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Influence of Cryogenic Coated Copper Tool Electrode in Electrochemical Micro Machining process of Stainless Steel 316

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Highlights

- The Cryogenic Treated tool electrodes results in higher MRR due to higher electrical conductivity.
- Better overcut has been obtained using Cryogenic Treated tool electrode.
- The Conicity values obtained while machining with Cryogenic Treated tool electrode is better.
- The Circularity of the hole machined with Cryogenic treated tool is better.
- The optimized values for Cryogenic Treated tool was achieved.

Abstract

Electrochemical micro-Machining (ECMM) is best suited for machining micro level profiles as it provides several advantages like better precision, less wear and machinability of wide range of materials. Micro level holes in Stainless Steel 316 are generally present in surgical equipment like syringe, suction tips and surgical suture etc. Using various levels of process parameters like voltage, electrolyte concentration, frequency and duty cycle, electrochemical micro machining was performed using untreated and cryogenic treated electrodes and its effect on various response parameters while machining Stainless Steel 316 are studied. From the results obtained, the cryogenic treated tool electrode had a high MRR, 9.8 % of lower overcut, 11.2 % of lower conicity and 3.8 % 0f higher circularity compared to untreated tool electrode because the treated tool has high electrical conductance, high corrosion resistance and smaller grain size. The optimized values for Cryogenic Treated tool was achieved when applied voltage was 10V, electrolyte concentration was 30 g/L, frequency was 50 Hz and duty cycle was 33 %.

Keywords
Cryogenic, TGRA, MRR, ECM, overcut

1. Introduction

Non-conventional machining methods are crucial in modern manufacturing for handling difficult-to-machine materials, achieving tight tolerances, and creating complex geometries that traditional machining cannot accomplish [1, 2]. They have wide-ranging applications in industries such as aerospace, automotive, medical, and semiconductor manufacturing [3]. The effects of process parameters such as electrolyte concentration (EC), applied voltage, machining current,

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frequency and duty cycle on material removal rate (MRR) in Electro Chemical micro machining (ECMM) process during machining of stainless steel. It was observed that the duty cycle is the most influencing, parameter on MRR [4]. It was said that ECMM was believed to be one of the few more effective advanced micro machining methods that may be used to meet a broad variety of applications [5]. Based on the findings of the experiment, it has been determined that the most common factors, including voltage and electrolyte concentration, provide improved MRR with a reduced overcut [6]. The experiments ECMM processes were conducted with process parameters such as voltage supplied, concentration of electrolyte, feed rate and duty cycle on MRR, roughness (R_a) for various parameter levels using two different electrolytes. The formation of sludge error occurs on repeated occasions and thus memory errors seem to occur and addressing of wastage and accuracy improvement is the only answer [7]. The experiment has to be verified the predicted results using an ECM system. The passivating electrolyte reduces the sludge formation and provides better accuracy. The research has provided a method for bettering the machining accuracy by using a tool and the epoxy coating [8]. The field of current in the gap present in the sides is removed as the bush is connected as it is connected to the anode and the side gap area of the machining is weakened. A study was provided to determine the current efficiency in electrochemical processing using an electrochemical current determination of HSS from sodium nitrate [9]. The influence of the density of current, concentration of electrolyte and temperature, and the flow rate on the efficiency of were determined. A micro-tool vibration system was manufactured, with a tool holder and vibrator [10]. The manufactured setup controls the accuracy of machining and MRR. Micro holes were drilled on a thin job by ECMM using a micro-tool. The influence of process characteristics on surface roughness, using Titanium alloy Ti 60 was presented [11]. It was concluded that frequency of pulsed power supply and temperature are the parameters influencing ECMM using Titanium alloy. It was observed that the R_a is directly proportional to temperature. The usage of short pulse current influence was studied in electrochemical micro machining [12]. Very short current pulses and micron level IEG gave best micro machining. The performance of Nickel coated Tungsten tool electrode on ECMM was performed [13]. This study concluded that coated tool has higher corrosion resistance and produce better shape accuracy compared to bare tool. A study was performed on carbon fibres as tool electrodes in ECMM [14]. Since carbon fiber is electrically conductive, smaller overcuts and small cut geometries could be achieved. A number of distinct tool designs were evaluated in terms of their performance in ECMM [15]. Changing the concentration of the electrolyte allowed for the determination of the MRR and Overcut using tool electrodes that were wedged, flat, and conical with rounded surface areas. The influence of Treatment at Cryogenic temperature of Tungsten micro tool was done on wear rate in ECMM. The corrosion resistance has been improved during ECMM using treated tungsten electrode [16]. It was concluded that the Electrical Conductivity increases upon Cryogenic treatment due to the compressive stress generated. The grain boundaries are significantly increased and the grain boundary area is increased [17]. The comparison was made of various machining process parameters like applied voltage, concentration of electrolyte and frequency on output parameters [18] under L_{27} orthogonal array (OA). The voltage and electrolyte concentration were the most influencing factors on material removal rate and overcut [19]. According to the findings, the pace of machining and the amount of overcut were directly related to the voltage that was applied and the concentration of the electrolyte. The properties of Ti-6Al-4V in 10% $NaNO_3$ solution in ECMM process [20]. With the help of polarization and current efficiency curve, it was noted that holes can be obtained in a 10% $NaNO_3$ solution. The MRR and surface roughness value using annealing was optimized and the effect of input characteristics were found by optimization while machining EN19 steel [21]. A research was done to find the influence of electrolyte on MRR using standard orthogonal L_9 array [22]. The input characteristics like voltage, EC and Inter-electrode gap (IEG) was chosen. The applied voltage was the most influential parameter on affecting MRR. It was concluded that KOH has a higher material removal rate than K_2SO_4. A multi response optimization using Taguchi-Grey analysis was investigated for Electrochemical Machining on Inconel 625 [23]. Feed rate (FR), rate of flow and EC were used as input factors. Overcut, form and tolerance were chosen as response characteristics. The FR was the most influential parameter for desired performance characteristics. The influence of ECMM on MRR of Beryllium copper C17200 was performed [24]. The input characteristics considered are concentration of electrolyte and machining voltage. It was concluded that feed rate was the most influencing parameter on MRR. The effect of using Taguchi analysis was studied to optimize the characteristics with a number of responses in ECM of aluminium (Al) specimens [25]. It was further found that the machining can be improved by using the optimum parameters found using Taguchi analysis. The performance of various electrodes and input characteristics on MRR and roughness was presented in ECM on machining AISI D2 [26, 27]. The effect on machining parameters were found using ANOVA and regression analysis in MiniTab 16 software. It was concluded that inter electrode gap was the most influential parameter for MRR and electrolyte concentration for R_a [28, 29]. It was concluded that the selected input parameters could significantly influence the chosen output parameters in the machining process.

Despite the fact that there are several works accessible to explore the impact of various electrodes on the performance of ECMM, there are less works that are related to the use of cryogenic electrodes in the process. Because of this, the current study was carried out. The main objective of this study on machining of cryogenic treated copper(Cu) tool electrode in the ECMM with different process parameters are as follows.

- To examine the effects of cryogenic treated Cu tool electrode on electrochemical micro machining process.
- To investigate the various output parameters such as MRR, Overcut (OC), Circularity (CY) and Conicity (CO) by altering the process parameters.
- To optimize the quality measures of electrochemical micro machining process using Taguchi GRA.
- To find the most significant parameters on electrochemical machining using analysis of variance.

2. EXPERIMENTS AND METHODS

Figure 1 depicts the experimental system features in the ECMM arrangement that was constructed by Sinergy Nano Systems (Navi Mumbai, India) for the current work. The electrochemical process Micro Machining is a procedure that is carefully monitored and regulated, and it includes the removal of conductive material in an electrolyte chamber. In this chamber, the (+) ve polarity is linked to the tool electrode, while the (-) ve polarity is attached to the specimen. The DC pump, stepper motor, and pulsed energy system are the primary components that make up this ECMM framework. Additionally, the acyclic tank is 200 mm by 100 mm by 80 mm, and it has a capacity of 1.5 litres. A Stepper Motor that is controlled by the microcontroller is responsible for providing power for the tool holder's vertical motion. In order to begin drilling the hole in the specimen using the system, the input that is provided for it includes the parameters supply voltage, feed rate, and duty cycle.

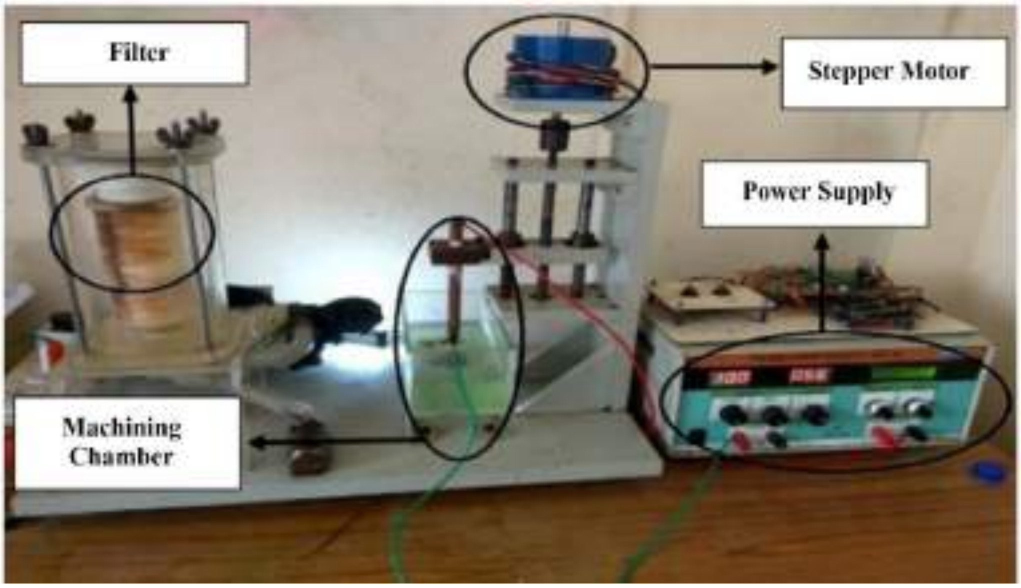


Fig. 1. ECMM setup used in the present work.

2.1. Cryogenic Treatment

The cryogenic tool electrode has high electrical conductance, high corrosion resistance and smaller grain size than normal tool electrode [29, 30]. Cryogenic treatment is a process where a material is treated at -196 ˚C, which is the boiling point of liquid N_2. Cryogenic Treatment was comprised of 3 stages such as cooling period, soaking period and reheating period. In cooling stage, the material is to be cooled gradually from room temperature to -196 ˚C. The material has to be soaked for a particular time period based on type of Cryogenic treatment. In reheating stage, the material which is at cold temperature is gradually back to room temperature gradually [29, 30]. The Cryogenic Treatment setup consists of a Cryocan, Canisters made of Copper, a PT100 Sensor and a digital Temperature indicator. The Cryocan is made up of Double walled Stainless-Steel material with a fibre glass neck. Tool electrodes are to put into the cylindrical Copper canister which is connected to a PT100 sensor while immersing the tool electrodes into the Cryocan filled with Liquid Nitrogen for Cryogenic treatment as shown in Figure 2.

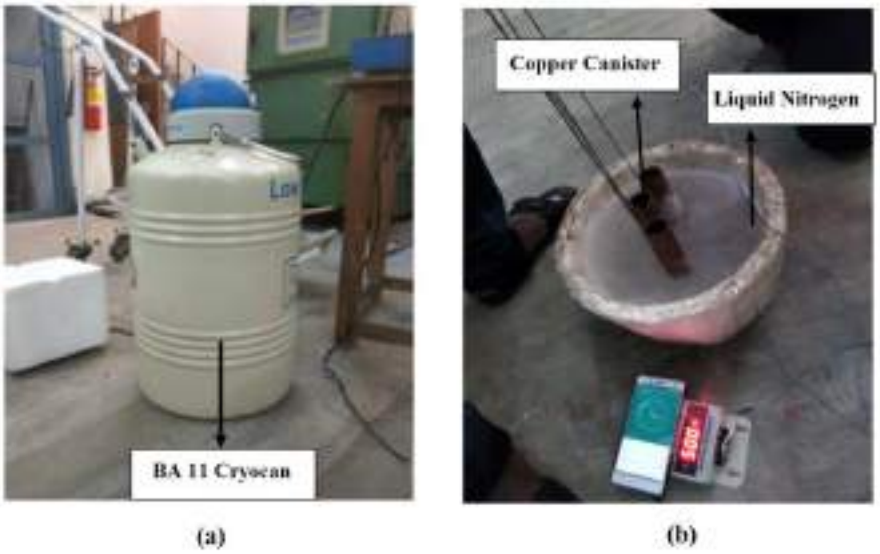


Fig. 2. Cryogenic Treatment Setup (a) Cryocan (b) Canisters in Liquid Nitrogen.

Due to cryogenic treatment the metal ion spacing is reduced and the lattice distortion is reduced. At the same time, shrinkage of grain boundaries occurs and the vacancy concentration decreases sharply. Thus, the Electrical conductivity of Cryogenic Treated Copper Tool electrode is improved when compared to Untreated Tool electrode. The electrical conductivity of copper tool electrode has been measured before and after Cryogenic Treatment using Agilent Desktop Multimeter which has a range of 1 micro ohm to 100 ohm. There are totally 6 trials have been performed to enhance the measuring accuracy. Table 1 shows the increaser in electrical conductivity of the tool electrode after cryogenic treatment. During treatment, it has been resulted in grain structure change of the tool material. Hence, the tool electrode will undergo corrosion to a certain extent due to the electrolytic reactions during the machining process. This hinders the flow of current. All these factors cause a decrease in electrical conductivity.

Table 1. Electrical Conductivity of Tool Electrode after treatment.

Tool No.	Electrical conductivity of untreated tool electrode (S/m) $*10^{-6}$	Electrical conductivity of treated tool electrode (S/m) $*10^{-6}$
1	0.336	2.58
2	0.731	2.212
3	0.262	0.323
4	0.280	0.431
5	0.289	0.374
6	1.06	1.449

2.2. Selection of Workpiece specimen

Stainless Steel (SS) 316 is commonly mainly used in Surgical Equipment as it has high resistance to corrosion and non-reactive with body fluids. The specimen used in this study is Stainless Steel 316. SS is an alloy, whose composition consists of Iron, Chromium (Cr), Nickel (Ni), Molybdenum (Mo), Manganese etc. at different percentages by weight as shown in Table 2. Since it contains high percentage of molybdenum and nickel, it is highly resistant to corrosion compared to other grades. It was also chosen due to its low cost and availability. The tool electrode material selected was a Cu of 0.5 mm diameter under with and without cryogenic treatment. The Inter-electrode gap (IEG) has been maintained at 50 microns.

Table 2. Chemical composition of SS 316.

Elements	Fe	C	Mn	Si	S	T	Ni	Cr	Mo
Composition	68.27	0.036	0.64	0.43	0.004	0.023	11.81	16.78	2.01

2.3. Range of the process factors

These are the variable parameters that were selected as input process parameters for this analysis since the ECMM technique places a significant emphasis on the importance of variable parameters. The applied voltage (AV), is the potential difference between the tool, which acts as the cathode, and the workpiece, which acts as the anode. The values of 9 V, 10 V, and 11 V were selected based on the parameters of the equipment. The quantity of salt that is dissolved in one litre of water is referred to as the concentration of the electrolyte (CE). 20, 25 and 30 grams of the electrolyte were added to one litre of distilled water, respectively. The frequency (f) for the machining process was set at 50 Hz, 60 Hz, and 70 Hz respectively. Duty cycle, often known as DC, refers to the amount of time that the energy is distributed across the zone. This machining will use a duty cycle percentage that is comprised of 33, 50, and 66 percent. $NaNO_3$ is a passivating electrolyte that has less throwing power than other electrolytes. As a consequence, it eliminates more material, which leads to a high machining rate and accuracy.

2.4. Measurement of Performance Measures

It was decided that MRR, overcut (OV), conicity (CY), and circularity (CI) would be the response measurements that would be carried out in order to ensure that the experiment would be considered successful. During the machining process, the MRR, which stands for the quantity of material removed per minute, may be calculated using Equation 1 [28].

$$\mathrm{MRR} = \frac{\mathrm{W1} - \mathrm{W2}}{\rho \cdot \mathrm{T}} \quad [\mathrm{mm3/min}] \qquad (1)$$

Where W1 represents the weight of the workpiece before to machining in grams, W2 represents the weight of the workpiece after machining in grams, T represents the amount of time required for machining in minutes, and ρ is the density of the material in grams per cubic centimeter. The change in diameter from the tool and the machined hole can be termed as overcut (OC) and was calculated using Equation 2.

$$\mathrm{OC} = \frac{D_i - D_t}{2} \qquad [\mu\mathrm{m}] \qquad (2)$$

D_t is the diameter of the external tool in millimeters, and D_i is the average diameter of the workpiece in millimeters. The degree of straightness of the through-hole that is machined is referred to as conicity (CY), and it is possible to determine it using Equation 3.

$$\mathrm{CY} = \frac{\text{Diameter at entry} - \text{Diameter at exit}}{2 \cdot \text{hole thickness}} \qquad [\mathrm{mm}] \qquad (3)$$

The circularity (CI) of a cylinder, sphere, or cone establishes the permissible amount of deviation from an ideal circular form for each circular portion of the shape. The diameter of the machined hole's circumscribed circle is the maximum diameter, whereas the diameter of the machined hole's inscribed circle is the lowest diameter. It is calculated using the vision measurement equipment, and the results are expressed in millimetres (mm). Using the three-point method, measurements were taken of the machine vision system in order to determine the circularity.

2.5. Taguchi – Grey Relational Approach (TGRA)

The number of trials was calculated by using the Taguchi method, and the L_9 orthogonal array (OA) was used to figure out the experimental design. Because this investigation focused on four characteristics and three levels, L_9 OA was determined to be constant, as seen in Table 3. Because of their impact on productivity, the response variable percentages of MRR, OV, CY and CI are considered output process parameters. The steps involved in TGRA technique are provided below.

First step: convert the replies into a signal-to-noise ratio.

Second step: is to convert the signal-to-noise ratio to the normalized S/N ratio.

Third step: Determine the grey relational coefficient for the normalized signal-to-noise ratio

Fourth Step: Determine the Grade of the Grey Relationship

Fifth step: Performing the computation of the Grey Relation Grade for the level of process parameters

Table 3. Experimental Design with Cryogenic and normal Tool Electrode of ECMM process.

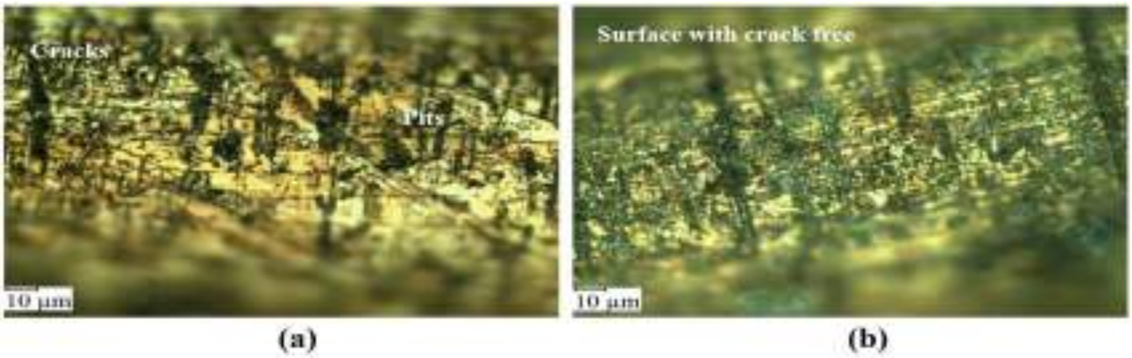
Exp No.	AV [V]	EC [g/L]	f [Hz]	DC [%]
1	9	20	50	33
2	9	25	60	50
3	9	30	70	66
4	10	20	60	66
5	10	25	70	33
6	10	30	50	50
7	11	20	70	50
8	11	25	50	66
9	11	30	60	33

3. RESULTS AND DISCUSSION

The thickness of the workpiece specimens that were drilled for 5 millimetres using ECMM process. After that, a discussion and analysis of the experimental values that were obtained using the L_9 technique were carried out, and a comparison of the performance of a cryogenic copper electrode and normal copper electrode was also carried out.

3.1. Surface topography analysis of cryogenic and untreated copper tool electrode

SIPCON vision measuring system was used to observe the surface topography of tool electrodes during the ECMM process. As per ASTM standard, the surfaces were polished prior to the investigation. With the cryogenic treated electrodes, the surface of the instrument was observed to have fewer cracks [31]. This has resulted in the cryogenic treated electrode developing a smooth surface, as can be seen in the photographs of the surface morphology. Comparatively, the copper tool electrode that has not been treated with cryogenic treatment has a lower electrical conductivity than the tool electrode that has been treated with cryogenic treatment.



(a) (b)

Fig. 3. Surface topography of Cu electrode after machining (a) Untreated (b) Cryogenically treated.

Figure 3 illustrates the surface morphology of copper tool electrodes that have been ECMM machined after being uncoated and silver-coated, respectively. Owing to the transfer of ions from the tool to the specimen, the surface morphology images of tool electrodes after machining reveal an increase in pits and craters [32]. Due to cryogenic treatment the metal ion spacing is reduced and the lattice distortion is reduced. At the same time, shrinkage of grain boundaries occurs and the vacancy concentration decreases sharply. Thus, the Electrical conductance of Cryogenic Treated Copper Tool electrode is improved than Untreated Tool electrode.

3.2. Effect of Cryogenic treated electrode on MR

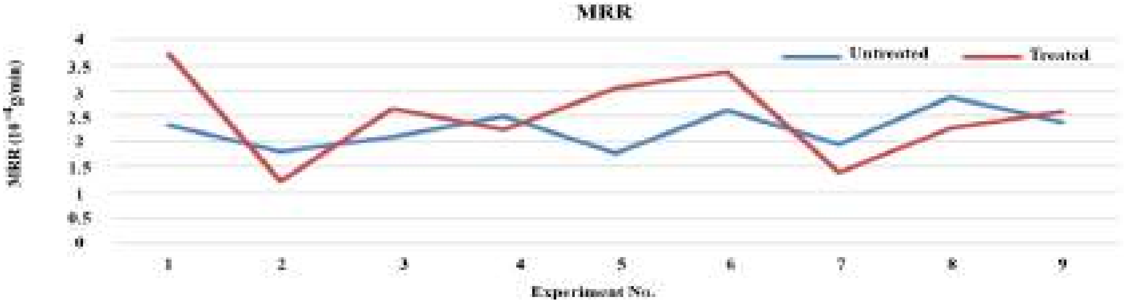


Fig. 4. Comparison of MRR between Bare and Cryogenic Treated Tool Electrode.

From the fig 5, it was realized that the MRR of treated tool is 10.8 % more than the untreated tool. Experiment 1 shows a maximum MRR. The process parameter for this experiment shows that it has a duty cycle ratio of 33 %. This means the pulse-on time is less and flashing time is more. During the flashing time, the material removed during machining is washed out. So, there won't be any deposits left on the machining place. Since the electrical conductance of tool increases after cryogenic treatment, even the less pulse on time is enough to remove more material.

The maximum value of MRR is obtained at 50 Hz and decreases with increase in Frequency. At lower frequency the Ton time is less than Toff time and hence the material that is machined when current is passed through the tool is removed during the Pulse OFF time, thus it has higher MRR. At higher frequency the Ton time is more than the T_{off} time and hence the time available to remove the machined material during pulse OFF time is less which makes the tool touch the workpiece that generates spark [33]. To continue machining the tool has to lifted up to prevent it from touching the workpiece. This delays the machining time, thus reducing MRR. Duty Cycle is the second most influencing parameter. MRR is high at higher Duty Ratio and reduces with decreasing duty ratio. This is because the time for which the current supplied is high at 66 % and low at 33 % hence the material removed is low at 33 % and high at 66 %. AV is the third most influencing parameter. For this tool the MRR increases with increase in applied voltage. This is because it has lesser electrical conductivity than treated tool and hence when the voltage is high, more material is removed per unit time. The least influencing parameter for untreated tool is Electrolyte concentration. MRR is high at both lower and higher electrolyte concentration. The most influencing parameter of MRR for Treated tool is Duty Cycle. Since the electrical conductivity of treated tool is high, less Pulse ON time at 33 % is enough to machine the hole at less time thus improving MRR. At 66 % the current is supplied for more time and the flashing time is less which produces spark as the tool touches the workpiece thus reducing MRR. At 50 % duty ratio the material removal and flashing time are equal and hence at this level the MRR is less than the other two levels. The second most influencing parameter is Frequency. Like duty cycle, MRR is high at low Frequency and less at high Frequency. At 50 Hz the flashing time is more and hence the removed material is flushed away from the top surface improving MRR. At 70 Hz flushing time is less which causes the tool to touch the workpiece surface reducing MRR. The next most influencing parameter is Applied voltage. Maximum MRR is obtained at 10 V and minimum MRR is obtained at 11 V. A decrease in voltage is sufficient to remove a greater quantity of material as the electrical conductivity of the tool electrode gradually rises. However, sparks are formed at 11 V, which results in a decrease in the MRR. The electrolyte concentration is the parameter that has the least amount of influence, with the highest MRR being achieved at 30 g/L and the smallest MRR being produced at 25 g/L. When the concentration is greater, the number of NO_3 ions that are accessible is also larger, which results in a higher MRR. On the other hand, when the concentration is low, the voltage that is applied helps to enhance the MRR.

Anode Reactions:

$Fe \Longrightarrow Fe^{2+} + 2e^-$

$Cr \Longrightarrow Cr^{3+} + 3e^-$

$Ni \Longrightarrow Ni^{2+} + 2e^-$

Electrolytic Reaction:

$NaNO_3 \Longrightarrow Na^+ + NO_3^-$

Material removal reaction:

$Fe(OH)_2 + 2NaNO_3 \Longrightarrow Fe(NO_3)_2 + 2NaOH$

$Cr(OH)_3 + 3NaNO_3 \Longrightarrow Cr(NO_3)_3 + 3NaOH$

$Ni(OH)_2 + 2NaNO_3 \Longrightarrow Ni(NO_3)_2 + 2NaOH$

Cathode Reactions:

$2H^+ + 2e^- \Longrightarrow H_2$

3.3. Effect of Cryogenic treated electrode on overcut

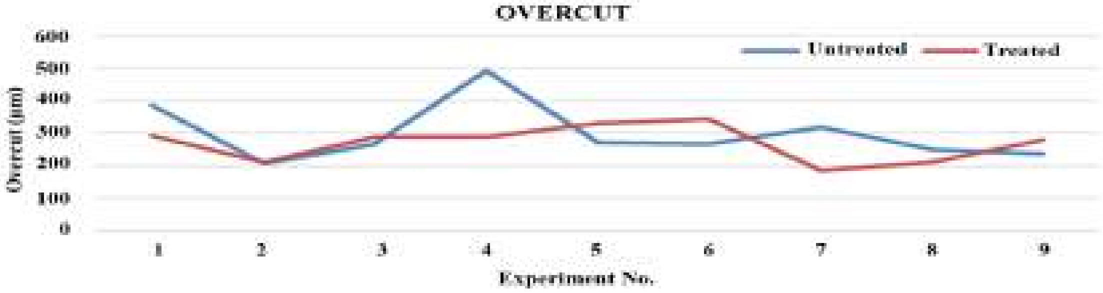


Fig. 5. Comparison of OV between Bare and Cryogenic Treated Tool Electrode.

From figure 6, it was found that the treated tool has 9.8 % smaller overcut than the untreated tool. Experiment 7 shows less overcut. The process parameter for this experiment shows that it has voltage of 10 V, 20 g/L of EC, frequency 70 Hz and duty ratio of 50 %. Since the electrolyte concentration is less the MRR will be less. The T_{on} time and T_{off} time is 7.14 ms at 50 % duty ratio.

Since the time taken to machine the workpiece and removing machined material from the surface are same and the amount of current passed is moderate at 10 V the overcut obtained is less. 20 g/L is the most amount of overcut that can be achieved, whereas 25 g/L is the smallest amount that may be achieved. It is inevitable that there would be stray current around the tool electrode whenever current flows through it. A greater amount of material will be machined around the hole by the stray current since the bubble that is produced is of a tiny size. In situations when the concentration of electrolyte is greater, the size of the bubble that is created is larger. This prevents the stray current from flowing, which creates reduced overcut.

Applied voltage is the second most significant parameter with maximum overcut obtained at 10 V, and minimum OC obtained at 11 V. As the Voltage increases, current passing through tool tip increases and so the amount of material removed is more, but other factors help to reduce the Overcut. Duty Cycle is the third most significant parameter. Maximum Overcut is obtained at 66 % while minimum Overcut is obtained at 50 %. At 50 % duty ratio the material removal and flushing time are equal and hence at this level the Overcut is less. At 66 % of duty ratio, the material removal time is more than flushing time, and so higher Overcut is obtained. Frequency is the least influencing parameter with maximum Overcut obtained at 60 Hz and minimum Overcut obtained at 70 Hz. Applied Voltage shows the most deviation for Treated tool electrodes. The maximum overcut is obtained at 10 V and the minimum overcut is obtained at 11 V. The resistance is linearly proportional to temperature. When applied voltage is high, the temperature of the tool electrode increases, hence resistance increases. When resistance is high the current across the tool is low which resulting to a low overcut.

The second most influencing parameter is Electrolyte Concentration. Minimum OC is obtained at 25 g/L while maximum Overcut is obtained at 30 g/l. As electrolyte concentration increases, the ions present in the electrolyte increases thereby increasing material removal amount thus increasing the Overcut. The third most influencing parameter is Duty Cycle with maximum Overcut obtained at 33 % and minimum Overcut obtained at 50 %. At 50 % duty ratio, machining time and flushing time are same and so less overcut is obtained. Frequency is the least influencing parameter for Overcut with minimum value obtained at 60 Hz and maximum value obtained at 50 Hz. At 60 Hz and 50 % duty ratio, the T_{on} time and T_{off} time is 8.33 ms while at 50 Hz and 33 % duty ratio, the T_{on} time and T_{off} time is 6.66 ms and 13.33 ms respectively. Since the pulse on time is less at 50 Hz, time taken to machine the hole will be more and hence the Overcut is large. The Ton time and Toff time is equal in 60 Hz, thus Overcut is less.

3.4. Effect of Cryogenic treated electrode on conicity

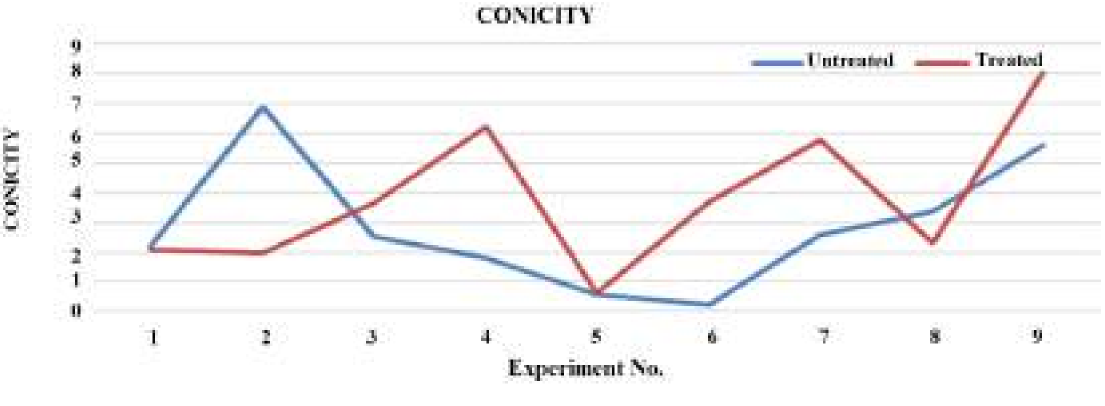


Fig. 6. Comparison of conicity between Bare and Cryogenic Treated Tool Electrode.

From figure 6, it was inferred that the conicity for treated tool is 11.2 % lesser than untreated tool. The Experiment 5 shows less Conicity. The process parameters for this experiment shows that it has 25 g/L of EC and Duty ratio of 33 %. When the duty ratio is low the Pulse ON time is less resulting in a low MRR, when MRR is less the amount of conicity is also low as the overcut produced is low at low duty cycle ratio.

It is also possible to deduce from the primary effect plot that the lowest frequency of conicity is 70 Hz, while the maximum frequency is 60 Hz. There is a correlation between an increase in frequency and an increase in pulse duration. When the f is high, it is important to remember that the duty cycle ratio is also present at high levels. This shows that the T_{on} time is high, thus the current is supplied for a longer duration of time. When current supplied is high, the amount of material removed will be more which increases conicity. When the Frequency is low the Pulse on time is low resulting to a lesser MRR, thereby causing low level of conicity. Applied Voltage is the second most influencing parameter with minimum conicity obtained at 10 V and maximum conicity obtained at 11 V. As the voltage increases, the amount of current passing through tool electrode increases, thereby increasing the material removed on the top surface of SS316. This increases conicity. At lesser Voltage, current passing through tool is less thereby decreasing conicity. The third most influencing parameter is EC with minimum conicity obtained at 20 g/L while maximum conicity is obtained at 25 g/l.

As the concentration of electrolyte increases, the ions present in the electrolyte removes more Cr^{3+} ions which increases the amount material remove on the top surface than bottom surface thereby causing high conicity. Duty ratio is the least influencing parameter with maximum conicity obtained at 50 % while minimum conicity obtained at 66 %. At 50 % duty ratio material removal is less, but frequency and applied voltage cause an increase in conicity. For Treated tool the most significant parameter is Electrolyte concentration as it shows the maximum deviation from the mean line. Maximum conicity is obtained at 25 g/L and minimum conicity is obtained at 20 g/L. When the electrolyte concentration is less, the overcut is more as discussed in the previous topic and when overcut is high it results to a higher conicity. This is due to the fact that when the concentration is low, the bubbles that are generated during the machining process are smaller. This therefore enables the stray current to cut out more material, resulting in a high conicity.

In situations when the concentration of electrolyte is high, the bubble that is created is of a big size. This vacuum gap prevents the side current from removing additional material from the work piece, which ultimately results in a poor connectivity. The second most influencing parameter is Applied Voltage. Conicity increases with increasing applied voltage. Minimum Conicity is obtained at 9 V, while maximum conicity is obtained at 11 V. As voltage increases, the amount of current passing through tool electrode increases which removes more material on the surface. The third most influencing parameter is Frequency. Minimum conicity is obtained at 50 Hz (i.e.) 20 ms time period and maximum conicity is obtained at 60 Hz (i.e.) 16.66 ms time period. Since the total time for 50 Hz is more, faster removal of material takes place which results in lower conicity. The least influencing parameter is duty ratio with minimum value obtained at 33 % while maximum value obtained at 66 %. Since pulse on time is more and flushing time is less, the removed material which is on the surface hinders the current flow. This causes removal of material over large surface area thereby increasing conicity.

3.5. Effect of Cryogenic treated electrode on circularity

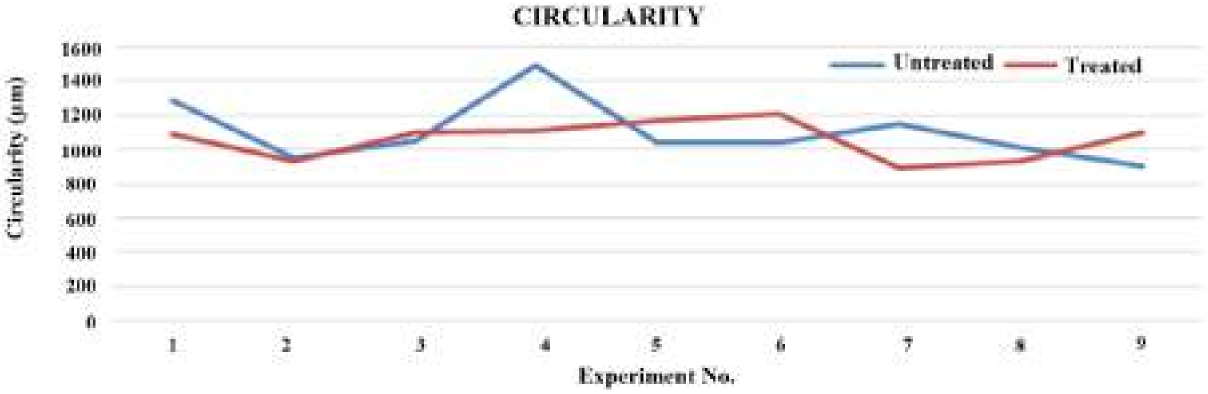


Fig. 7. Comparison of circularity between Bare and Cryogenic Treated Tool Electrode.

From figure 7, it was found that the circularity of treated tool is 3.8 % less than the treated tool. The Experiment 7 shows a better circularity. The process parameters for this experiment shows that applied voltage of 11 V and electrolyte concentration of 25 g/L. At moderate electrolyte concentration the machining rate will be minimum which means the tool feed rate is low which causes less ionization of electrolyte resulting to a better circularity. It was noted that for untreated tool the most influential parameter is Electrolyte concentration. Minimum Circularity at Entry is obtained at 20 g/L and maximum Circularity at Entry is obtained at 30 g/L.

When the electrolyte concentration is less, then the ionization rate is less which means the amount of Nitrate ions generated per unit time is less indicating to low MRR. Low MRR means a lesser machining rate, which indicates that the feed rate of the Tool is minimum. This results to a more Circular hole due to low possibility of the tool touching the workpiece while lowering the electrode for machining. At 30 g/L the number of NO ions produced is more and hence the material removed is more and uneven, that results to high circularity. The second most influencing parameter is applied voltage. Circularity is minimum at 10 voltage and maximum at 11 voltage. When the voltage is high, the quantity of current that is flowing through the electrode is also high. This indicates that the stray current that is flowing through the sides of the tool is high and not uniform, which results in the hole having a poor degree of circularity. At low voltage the current through the tool is low which leads to low side current that results to high circularity. The next most influencing parameter is Duty cycle.

Circularity is minimum at 50 % and maximum at 66 %. When the duty ratio is 50 % Ton time is less thus the machining time increases which leads to uneven material removal resulting to low circularity. At 66 % the T_{on} time is more which reduces the machining time leading to steady material removal that results to high circularity. The least influencing parameter is Frequency. Circularity decreases with increase in frequency. This because at high frequency even with 33 % duty ratio the T_{on} time is more than low frequency. Hence current is supplied for a long period at high frequency resulting to low circularity due to uneven material removal. For Treated tool the Applied Voltage is inferred to be the most influential parameter. Circularity at the Entry is maximum at 10 V and it is minimum at 11 V. At high voltage the current through the electrode is high and hence the localization effect is more that causes an uneven circular profile. When the voltage is low, the current through the tool is also low and the side current is also low that helps in producing a circular profile. The second most influencing parameter is Electrolyte Concentration. Circularity is maximum at 30 g/L and minimum at 25 g/L.

At high electrolyte concentration the temperature of the tool increases thus increasing the resistance of the electrode. When resistance is high the current through the hole is less resulting to a reduced ionization rate. This causes a decrease in MRR which means the feed rate is less that results to a high circularity. At 25 g/L the temperature of the tool is moderate, thus the current through the treated tool is more which causes irregular circular hole due to high stray current. The third most influencing parameter is Duty Cycle. Circularity is maximum at 33 % and minimum at 50 %. When the duty ratio is less the pulse ON time is less which allows less current to pass through the tool for machining and at high duty ratio the pulse ON time is more which allows more current to pass through the electrode. When the current through the tool is less the circularity is maximum as the machining is done at a slow pace and when current is more the machining is done rapidly causing more overcut resulting to low circularity. The least influencing parameter is Frequency. Circularity is maximum at 50 Hz and minimum at 70 Hz. When the frequency is low the pulse OFF time is high for the same duty ratio which helps in removing the machined material from the top surface of the workpiece thus reducing the probability of contact between tool and the workpiece. Therefore, the circularity is maximum at low frequency.

3.6. TGRA optimization

It was found that the treated tool electrode can produce better machinability than untreated tool electrode. It is further essential to perform TGRA optimization for getting optimal process parameters. In the ECMM process, the L_9 orthogonal table is shown in Table 4, along with the input factors and response values. The signal-to-noise ratio (S/N ratio) of the chosen performance metrics is shown in Table 5, together with their respective normalized values (N S/N). MRR and CY were selected as larger-the-better (LTB) quality level characteristics, whereas OC and CI were selected as smaller-the-better (STB) level characteristics. The current investigation of surface performance measures was finished using both the LTB and STM quality features; thus, the value of the differentiating coefficient was decided to be 0.5 [6]. Table 6 provides the values of the Grey Relational (GR) components as well as their position relative to the total number of trials. The average value on the GR scale for all of the different levels of process components is shown in Table 7. The value that is obtained by averaging the results of the Grey approach is used to determine the relationship levels between comparative values and a reference value. As a result, the greatest average GR value across the process should be considered the ideal evaluation of each process element.

Table 4. Response Parameters for Machining SS 316 with Treated Copper Tool Electrode.

Exp No.	MRR	OV	CI	CY
1	3.716	291.045	2.11	1093.065
2	1.233	212.972	1.96	936.160
3	2.655	288.902	3.63	1096.699
4	2.232	288.125	6.23	1108.682
5	3.042	330.672	0.62	1164.597
6	3.358	342.917	3.69	1205.058
7	1.404	184.084	5.79	898.315
8	2.269	210.587	2.31	933.194
9	2.6	278.855	8.05	1099.572

Table 5. S/N Ratio and Normalized S/N Ratio.

No.	MRR		OV		CI		CY	
	S/N	N S/N	S/N	N S/N	S/N	N S/N	S/N	N S/N
1	11.4029	1	-49.2792	0.7364	-6.4850	0.4777	-60.7720	0.6679
2	1.8214	0	-46.5665	0.2343	-5.8450	0.4489	-59.4270	0.1405
3	8.4806	0.6950	-49.2150	0.7245	-11.1980	0.6893	-60.8010	0.6793
4	6.9754	0.5379	-49.1916	0.7201	-15.8890	0.9001	-60.8960	0.7162
5	9.6626	0.8184	-50.3879	0.9416	4.1520	0	-61.3230	0.8837
6	10.5214	0.9079	-50.7038	0	-11.3400	0.6957	-61.6200	1
7	2.9498	0.1178	-45.3003	1	-15.2530	0.8715	-59.0680	0
8	7.1152	0.5525	-46.4686	0.2162	-7.2720	0.5104	-59.3990	0.1297
9	8.2995	0.6761	-48.9076	0.6676	-18.1150	1	-60.8240	0.6882

Table 6. Response Parameters for Machining SS 316 with Treated Copper Tool Electrode.

Exp No.	Grey relational coefficient				Grey relational grade
	MRR	OV	CI	CY	
1	1	0.6547	0.4891	0.6009	0.6749
2	0.3333	0.3950	0.4757	0.3678	0.3916
3	0.6211	0.6447	0.6168	0.6092	0.6224
4	0.5197	0.6411	0.8334	0.6379	0.6497
5	0.7335	0.8953	0.3333	0.8113	0.7311
6	0.8446	1	0.6217	1	0.8932
7	0.3617	0.3333	0.7954	0.3333	0.4314
8	0.5277	0.3895	0.5066	0.3648	0.4341
9	2.6	278.855	8.05	1099.572	0.6801

Table 7. Average Grey Relational Grade.

S.No	Factors	Average Grey Relational Grade			Max - Min
		Level 1	Level 2	Level 3	
1	AV	0.5630	0.7580	0.5152	0.2428
2	CE	0.5854	0.5189	0.7319	0.2129
3	f	0.6674	0.5738	0.5949	0.0936
4	DC	0.6954	0.5721	0.5687	0.1266

Total mean grey relational grade = 0.1690065

The optimized values for Treated tool was achieved when AV was 10 V, EC was 30 g/L, frequency was 50 Hz and DC was 50 %. Since the electrical conductance of tool electrode increases, moderate voltage is enough to remove more material. At 50 % duty ratio, the machining time and flashing time are same which reduces the overcut, conicity and circularity.

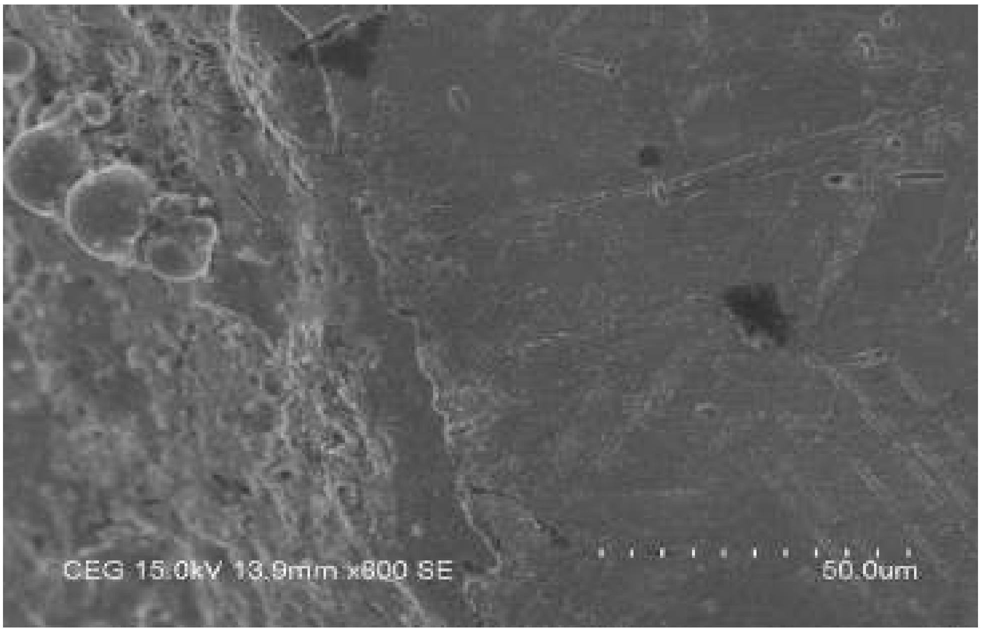
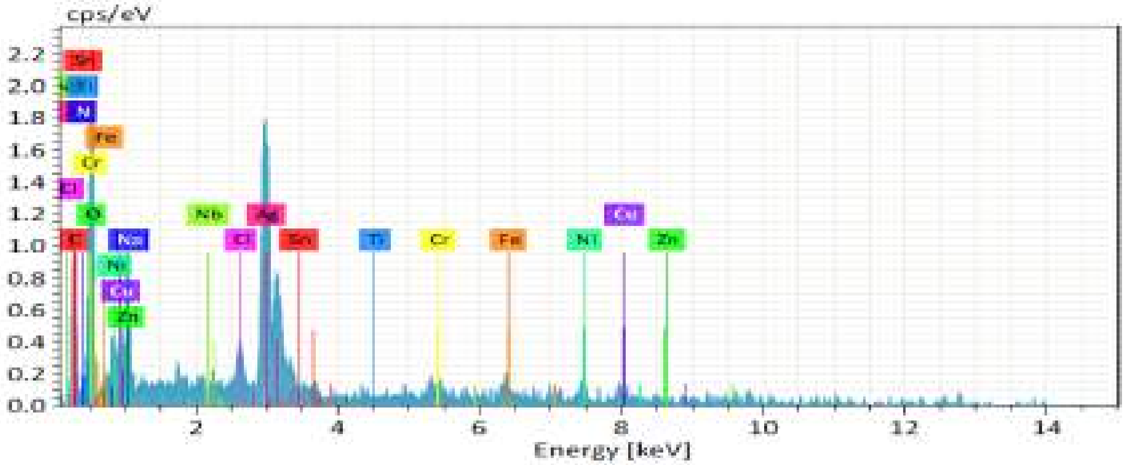
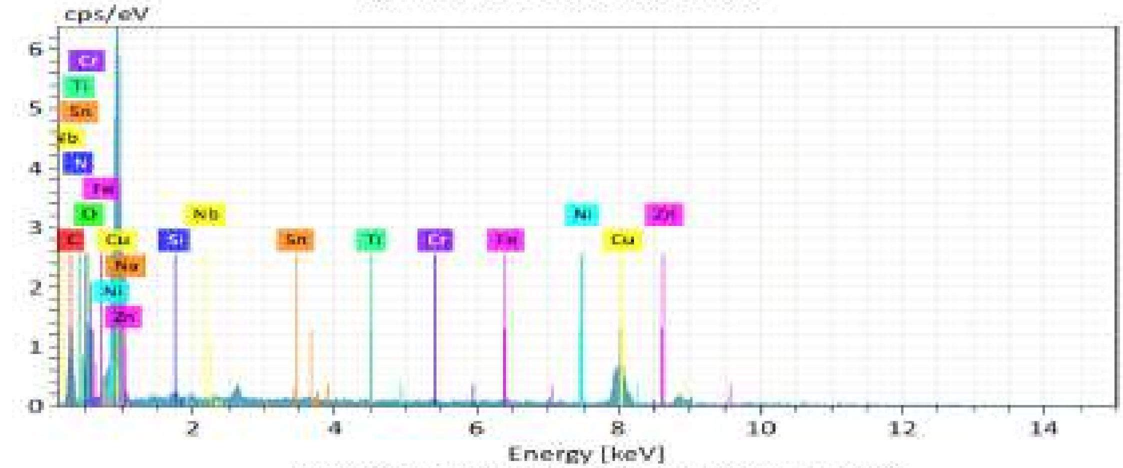


Fig. 8. Surface topography of machined specimens with cryogenic Treated Tool.



(i) with bare tool electrode



(ii) with Cryogenic treated tool electrode

Fig. 9. Comparison of circularity between Bare and Cryogenic Treated Tool Electrode.

But for further verification of these optimized values, a confirmation test was carried out using the optimized process parameters. The most influential process parameter for Treated tool electrodes is Voltage with a max-min deviation of 0.2428. Predicted Process Parameters to get best response from the Average Grey Relational grade for Treated tool the predicted process parameters are AV - 10 V, CE - 30 g/l, f – 50 Hz DC – 33 %. When the EC is less, then the ionization rate is less which means the amount of Nitrate ions generated per unit time is less indicating to low MRR. Low MRR means a lesser machining rate, which indicates that the feed rate of the Tool is minimum. This results to the required diameter hole being machined due to lesser chance of the tool touching the workpiece while lowering the electrode for machining. Figure 8 shows the scanned electron microscope (SEM) based surface morphology of the machined specimen. Since the specimen has been machined under the optimal process parameters combination, the tiny craters with lower cracks have been observed over the machined specimen as shown in Figure 8. At high electrolyte concentration the ions produced are more and hence the material is machined faster and uneven that results to the diameter of the machined hole to be larger than the expected size. Figure 9 shows the Energy-dispersive X-ray analysis (EDAX) performed of machined specimens under area mode with bare tool electrode and cryogenic treated tool electrode. It was observed that copper particles from the tool electrode have been observed over the machined specimens. However 12 % of less copper deposition have been found over the machined specimen. Since the lower copper particles were observed over the machined specimen, the foreign particles content could be reduced with the cryogenic treated tool electrode. It can further enhance the surface quality of the machined specimen.

4. CONCLUSIONS

Within the scope of this research, Stainless Steel 316 was machined with ECMM process settings, the tool electrode being either untreated or cryogenically treated. In order to get the optimal values of response parameters such as MRR, overcut, conicity, and circularity, the input characteristics such as AV, EC, frequency, and duty cycle were modified in a manner that was appropriate. Following are the results that have been obtained as a result of the studies that have been carried out employing tool electrodes that have been either bare or cryogenically treated.

- Using Cryogenic Treated tool electrodes results in higher MRR than untreated ones due to higher electrical conductivity, reducing machining time with the same applied voltage.
- Better overcut has been obtained using Cryogenic Treated tool electrode is 9.8 % lesser when compared to the untreated tool electrode because the Cryogenic Treated tool has a high conductivity which helps in increasing the ionization rate thus producing large bubbles with vacuum created by the reactions taking place which prevents the stray current from producing large Overcut.
- The Conicity values obtained while machining with Cryogenic Treated tool electrode is 11.2 % better than the untreated tool electrode because the treatment of the tool at Cryogenic temperatures followed by heating it to high temperature leads to a smaller grain structure and better tool surface thus improving its conicity.
- The Circularity of the hole machined with Cryogenic treated tool is better than untreated tool because the localization effect of treated tool is 3.8 % more than that of untreated tool electrode.
- The optimized values for Cryogenic Treated tool was achieved when applied voltage was 10 V, electrolyte concentration was 30 g/L, frequency was 50 Hz and duty cycle was 33 %.

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