# EFFECT OF CRYOTREATED POST TEMPERED ELECTRODES ON EDM PERFORMANCE OF AISI 304: A COMPARATIVE STUDY

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***Abstract:***

*In the present investigation, a comparison study has been conducted to investigate the effect of process parameters and three different type of electrodes {untreated (UT), cryotreated single tempered (CT1) and cryotreated double tempered (CT2)} during electro discharge machining (EDM) operation. For this purpose, WC and AISI 304 stainless steel was used as electrode and work material. Peak current, pulse on time, duty cycle, gap voltage, and flushing pressure were considered as process parameters and performance characteristics were measured by means of tool wear rate (TWR), material removal rate (MRR) and surface roughness ($R_a$). Microstructural analysis was conducted on the EDMed surfaces machined by UT, CT1 and CT2 electrodes. It is found from the investigation that UT electrode provides higher tool wear rate (TWR), material removal rate (MRR), and surface roughness ($R_a$) compare to cryotreated post tempered electrodes. Better surface quality has been achieved for EDMed surface machined by CT2 electrode compare to UT and CT1 electrodes.*

## 1 Introduction

Electro discharge machining (EDM) is one of the most popular non-traditional, thermo-electrical machining process in which electrical energy generates the series of spark and material removal occurs due to thermal energy of the spark. It can be used to machine complex geometries such as helical profiles, thread cutting, rotary forming, curved hole drilling and used to machine difficult-to-machine materials such as Titanium, Stainless steel, Tungsten, Kovar, Inconel. Iqbal et al. [1] determined recast layer thickness, micro-cracks and material migration on AISI 304 machined surface during EDM operation. Tool wear is a significant problem in EDM process. In order to reduce tool wear as well as machining cost, cryotreatment process has been introduced. It is an advanced method to improve cutting tool property.

The effect of cryotreatment on conventional and non-conventional machining has been reported by many researchers. Stewart [2] performed cryotreatment on C2 tungsten carbide (WC- 6%Co) and compared the treated and untreated tool insert in terms of tool wear during turning operation. Srivastava and Pandey [3] studied the effect of cryogenically cooled copper electrode on M2 grade high-speed steel during EDM operation. They noticed that electrode shape retention is better in the case of cryogenically assisted EDM compared to conventional EDM. Furthermore, they determined electrode wear rate (EWR) and surface roughness (SR) for that material using the same electrode [4]. They reported that using cryogenically cooled electrode, EWR is reduced up to 20%.

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Mathai et al. [5] reported that surface hardness was enhanced by cryotreatment and tool wear was also considerably reduced by using cryogenically treated electrode. Kalsi et al. [6] presented the effect of cryotreated post tempered cycles during the machining of tungsten carbide-cobalt inserts. Kumar et al. [7] used cryotreated double tempered (CT2) copper electrode to evaluate machining efficiency of Inconel 718. They found a significant improvement in tool wear of CT2 electrode over the untreated (UT) electrode in additive mixed EDM. Gill et al. [8] performed deep cryotreatment of Aluminium which was further used as a tool electrode on the machinability of hot die steel (AISI H11) and found that surface finish was improved by about 27.9% after cryotreatment. Srivastava and Pandey [9] prepared a cermet electrode and used for ultrasonic assisted cryogenically cooled EDM process. They reported that EWR reduced significantly when cermet electrode is used compared to copper electrode. Jefferson and Hariharan [10] made a comparative study on the machining performance of cryotreated and untreated electrodes during µ-EDM of AISI 304.

They concluded that tool wear is reduced about 58% using WC tool followed by brass and copper electrode with a reduction of 51% and 35% respectively. Abdulkareem et al. [11] compared the erosion behaviour of nitrogen cooled copper electrode (cooled at -195$^0$C) during EDM of Ti-6Al-4V. Yildiz [12] studied the effect of cold and cryogenic treatment on the machinability of beryllium-copper alloy during EDM operation. They reported that MRR is increased about 20-30% after cold and cryogenic treatment. Singh and Singh [13] compared the performance of untreated and cryotreated copper and brass electrodes during EDM of AISI D3 Die Steel. They found that cryotreated copper electrode exhibits lower tool wear than the brass electrode. Singh et al. [14] analyzed the machining characteristics of die steels (High Carbon High Chromium (HCHCr), EN8 and EN31) before and after deep cryotreatment. They reported that tool wear and surface finish is improved for HCHCr followed by EN8 and EN31. Gogte et al. [15] investigated the effect of cryotreated single ageing tool for a different period of cryotreatment on age hardenable AA6061 alloy and found that surface roughness is highly influenced by the cryotreatment. Gaikwad et al. [16] reported the effect of cryotreated NiTi alloy on MRR and TWR. They noticed after cryotreatment MRR has been improved significantly. Grewal and Dhiman [17] investigated the effect of cryotreated and UT copper electrode on the EDM machining efficiency of EN24 material in terms of overcut (OC), TWR and $R_a$. They reported 9%, 13.22% and 15.75% reduction in OC, TWR and $R_a$ respectively using cryotreated electrode. Ishfaq et al. [18] used untreated and cryotreated copper, brass and graphite electrodes during EDM of Inconel 617 to find out the different magnitudes of MRR while using different dielectric fluid. Jatti et al. [19] studied the effect of cryotreated workpieces (Nitinol alloy, Monel alloy and Beryllium copper alloy) and electrode on MRR and TWR.

They reported that after cryotreatment electrical conductivity enhanced for all the cases. Hence reduction of TWR and enhancement of MRR have been found out. From the above literature survey, it is evident that number of investigations have been done related to the cryotreatment and cryotreated double tempered electrode considering tool wear rate, material removal rate, and surface roughness as responses. But adequate work has not been carried out to study the effect of cryotreated post tempered electrodes on the aforementioned responses during electro discharge machining. The main objective of this investigation is to study and compare the effect of EDM process parameters using untreated and cryotreated post tempered electrodes (single and double tempered) for measuring responses such as surface roughness, material removal rate and tool wear rate during EDM operation of AISI 304 Stainless Steel.

## 2 Experimental details

### *2.1 Cryotreatment*

In this investigation, two WC electrodes were subjected to deep cryotreatment at a temperature of -193.15$^0$C with a steady cooling rate of 2.2$^0$C/minute, followed by soaking at the same temperature for 24 hours. The electrodes were gradually brought to cryogenic temperature because there is a chance of developing micro-cracks on the electrode surface if they are directly exposed to cryogenic heat [8, 20]. After cryotreatment, one electrode was subjected to single tempering, while the other one was subjected to double tempering at 200$^0$C for relieving stress induced by the cryotreatment. The temperature vs. time curve is shown in Figure 1.

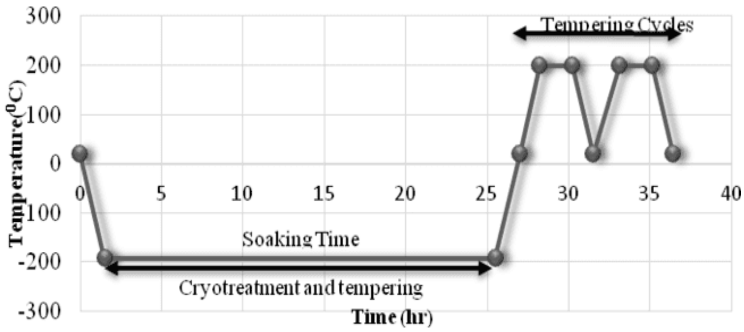



*Figure 1. Temperature vs. time for the cryotreatment and tempering.*

### 2.2 Materials

AISI 304 stainless steel and cylindrical WC (10 mm diameter) was used as workpiece and tool material for this investigation. The required properties of AISI 304 and WC are mentioned in Table 1.

*Table 1. Property of workpiece and electrode material.*

| Properties | Material | |
|---|---|---|
| | AISI 304 | WC |
| Density (g/cm$^3$) | 8.00 | 15.63 |
| Thermal conductivity (W/m.k.) | 16.2 | 84.02 |
| Melting temperature ($^0$C) | 1450 | 2870 |

### 2.3 Experimental Plan

This investigation was carried out in ELECTRONICA-ELECTRAPLUS PS 50 ZNC (die-sinking type) EDM machine. Experiments were carried out on AISI 304 using three different types of electrode i.e. i) untreated (UT), ii) cryotreated single tempered (CT1) and iii) cryotreated double tempered (CT2). The process parameters considered in the study were i) gap voltage, ii) peak current, iii) duty cycle, iv) pulse on time, v) flushing pressure.

The EDM responses considered were i) surface roughness ($R_a$) (µm), ii) tool wear rate (TWR) (mm$^3$min$^{-1}$) and iii) material removal rate (MRR) (mm$^3$min$^{-1}$). The various experimental conditions and levels of process parameters are tabulated in Table 2. The experimental designs are tabulated in Table 3. The process parameters are selected in such a way that the machining process falls under semi finishing machining.

*Table 2. Experimental conditions.*

| Working Parameters | Description |
|---|---|
| Electrode material | WC |
| Dielectric Fluid | EDM oil |
| Workpiece material | AISI 304 stainless steel |
| Pulse on time ($T_{on}$)(µs) | 50,100, 150, 200, 300 |
| Gap voltage ($V_g$) (V) | 40, 50, 60, 70, 80 |
| Flushing pressure ($F_P$) (kgf/cm$^2$) | 0.2, 0.3, 0.4, 0.5, 0.6 |
| Duty cycle (Γ) (%) | 55, 60, 65, 70, 75 |
| Peak current ($I_P$) (A) | 2, 4, 6, 8, 10 |
| Machining time (min) | 10 |

### *2.4 Experimental Procedure*

Experiments were carried out according to the design matrix in die-sinking electro discharge machine. Figure 2. shows the experimental set up. Material removed from the workpiece and electrode calculated by using weight loss method and then converted to volumetric metal loss method. Surface roughness was measured by Talysurf (Model: Taylor Hobson, Surtronic 3+). Scanning Electron Microscope (SEM) was used for studying the surface morphology of the EDMed surface. Responses like MRR and TWR of the machining holes were calculated from the observed data using these formulae;

$$Material\ \text{Removal}\ Rate\ (MRR) = \frac{Volumetric\ material\ loss\ from\ workpiece\ (mm^3)}{Machining\ Time\ (\text{min})} \tag{1}$$

$$Tool\ Wear\ Rate\ (TWR) = \frac{Volumetric\ material\ loss\ from\ electrode\ (mm^3)}{Machining\ Time\ (\text{min})} \tag{2}$$

,



*Figure 2. Experimental set up.*

*Table 3. Experimental design.*

| Sl. No. | Peak Current | Gap Voltage | Pulse on time | Duty Cycle | Flushing Pressure |
|---|---|---|---|---|---|
| 1 | 2 | 45 | 50 | 60 | 0.2 |
| 2 | 4 | 45 | 50 | 60 | 0.2 |
| 3 | 6 | 45 | 50 | 60 | 0.2 |
| 4 | 8 | 45 | 50 | 60 | 0.2 |
| 5 | 10 | 45 | 50 | 60 | 0.2 |
| 6 | 5 | 40 | 50 | 60 | 0.2 |
| 7 | 5 | 50 | 50 | 60 | 0.2 |
| 8 | 5 | 60 | 50 | 60 | 0.2 |
| 9 | 5 | 70 | 50 | 60 | 0.2 |
| 10 | 5 | 80 | 50 | 60 | 0.2 |
| 11 | 5 | 45 | 50 | 60 | 0.2 |
| 12 | 5 | 45 | 100 | 60 | 0.2 |
| 13 | 5 | 45 | 150 | 60 | 0.2 |
| 14 | 5 | 45 | 200 | 60 | 0.2 |
| 15 | 5 | 45 | 300 | 60 | 0.2 |
| 16 | 5 | 45 | 50 | 55 | 0.2 |
| 17 | 5 | 45 | 50 | 60 | 0.2 |
| 18 | 5 | 45 | 50 | 65 | 0.2 |
| 19 | 5 | 45 | 50 | 70 | 0.2 |
| 20 | 5 | 45 | 50 | 75 | 0.2 |
| 21 | 5 | 45 | 50 | 60 | 0.2 |
| 22 | 5 | 45 | 50 | 60 | 0.3 |
| 23 | 5 | 45 | 50 | 60 | 0.4 |
| 24 | 5 | 45 | 50 | 60 | 0.5 |
| 25 | 5 | 45 | 50 | 60 | 0.6 |

## 3 Results and discussion

### *3.1 Properties of cryotreated post tempered electrodes*

Cryotreatment is also a heat treatment process that is applied to materials at low temperatures. The mechanical property (i.e. hardness) and electrical property (i.e. electrical conductivity) have been measured for untreated and cryotreated post tempered electrodes. Table 4 and Table 5 depicts the hardness values and electrical resistivity values respectively [21, 22].

*Table 4. Hardness values of electrodes.*

| Electrode type | Hardness (HV) | % increase after treatment |
|---|---|---|
| Untreated (UT) | 1438.4 | - |
| Cryotreated single tempered (CT1) | 1785.9 | 20.32 |
| Cryotreated double tempered (CT2) | 1641.1 | 14.09 |

From the hardness table it is clearly seen that UT electrode possesses less hardness compared to cryotreated post tempered electrodes. Hardness is increased by 20.32% and 14.09% for CT1 and CT2 electrode respectively. From the table 5, it is seen that, UT electrode possesses higher electrical resistivity then the cryotreated electrodes. Electrical conductivity increases for the tempering cycle after cryotreatment [20]. The increase in thermal conductivity is due to the cryogenic treatment that leads to a faster rate of heat conduction hence decrease in tool wear. As per Wiedemann-Franz law, for a given temperature, thermal conductivity is directly proportional to the electrical conductivity.

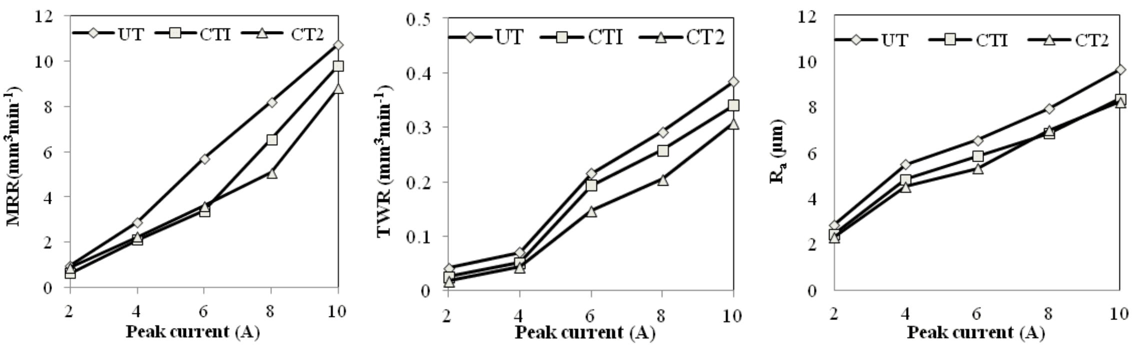
*Table 5. Electrical resistivity values of electrodes.*

| Electrode type | Electrical resistivity (Ohm-m) |
|---|---|
| Untreated (UT) | $2.11\times10^{-7}$ |
| Cryotreated Single Tempered (CT1) | $1.92\times10^{-7}$ |
| Cryotreated Double Tempered (CT2) | $1.78\times10^{-7}$ |

### *3.2 Effect of peak current*

The influence of $I_P$ on MRR, TWR and $R_a$ is shown in Figure 3(a)-Figure 3(c). With increase in $I_P$, MRR, TWR and $R_a$ increases up to a significant level. MRR increases gradually with the increase of $I_P$ for all the electrodes. When $I_P$ increases, effective energy in the tool-workpiece interface also increases that results increase of MRR. MRR for two cryotreated electrodes is less than UT electrode because, thermal conductivity of electrodes increases after cryotreatment. Consequently, due to faster heat conduction rate, spark ignition of discharge continues for a less time as compared to UT electrode. So, less amount of heat is transferred to the workpiece resulting formation of smaller crater. Hence, MRR reduces. From this study, it is seen that MRR decreases up to 34.66% and 38.05% for CT1 and CT2 electrode respectively when $I_P$ increases from 2A to 10A. TWR increases with increase of $I_P$ because of construction of electrical discharge column in the sparking gap which removes the undesirable work material as well as wear down the electrode. UT electrode gives higher TWR than cryotreated post tempered electrodes.

This is because; during cryotreatment thermal conductivity of tool increases. So, during machining generation of local temperature is less due to faster heat conduction rate of electrode, resulting less TWR for the same heat load. CT1 electrode gives less tool wear than CT2 electrode because of more hardness. Tempering cycles after cryotreatment does not affect the MRR and TWR for a lower machining condition. The possible reason is that, at lower machining conditions, heat produced between tool-workpiece interfaces is less which has no effect on the cryogenic properties of the electrode. When $I_P$ increases from 2A to 10A, TWR reduces up to 38.57% for CT1electrode followed by CT2 electrode with a reduction of 57.14%. $R_a$ is directly proportional to the energy discharge by EDM process. Increase of $I_P$, discharge energy density and impulsive force increases resulting generation of larger and deeper crater that increases $R_a$. From the Figures, it is apparent that, UT electrode provides more roughness than the two cryotreated post tempered electrodes. Both the cryotreated electrodes have almost same effect on surface finish. $R_a$ decreases up to 14.68% and 18.9% for CT1 and CT2 electrode respectively when $I_P$ increases from 2A to 10A.



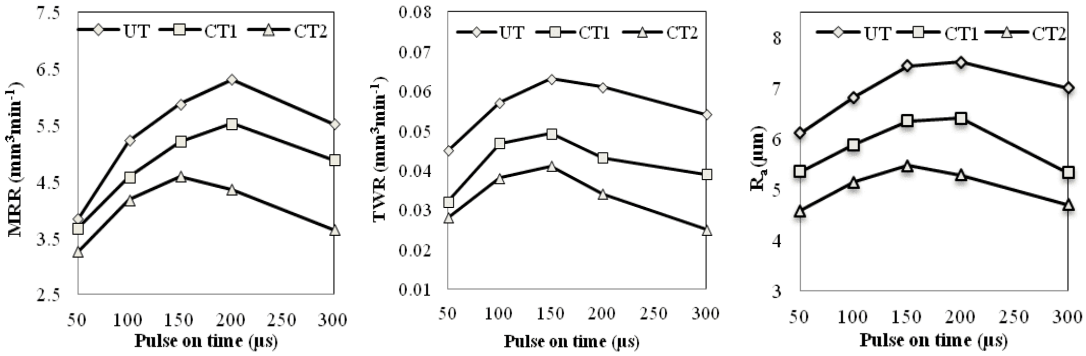

*(a)* *(b)* *(c)*

*Figure 3. Effect of $I_P$ on (a) MRR, (b) TWR and (c) $R_a$.*

### *3.3 Effect of pulse on time*

The influence of $T_{on}$ on MRR, TWR and $R_a$ is depicted in Figure 4(a)-Figure 4(c). With increase of $T_{on}$, initially MRR increases and then starts falling off in a slow manner. When $T_{on}$ increases, amount of spark energy increases, resulting higher MRR. But at higher $T_{on}$, diameter of the discharge column increases. So, energy density decreases on the discharge surface resulting less MRR. MRR decreases up to 12.34% and 33.9% for CT1 and CT2 electrode respectively. With increase of $T_{on}$, initially TWR increases and then decreases gradually. This happens because; increase in $T_{on}$, spark energy increases leading to higher heat generation and more fraction of heat being transferred to the electrode causing higher TWR. Decrease of TWR may be attributed to two reasons; the first one is that increase in $T_{on}$, discharge column diameter increases resulting reduction of spark discharge energy density in the discharge area. The second reason is that, as the pulse duration increases, carbon particle that is formed from the decomposition of dielectric fluid starts depositing on the electrode surface that results an enhancement of wear resistance of the electrodes. Thus, TWR reduces. UT electrode results more tool wear compared to cryotreated tempered electrodes.

This happens because, after the cryotreatment, tool improved its thermal conductivity. So, generated local temperature dissipates at faster heat conduction rate to the bulk of electrode resulting less tool wear for the same heat load. Tempering cycle has significant effect on TWR.



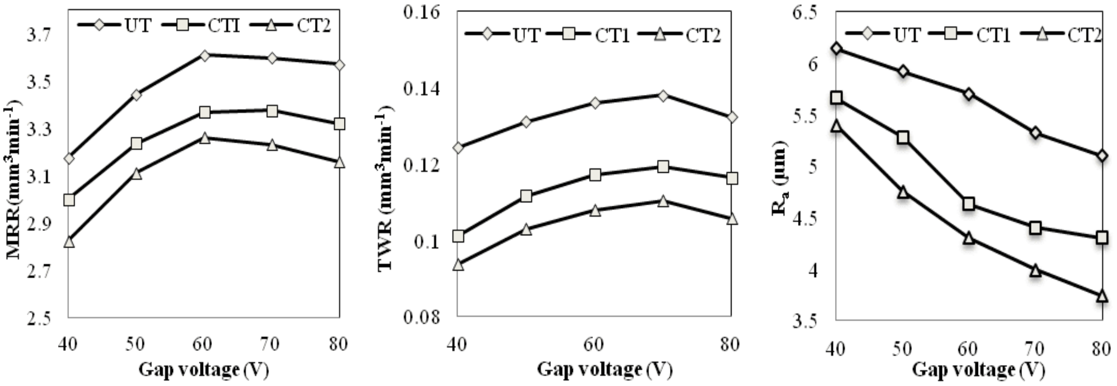

*(a)* *(b)* *(c)*

*Figure 4. Effect of $T_{on}$ on (a) MRR, (b) TWR and (c) $R_a$.*

TWR reduces up to 29.34% for CT1 and 33.33% for CT2 electrode. With increase of $T_{on}$, discharge energy increases, resulting more material removal from the workpiece. That leads to generation of larger and deeper crater on the workpiece surface. Consequently, surface becomes rough. With increase in $T_{on}$, surface roughness increases to a maximum level and then starts decreasing. The $R_a$ value for UT electrode is higher than CT1 and CT2 electrodes. $R_a$ reduces up to 23.96% and 32.95% using CT1and CT2 electrodes respectively compared to UT electrode.

### *3.4 Effect of gap voltage*

The influence of $V_g$ on MRR, TWR and $R_a$ is shown in Figure 5(a)-Figure 5(c). MRR increases with increase in $V_g$ up to a certain value and then starts declining for the three electrodes. With increase in $V_g$ spark energy increases, resulting increase in MRR. When $V_g$ increases, harsh and intense discharge occurs and due to insufficient cooling MRR decreases. MRR machined by CT2 electrode is less than the two electrodes due to less spark energy. MRR decreases up to 7% for the CT1electrode and 11.48% for the CT2 electrode. TWR increases with increase in $V_g$ for all the electrodes. TWR is highest at 70V for all the electrodes. TWR increases initially because of the availability of more spark energy during discharge. TWR decreases up to 18.58% for CT1and 24.62% for CT2 electrode. Surface finish enhances with increase of $V_g$. Increase in $V_g$, gap between two electrodes becomes very large with decrease in spark frequency. Surface finish obtained by cryotreated tempered electrodes is better than UT electrode. Surface finish enhances up to 18.77% for CT1electrode followed by CT2 electrode with 26.66%.

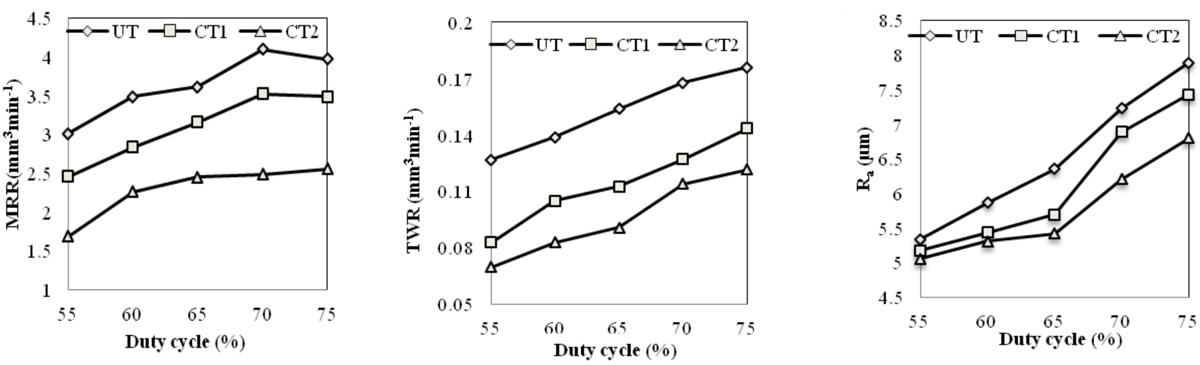



*(a)* *(b)* *(c)*

*Figure 5. Effect of $V_g$ on (a) MRR, (b) TWR and (c) $R_a$.*

### 3.5 *Effect of duty cycle*

The influence of r on MRR, TWR and $R_a$ is shown in Figure 6(a)-Figure 6(c). MRR of each level of r machined by three electrodes is clearly seen in Figure 6(a). It is seen that MRR increases rapidly for all the electrodes. MRR obtained by the two cryotreated electrodes is comparatively lower than UT electrode. MRR decreases up to 18.64% for CT1 and 44% for CT2 electrode. TWR increases gradually with increase of r for all the electrodes. It may takes place because, increase in r leads to the formation of higher discharge energy resulting increase in TWR. At higher rate of r, spark holds itself for a longer time in the spark gap for the total cycle time. CT2 electrode undergoes lower TWR than the other two electrodes because of its higher thermal conduction rate. TWR reduces up to 34.5% for CT1 and 44.8% for CT2 electrode with increase of r. Surface roughness increases with increase in r for the three electrodes. With the increase of r, sparking occurs for more duration in a complete cycle. Apart from this, a decrease in pulse off time results an insufficient cooling of the workpiece. So, the process becomes unstable resulting deeper and widened craters on the work surface that leads to $R_a$. Roughness reduces up to 10.37% and 13.81% for CT1and CT2 electrode.

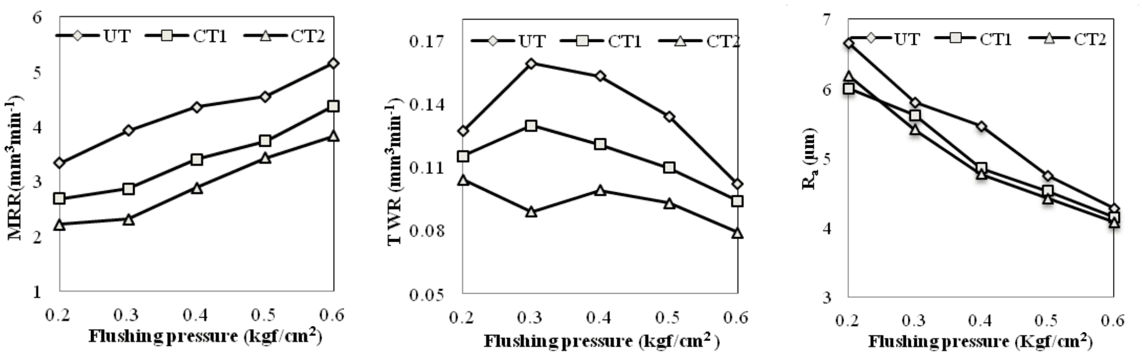



*(a)* *(b)* *(c)*

*Figure 6. Effect of r on (a) MRR, (b) TWR and (c) $R_a$.*

### 3.6 *Effect of flushing pressure*

The influence of $F_P$ on MRR, TWR and $R_a$ is shown in Figure 7(a)-Figure 7(c). Type of $F_P$ has a significant effect on EDM performance. MRR increases with increase of $F_P$. The possible reason may be, with increase of $F_P$, effective number of discharges is possible results increase in MRR. MRR decreases up to 27% for CT1 and 41% for CT2 electrode with increase of $F_P$. TWR decreases with increase of $F_P$ for the three electrodes because of effective removal of heat generated during sparking facilitating a reduction in temperature around the electrode surface at a higher $F_P$ [23]. This also results reduction in $R_a$. UT electrode exhibits higher tool wear than the two cryotreated electrodes due to the differences in thermal conductivity. TWR reduces up to 21.11% and 44% for CT1 and CT2 electrode respectively with increase in $F_P$. With increase in $F_P$, material particle that generates during machining is washed out from the machining surface. Hence, Surface finish gets enhanced. This trend seems to be the same for all the electrodes irrespective of cryotreatment and post tempering condition. Surface finish is improved upto 11% for CT1 and 12.63% for CT2 electrode.




(a) (b) (c)

*Figure 7. Effect of $F_P$ on (a) MRR, (b) TWR and (c) $R_a$.*

### 3.7 Microstructural Analysis

During EDM process, material removed from the workpiece is due to the repeated spark from the electrode. During electron discharge, temperature of the spot attains a high temperature about 10,000$^0$C. At this temperature, material on the spot melts and then vaporizes from the workpiece. However, a small amount of molten material cools rapidly due to the effect of dielectric fluid [24]. Rapid heating and cooling effect generates a highly discrete surface morphology on EDMed surfaces. Surface characteristics of UT, CT1 and CT2 electrode are portrayed in Figure 8, Figure 9 and Figure 10. Surface cracks are clearly evident in the microstructures. Surface crack formation is credited to the differentials of residual/contraction stress within the white layer and contraction stress exceeds the material's ultimate tensile stress resulting development of surface cracks. Microstructural investigation of EDM surfaces expose the surface irregularities such as micropores, deposition of re-solidified material, surface cracks as a consequence of rapid heating and cooling process. From those images, it is apparent that lesser crack density is found for the surface machined by CT1 and CT2 electrodes compared to UT electrode.

These cracks are called "short" because of less penetration in the workpiece. Micropores and scar marks are also visible on the machined surfaces. Formation of micropores and scars are also responsible for the increase of surface roughness. It is evident that, width of crack is much wider on the EDMed surface machined by UT electrode (1.42 µm) and decreases for CT1 (1.36µm) and CT2 electrode (1.02 µm).

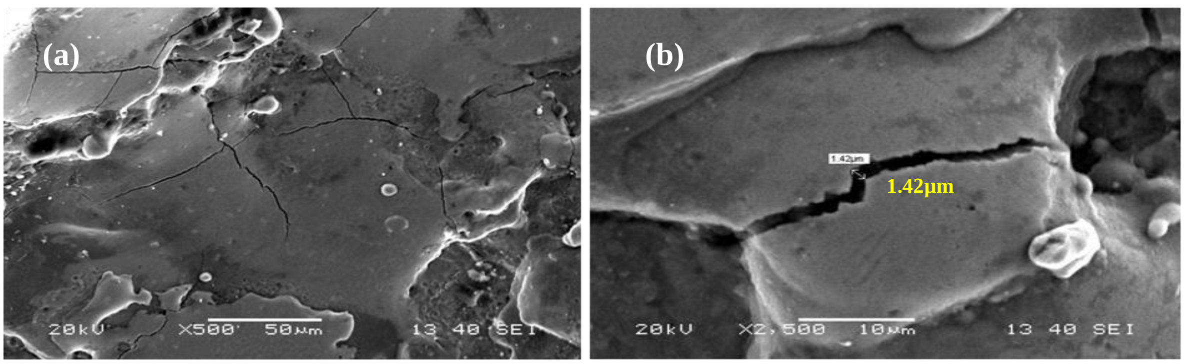



*Figure 8. (a) Characteristics of surfaces for UT electrode and (b) crack width at $I_P$=10A, $V_g$=45V, $T_{on}$=50 µs, r =60%, $F_P$= 0.2kgf/cm$^2$.*

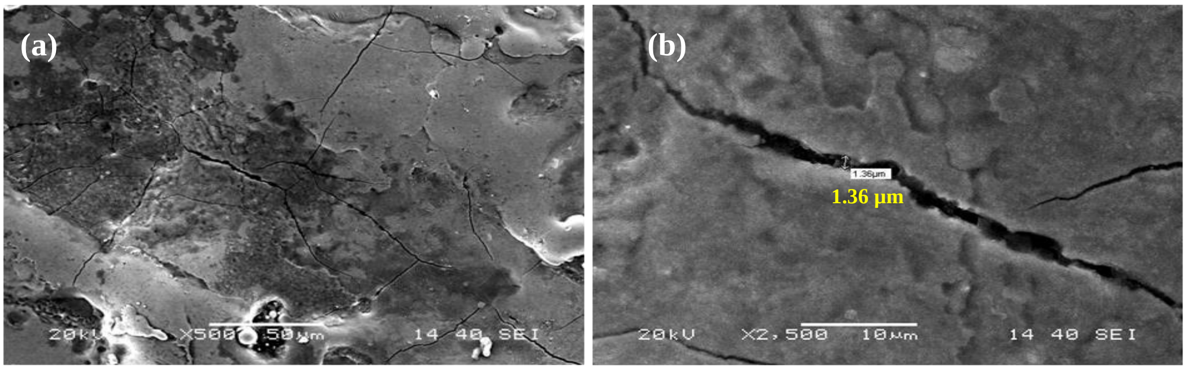



*Figure 9. (a) Characteristics of surfaces for CT1 electrode and (b) crack width at $I_P$=10A, $V_g$=45V, $T_{on}$=50 µs, r =60%, $F_P$ = 0.2kgf/cm$^2$.*

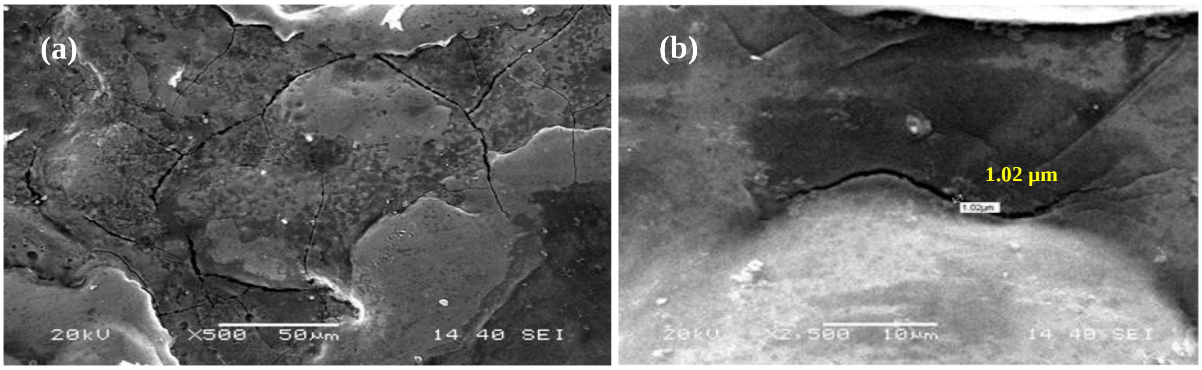



*Figure. 10 (a) Characteristics of surfaces for CT2 electrode and (b) crack width at $I_P$ =10A, $V_g$ =45V, $T_{on}$ =50 µs, r =60%, $F_P$ = 0.2kgf/cm$^2$.*

## 4 Conclusion

The effect of $T_{on}$, $I_P$, r, $V_g$ and $F_P$ during electro discharge machining of AISI 304 were studied using WC electrodes (UT, CT1 and CT2). The conclusions from the experiments are drawn below:

- MRR machined by UT electrode is relatively higher followed by CT1 and CT2 electrode. MRR enhances with the increase of all the process parameters but at higher value of $T_{on}$ and $V_g$ a decreasing trend has been observed for MRR.
- TWR increases with the increase of $I_P$, $T_{on}$, r, $V_g$ and decreases with the increase of $F_P$ for all the electrodes. Least TWR is obtained for the cryotreated post tempered electrodes.
- $R_a$ increases with the increase of $I_P$, $T_{on}$ and r. Surface finish enhances with increase of $V_g$ and $F_P$. For each case, CT1 and CT2 electrodes provide better surface finish compared to UT electrode.
- EDMed surface machined by UT electrode generates rough surface compared to CT1 and CT2 electrodes. Crack width is found lesser for CT1 and CT2 electrodes compared to UT electrode.

The levels of process parameters are selected in this machining for semi finishing operation. Change of level of process parameters might change the quality of machining. In future, different type of cryotreated post tempered electrodes can be used to on the workpiece to compare the machining efficiency.

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