alloy-TC4 and impure metals such as magnesium-AZ31B [12]. Positive effects of low temperatures on mechanical, thermal and electric properties of materials has lead to the cold/sub-zero and cryogenic treatments of wide variety of cutting tools and mechanic parts in manufacturing and automotive industry to increase their strength, hardness and wear resistance and thus substantial savings were recorded. As the name suggests, cold treatment or sub-zero treatment involves temperatures below zero but higher temperatures than the cryogenic temperatures (down to about -80 ºC). Cryogenic treatment can be characterized by its application temperature, below 123°K or at about liquid nitrogen (LN_2) temperature (-196ºC).

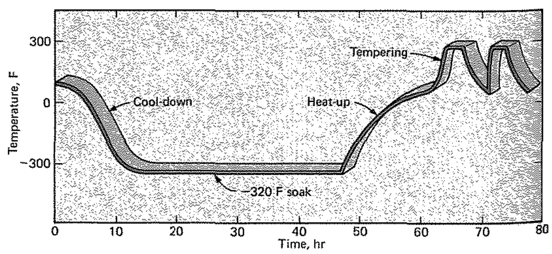

Figure 1: A typical cryogenic treatment cycle [13]

In the beginning, cryogenic treatment was tried by immersing of tools into liquid nitrogen; however, it resulted in damaging of tools by thermal shocks. So, more effective and controlled techniques including programmable temperature controllers, a solenoid valve to control liquid nitrogen flow and a thermocouple to monitor the work temperature were used [14]. Generally, cold and cryogenic treatment processes are operated in three main stages, as seen in Figure 1, including slow cooling stage (the cool-down cycle/period) in which the parts are cooled from ambient temperature to cold/cryogenic temperatures during a time period (degrees per hour or minute), soaking stage in which the parts are maintained at cold/cryogenic temperatures for a given duration (hour) and tempering/warming stage (warm-up cycle/period) in which the parts are heated from cold/cryogenic temperatures to tempering temperatures during another time period (degrees per hour or minute). Characteristics of these stages depend on the desired properties, time-cost and the shape and size of the parts to be treated [15].

2.1 Cooling Stage

It has been determined that the cooling stage had little effect on the final properties of the material being treated [16]. So, it has been recommended that the materials are supposed to be cooled as rapidly as possible to the treatment temperature without causing thermal shocks to minimize the treatment time and thus to reduce the cost.

2.2 Soaking Stage

It was stated that the soaking time in which the material is subjected to stay in the cold or cryogenic temperatures is important for the final properties and this soaking time is required for the atoms in the material to disperse to new locations [16]. For the soaking time, some findings showed that the variable cryogenic holding times did not affect hardness of D2 tool steel, but hardness of H13 tool steel increased with the time. However, it also revealed that increased time at cryogenic temperatures improved wear resistance of D2 tool steel [17]. A minimum soaking time of 24 hours at cryogenic temperature has been recommended to derive maximum benefit from cryogenic treatment in terms of carbide count and consequently wear resistance. The conclusion is that the longer the holding time at the cryogenic temperature, the finer the carbide distribution is and the greater the increase in wear resistance for tool steels. A comparison made between 24 hours and 48 hours soaking times for the T1 and M2 high-speed steels showed that the impact toughness and bending strength of T1 tool steel increased by 48 hours soaking, but the effect of this extended soaking time on M2 tool steel were negligible [18]. An investigation on the effect of cold and cryogenic treatment on the wear characteristics of M2, T1 and D3 tool steels showed that the samples treated at 163 K for 24 hours were better than the samples treated at 93 K for 6 hours which suggests that soaking time is more important than lowering the temperature [19]. However, another study [20] conducted on a 7075 Al alloy with different soaking time (2-hours and 48-hours soaking) did not show significant difference in the properties such as yield, ultimate/tensile strength, elongation and hardness. It appears that the effects of soaking time varies, depending on material characteristics.

2.3 Warming and Tempering Stage

Tempering is usually performed after cryogenic treatment to improve impact resistance of treated materials. It can be carried out as a single, double or triple cycles depending on material characteristics and desired properties [15]. However, for the ultimate effect, no tempering prior to treatment process is recommended and the greatest benefit was derived when cryogenic treatment had been inserted between hardening (quenching) and tempering. Additionally, warming stage should take place slowly and it has been reported that increasing the temperature above 500ºC for the tempering could remove the beneficial effects of cold treatment [16].

2.4 Effects of Cold/Cryogenic Treatments on Copper and Copper Alloys

The effects of cryogenics on copper and its alloys have been investigated less in comparison to steel materials. Effect of cryogenic treatment including tempering (2 hours at 589 K) on thermal conductivity of copper-based (Cr-Cu alloy 182) resistance welding electrodes was investigated in a study [21]. It was found that the cryogenic treatment increased the thermal conductivity from 3% to 4% without affecting the hardness due to the fact that the equilibrium amount of chromium in solution in copper was lower at lower temperatures. Another study [22] on the effect of cryogenic treatment on another copper alloy (GRCop-84) showed that cryogenic treatment followed by tempering reduced the hardness by 6% and it was also resulted reduction in electrical resistivity by 5-6% and correspondingly (according to the Wiedemann-Franz-Lorenz Law) higher thermal conductivity. However, cryogenic treatment without tempering was resulted larger electrical resistivity values. So, it can be concluded that a proper cryogenic treatment process is beneficial to copper alloys.

3 EXPERIMENTAL DETAILS

3.1 Materials

Moldmax Be-Cu alloy workpiece and web type 2-channel C-122 copper electrodes were used in this study. The pure copper electrodes are extruded and are known as a half hard material. Copper has some very attractive qualities such as easily obtainable, consistent in quality and low in cost. Table 1 and 2 show some properties of the copper electrode and the Be-Cu alloy workpiece materials respectively.

Chemical Composition (by weight %)	Copper (Cu)		Phosphorus (P)
	99.90		0.015-0.04
Physical and Mechanical Properties	Density (kg/m^3)	Tensile Strength (MPa)	Yield Strength (MPa)
	8940.609	220.632	68.947

Table 1: Some chemical, physical and mechanical properties of C-122 copper electrodes

Be	Co+Ni	Co+Ni+Fe	Pb	Cu
1.8	0.2	0.6	0.4	97
ρ (kg/m^3)	*E* (N/mm^2)	α (in./in./°F, 70-400°F)	*k* (W/m.°F)	Melt. P. (°F)
2.24E-06	1.31E05	9.7E-06	5.35	1600-1700

Table 2: Some chemical, physical and mechanical properties of Moldmax beryllium-copper alloy

3.2 Cold and Cryogenic Treatment Cycles

Cold and cryogenic treatment processes in this study consist of three main periods and soaking time, the most important stage for the final properties, was kept same for both treatment cycles for a valid comparison. The thermal cycle for the cold treatment was as follows: Linear ramp from room temperature to -150 ºF in about 4 hours, dwell at -150 ºF for 8 hours (soaking stage), warm by ambient heat gain into closed chamber to near room temperature over approximately 10 hour, linear ramp up to +300 ºF in 1 hour, dwell at +300 ºF for 1 hour, allow to cool in open chamber back to room temperature. And, the thermal cycle for the cryogenic treatment was as follows: linear ramp from room temperature to -300 ºF in 6 hours, dwell at -300 ºF for 8 hours (soaking stage), warm by ambient heat gain into closed chamber to near room temperature over approximately 52 hour, linear ramp up to +300 ºF in 1 hour, dwell at +300 ºF for 1 hour, allow to cool in open chamber back to room temperature.

3.3 EDM Tests

Experiments were conducted on ZNC/50A Drilling Electro-Discharge Machine at the Center for Nontraditional Manufacturing Research (CNMR) in the University of Nebraska-Lincoln (UNL). Experimental conditions are given in Table 3.

Workpiece material	Moldmax Be-Cu (26x26x13)
Tool electrode	Copper rod (Ø3x300 mm)
Dielectric medium	Commonwealth oil EDM-244
Working Current (A)	10, 15, 20, 25
Pulse On/Off Time (μsec)	20, 40, 60, 80
Duty Factor (%)	50

Table 3: EDM experimental conditions

A full factorial design (4x4) experiment with two factors and four levels was conducted to study the effect of various process parameters in the drilling of mesoscale holes in Be-Cu alloy workpieces. The experiments were repeated two times to reduce possible errors and means of these results were used for the evaluation. Other inputs such as working voltage, capacitance, spindle speed, gap voltage, servo feed speed and water pressure were kept constant as 150 V, 3 μF, 187 rpm, 20 V, and 50, 75 kg/cm^2 respectively. Flushing was provided from two inside holes of the electrodes. 20 mm drilling depth was set to obtain a blind hole.

4 RESULTS AND DISCUSSION

4.1 Electrical Resistivity/Conductivity

Electrical resistivity/conductivity tests were performed in NCEE Labs at Lincoln-Nebraska to determine the effect of cold and cryogenic treatments on subjected materials. Figure 2 shows electrical resistivity testing system. This system consist of one DC regulated power supply for voltage (BK Precision 1692), two multimeter (Fluke 45 Dual Display) for voltage and current readings, four resistors (Milwauke 11/00, 8 ohm, 12M59-8, Pat. 3581266, +-10%) and a fixture for handling of the sample to be measured resistivity. Resistors R_1, R_2, R_3 and R_4 were connected parallel to each other. The system works depending on basic Ohm's law for direct current (non-time varying current) circuits. The calibration of the system was performed by running the system without including sample. Calculation of the electrical resistivity and conductivities were done by the following formulas. Where "R_y" is the resistance of the system without including sample, "V" is the voltage (volts), "I" is the current (amps) supplied by the power supply, "R_x" is the resistance of the sample, "σ" is the electrical conductivity (mhos) and "ρ" is the electrical resistivity (Ωm). The values of voltage and current are measured by using calibrated multi-meters. This method was used in order to increase the current and voltage into a range where the resistance of the sample can be calculated.

$$R_y = R_1 + R_2 + R_3 + R_4 = V/I \quad (1)$$

$$R_x = (V - I \times R_y)/I \quad (2)$$

$$\sigma = 1/\rho \quad (3)$$

Figure 3 shows graphs of electrical conductivity measurements for cold and cryogencially treated copper and beryllium-copper materials. Electrical conductivity of beryllium-copper work-pieces were increased around 5% and 13% by cold and cryogenic treatments respectively. One reason is that, the thermal vibration of atoms in a metal will be weaker as the temperature decreases and these vibrations make the electrons easier to move through their way. As a result, this phenomena lead to decrease of electrical resistivity which means the electrical conductivity of a metal will be increased [23]. One of the findings concerning reasons for the effects of cryogenic treatment is transformation of retained austenite into martensite and the other is strengthening of the material in terms of wear resistance caused by precipitation of large numbers of very fine carbides for steel materials [17]. However, in the case of copper alloys, it was claimed that the cryogenic process increases the homogeneity of the crystal structure, dissolving gaps and dislocations of the alloying elements and consequently, the resulting improved structural compactness improves electrical conductivity [24]. In addition, another claim could be that tempering process after cold and cryogenic treatments could cause growth of grains in microstructure of Be-Cu alloy and this phenomenon resulted in reduction of grain boundaries and thus reduction in electrical resistivity. Similar studies [21, 24] have also reported increase of electrical conductivity after cryogenic treatments especially followed by tempering. Increases and decreases in electrical conductivities of materials would also cause increase or decrease of thermal conductivities of those materials as per Wiedemann-Franz-Lorenz Law [22].

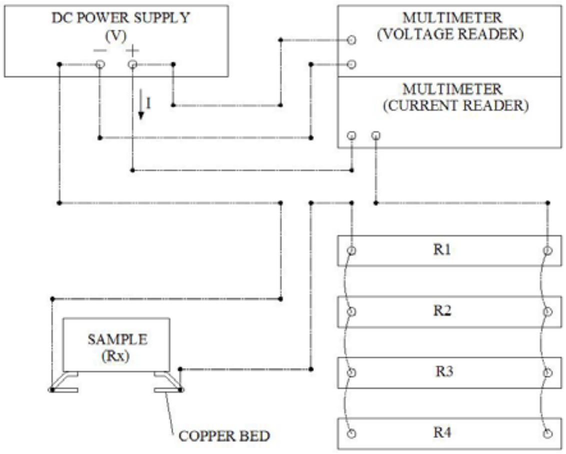

Figure 2: Electrical resistivity testing system

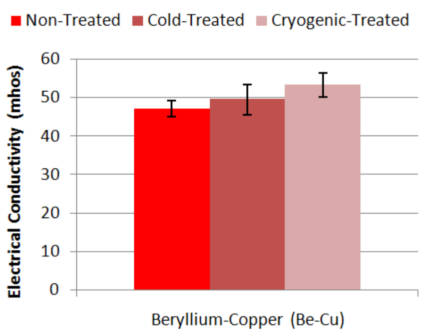

Figure 3: Results for electrical conductivity measurements

4.2 Material Removal Rate (MRR)

Material removal rates were determined by weight difference of the specimens before and after machining using a Sartorius precision scale type E-1200S having maximum 1210 g capacity and 0.001 g readability. Following calculation was used for MRR, where w_f is the first weight of the workpiece before EDM process, w_l is the last weight of the workpiece after EDM process, t_{sec} is the time of EDM process and ρ is the density of used workpiece material.

$$MRR = \left[w_f - w_l\right] / \rho \cdot t_{sec} \quad (1)$$

Material removal rates obtained under different experimental conditions are shown in Figure 4. Current is the most effective parameter affecting the MRR as shown previously in numerous studies. Based on data means, there is a 317% increase in MRR from 0.212 mm^3/sec for 10 A to 0.884mm^3/sec for 25A. Reason for this behavior is straightforward. When the working current is increased, more energy is supplied to the machining process and therefore, more material is removed. The MRR variations could be assumed negligible depending on pulse durations. In the case of using treated workpieces, MRR increased averagely by about 19% with cold treatment and by about 20% with cryogenic treatment according to data means. However, there were more remarkable results in some conditions. For example, MRR increased from 0.743mm^3/sec to 0.952mm^3/sec with cold treatment and to 0.982mm^3/sec with cryogenic treatment for the experimental condition with 80µs pulse on/off time and 25A working current. Increases in MRR are 28% with cold and 32% with cryogenic treatment in that condition. In addition, it should be noted that MRR differences between EDM of non-treated, cold-treated and cryogenically-treated Be-Cu workpieces are increased remarkably by increasing working current. As a result, it can be inferred that machinability performance of cold or cryogenically treated Be-Cu workpieces are superior at higher working currents. These increases in MRR will be especially related to increase in electrical conductivities of the Be-Cu alloys after cold and cryogenic treatments. On the other hand, melting point of a material can decrease by reduction in hardness, which can be result of a cold or cryogenic treatment [22], and the reduction in melting point will increase MRR by electrical sparks [25]. Another interesting result was obtained in a test condition with 25 A current and 20 µsec pulse duration. The highest MRR was obtained for non-treated, cold treated and cryogenically treated Be-Cu alloys in that condition. These results could be related to 50% duty factor since the discharge delay time will be less in lower pulse on times in comparison to large pulse on times. However, clear differences between MRR results of nontreated and treated materials were seen in 80 µsec pulse duration. So, wider intervals between pulse durations could be more useful for a better comparison.

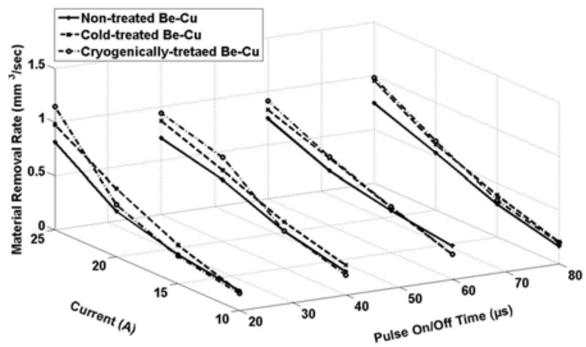

Figure 4: Material removal rate results

4.3 Electrode Wear Ratio (EWR)

Electrode wear ratios or relative electrode wears were determined as percentage by following equation, where V_T is the volume difference of tool (electrode) before and after EDM process and V_W is the volume difference of workpiece before and after EDM process.

$$EWR = \left[V_T / V_W\right] \times 100 \quad (1)$$

Figure 5 shows the experimental results for EWR. According to the main effects of data means, electrode wear ratio was increased by about 50% between 10 A and 25 A working currents. However, there was a decrease about 14% in EWR between 20 µsec and 80 µsec pulse durations. On the other hand, alterations in EWR results in using of cold and cryogenically treated Be-Cu workpieces are negligible. However, it was also seen some important reductions in EWR by cold and cryogenic treatments for some test conditions having higher working currents.

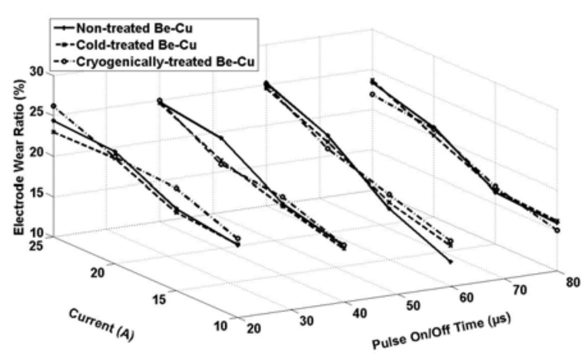

Figure 5: Electrode wear ratio results

4.4 Average Surface Roughness (R_a)

The average surface roughness R_a was measured using an AMBIOS XP-2 Stylus Profiler with maximum vertical range of 100 µm. Stylus speed, stylus tip radius, stylus force, measurement length and data points were 0.05 mm/sec, 2.5 micron, 10 mg, 10 mm and 12500 respectively. All measurements were done through hole beginning after 1 mm from top surface. The calibration was made before the measurements. All samples were cleaned in acetone by using an ultrasonic cleaner (3210 Branson) for 20 minutes before the measurements. Figure 6 shows surface roughness measurement results.

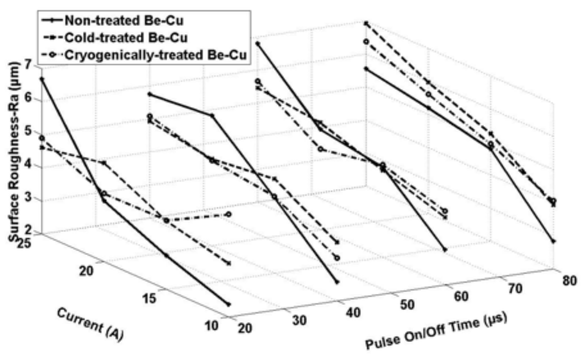

Figure 6: Surface Roughness (R_a) results

As expected, roughness values in general increase with corresponding increase in discharge energy [26]. According to data means, increase of working current increased R_a about 60% between 10A and 25A. R_a increased about 20% by increasing of pulse duration from 20µs to 80µs. The using of cold and cryogenically treated workpieces also resulted with increased R_a around 6% and 4%. These increases can be seen clearly at the experimental condition with 80µs pulse duration. It was assumed that the higher MRR of cold and cryogenically treated workpieces caused increases for R_a. The differences between results of cold and cryogenically treated workpieces are negligible. However, interesting result is that frequency analysis of the results showed that standard deviation, variance and range intervals of the surface roughness values of nontreated Be-Cu alloy workpieces were wider than the surface roughness values of cold and cryogenically treated Be-Cu alloy workpieces depending on increase in working current. So, it can be inferred that surface integrity of cold and cryogenically treated Be-Cu alloy workpieces are more stable or they are deteriorated less than the surface integrity of nontretaed Be-Cu alloy workpieces after EDM process. Additionally, R_a formations with 20µs, 40µs and 60µs pulse durations are not stationary as in 80µs pulse durations for all test conditions. These results could be related to characteristics of EDM process because of the fact that flushing cannot be effective in all experimental conditions and thus melted materials in the hole cannot be removed effectively. Consequently, hole surface formations become irregularly after melting and re-solidification processes.

4.5 Average White Layer Thickness (AWLT)

White layer or recast formed on EDM machined surfaces significantly differs from the base material in the metallurgical structures. So, it is easy to determine the thickness of the recast layer with an optical microscope after an appropriate etching process. In this study, all samples were first mechanically polished using 240, 320, 400 and 600 grit wet sand paper followed by 3, 1 and 0.05 micron aluminum oxide abrasives on polisher for the white layer formation investigations. The polishing time was 15 min., speed was 25 rpm and force was 8 pounds for this process. Finish polishing was done using diamond paste. After mechanical polishing, the samples were chemically etched by 20 ml. ammonium hydroxide (NH_4OH), 8-20 ml. 3% hydrogen peroxide (H_2O_2) and 0-20 ml. distilled water (H2O). This etchant is recommended for copper and beryllium-copper alloys [27]. Chemical etching was carried out on the surface of the materials for 1 to 5 sec. and then those surfaces were cleaned by water. After etching, the samples were viewed in 200x and 500x magnification using a Leica DM 2500 M optical microscope. For the AWLT measurements, the hole edge pictures were studied using a commercially available software (Photoshop) and the measurement values were obtained by pixel-micron conversion. These measurements were performed from hole beginning to 10mm deep at 2mm intervals and 15 measurement on each interval. So, average means of totally 75 measurement values were obtained for each hole to reduce error. Figure 7 shows average white layer thickness measurement results for cold and cryogenically treated workpieces. According to data means, AWLT increased about 38% between 10A and 25A and it increased about 43% from 20µs to 80µs pulse duration. There were decreases (3.4% and 2.8%), which could be assumed insignificant, in AWLT formations in using of cold and cryogenically treated Be-Cu alloy workpieces. These results could be related to higher electrical and consequently higher thermal conductivity properties of cold and cryogenically treated Be-Cu alloys in comparison to those nontreated materials. Because, white or recast layer formations is result of high temperatures on electro discharge machined surfaces after melting and resolidification processes [28]. So, thinner recast layer formations were seen in some conditions, which could be related to better heat dissipation property of the cold and cryogenically treated Be-Cu alloy workpieces.

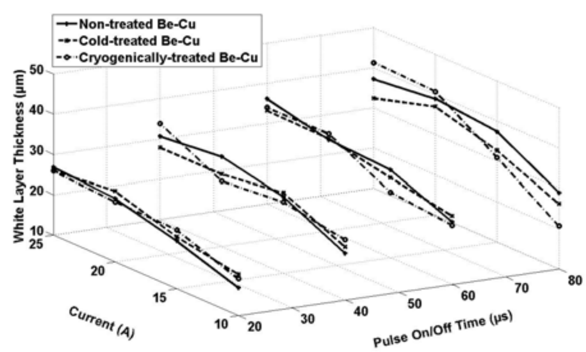

Figure 7: Average white layer thickness results

5 CONCLUSIONS

In this study, Be-Cu alloy workpieces were subjected to around -150° F for cold treatment and to around -300° F for cryogenic treatment and the effects of cold and cryogenic treatments on their machinability in EDM have been investigated. Experimental results showed about 20-30 % increase in material removal rate by cold and cryogenic treatment processes. Variations in electrode wear rate, surface roughness and average white layer thickness were found to be marginal. Supplemental electrical/thermal conductivity tests can be utilized in the future attempts. In addition, different combination of processes including deeper cryogenic temperatures down to -273 °C and variable tempering stages can be evaluated. Different kind of electrode-workpiece material pairs should be subjected to cold and cryogenic processes for the future EDM machinability researches.

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