

Comparison of machining characteristics of Inconel 601 with normal and cryogenic cooled electrode in EDM using RSM

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Abstract. In today's world cryogenic cooling is used in various fields to increase the physical and mechanical properties of the materials. It is used in various ways such as fuels for rockets, frizzing food and transporting it to different locations, storing rare blood groups, giving chilling and other special effects in nightclub etc. In this paper, we will compare the effect of normal copper electrode and cryogenically cooled copper electrode in Electric Discharge Machine (EDM) process with Inconel 601 as work piece. Peak current, gap voltage and pulse on time are the different input parameters and MRR, surface roughness and TWR are the output parameters for the process. The experimental work is done using Box-Behnken Design (BBD) in Design of Experiment (DOE). Further, the optimize result for variation of output parameters with change in input parameters is seen by using Analysis of Variance (ANOVA) and Response Surface Methodology (RSM). The paper will tell us about the effect of normal and cryogenic cooled electrode on Inconel 601 on EDM.

Keywords: EDM; Cryogenic Cooling; Inconel 601; DOE; RSM; ANOVA.

1. Introduction

Electric Discharge Machine is a type of manufacturing process which uses erosion process to remove materials and make different complex shapes in those types of materials which face difficulty when machined by other conventional machines such as lathe machine etc. In EDM, when the power supply is given then the process of removal of material begins as voltage is developed around work piece and tool electrode. As the voltage is developed, it leads to breakdown of dielectric materials which causes the rise of electrostatic field. Further, the electrons are released from the tool (cathode) and the work piece (anode) which strikes the dielectric molecule and break them into positive and negative ions. A series of continuous electric discharges results in removing of material from the work piece and the tool. Later, the removed material is flushed out with the help of flushing process and new dielectric replaces the old one and the process is carried on. The main advantage of using EDM is that the tool and the work piece don't make any physical contact with each other while the machining process is going on. Inconel 601 is a lightweight material which has wide range of applications as it is resistant to oxidation at very high



temperature up to 1250°C. It is used in high velocity gas burners, radiant tubes, refractory anchors, fabricating combustion chambers etc. It also has a high strength and is resistant to carburization. The composition of Inconel 601 is a FCC solid solution which includes nickel 61%, chromium 23%, aluminum 1.4%, manganese 1.0%, silicon 1.0%, carbon 0.1%, sulphur 0.015% and the remaining is iron. Cryogenics treatment is the process similar to conventional heat treatment process. In this process mainly the material is cooled to a very low temperature i.e. at or below -150°C to enhance their physical and mechanical properties. Cryogenics is made up from Greek words “Kryos” and “Genes” which means cold and to produce. Liquid nitrogen and liquid helium are the commonly used cryogenic liquids. Some of the important works which uses cryogenic liquid to cryogenically treat the tool or the work piece are shown along with few works on Inconel 601 and EDM. Liqing et al. [1] worked on the effect of oxygen mixed and cryogenically cooled work piece to improve surface integrity and material removal rate and found that when cryogenic treatment is used then surface roughness is improved by 1-10% and the material removal rate improves by 30-50%. Yildiz et al. [2, 3] worked with liquid nitrogen cryogenic liquid and found that surface finish is improved and tool wear is decreased as working temperature of machining is kept in control. Mathai et al. [4] investigate the effect of cryogenically treated electrode on EDM and notice that it mainly affects the tool wear. It was also seen that MRR and surface roughness are not affected as much as the tool wear rate. Kumar et al. [5] checked the effect of cryogenically cooled copper electrode for Inconel 718 with some additives powders added into the dielectric and found that the tool wear rate and the wear ratio decreases. Pandey et al. [6] worked on EDM with ultrasonic assisted cryogenically treated copper electrode and M2 grade HSS work piece. It is seen that the surface integrity was good and the tool life increases along with good shape retention ability.

Jafferson et al. [7] compares the effect of normal and cryogenically treated electrodes on micro EDM. It was found that the hardness and electrical conductivity of tool is increased with decrease in tool wear rate of brass, copper and graphite by 51%, 35% and 58% respectively. Singh et al. [8] investigate the effect of deep cryogenic on three tool materials namely brass, copper and graphite with EN-31 as work piece and check its effect on MRR and TWR. It was found that MRR increases by 109%, 173% and 230% in brass, copper and graphite respectively and the tool wear rate decreases by 9%, 18% and 31% in brass, copper and graphite tool electrode respectively.

Rajesh et al. [9] investigate the effect of duty factor, flushing pressure, gap voltage, pulse current and sensitivity factor on Inconel 718 on EDM. It was found that material removal rate increases from 14.4 to 22.6 mm³/min which is mainly due to variation in pulse current. Mohanty et al. [10] investigates the effect of different electrodes namely brass, copper and graphite with Inconel 718 as the work piece. It was seen that brass gives good surface quality but low MRR. Graphite gives high MRR but surface roughness is not good. It is also seen that graphite gives less TWR when compared with brass and copper tool. Rahul et al. [11] investigate the effect of machining on different types of Inconel namely, Inconel 601, Inconel 718, Inconel 625 and Inconel 825. Different input parameters were taken and with the help of 5-factor 4-level L₁₆ orthogonal array, it was seen that for Inconel 601, the best condition is when duty factor is 80%, gap voltage is 80V, flushing pressure is at 0.3bar, peak current is at 7A and pulse on time is at 500 μs.

2. Experimental Work

2.1 Material Used

In the present work, an alloy of nickel-chromium or Inconel 601 is taken as work piece and normal and cryogenically cooled electrolytic copper is taken as tool or electrode as shown in figure 1 and figure 2 respectively. The dimension of work piece is 52mm x 52mm x 5mm and the electrode is 20 cm in diameter. The electrode is machined and cut into a square shape with dimension of 12.5mm x

12.5mm. The composition of Inconel 601 is Ni 61%, Cr 23%, Al 1.4%, Si 1.0, Mn 1.0%, C 0.1%, S 0.015% and rest is iron.



Figure1. Work piece Inconel 601 **Figure2.** Electrode material (Electrolytic Copper)

2.2 Design of Experiment

Box-Behnken Design (BBD) is used to study the effect of process parameters in EDM. The experiments are carried out with three input parameters namely pulse on time (T_{on} in microsecond, μs), gap voltage (V_g in Voltage, V) and peak current (I_p in Ampere, A). The factors with different levels are shown in table 1 below.

Table1. Process parameters with their respective levels

Factors	Name	Low Level (-1)	Medium Level (0)	High Level (1)
A	Pulse on Time	100	150	200
B	Gap Voltage	60	70	80
C	Peak Current	6	8	10

Inconel 601 is machined with normal and cryogenically cooled copper electrode in electric discharge machine setup up to a depth of 1.5 mm with a constant flushing pressure of 8 kg/cm². The time for machining each work piece is recorded and is used to find the MRR and TWR later on. Mitutoyo Surface roughness tester is used to measuring the surface roughness of the work piece after machining. Later, MRR and TWR are calculated by considering the weight loss of work piece and tool after the machining. The experimental responses are shown in Table 2 and Table 3.

Table2. Experimental Response in EDM for Inconel 601 for Normal Electrode

S. No.	Pulse on Time	Gap Voltage	Peak Current	MRR	TWR	R_a
1.	100	60	8	7.8467	0.068066	6.910
2.	200	60	8	8.3671	0.080221	8.790
3.	100	80	8	4.8355	0.044043	7.230
4.	200	80	8	3.7746	0.045840	8.650
5.	100	70	6	5.5781	0.045600	4.660
6.	200	70	6	6.1652	0.059110	6.860

7.	100	70	10	13.0155	0.155985	7.240
8.	200	70	10	11.1561	0.155000	8.620
9.	150	60	6	5.0443	0.063812	7.050
10.	150	80	6	1.8410	0.082580	7.575
11.	150	60	10	11.1490	0.255248	8.765
12.	150	80	10	7.5574	0.181144	9.790
13.	150	70	8	8.2203	0.187182	7.190
14.	150	70	8	8.2412	0.190110	7.220
15.	150	70	8	8.5412	0.213210	7.020

Table3. Experimental Response in EDM for Inconel 601 for Cryogenically Cooled Electrode

Sl. No.	Pulse on Time	Gap Voltage	Peak Current	MRR	TWR	R _a
1.	100	60	8	8.3012	0.053713	8.6825
2.	200	60	8	9.9037	0.015509	5.279
3.	100	80	8	5.0601	0.026937	6.305
4.	200	80	8	4.5463	0.038372	5.307
5.	100	70	6	4.0479	0.003561	6.434
6.	200	70	6	4.5132	0.009664	3.746
7.	100	70	10	10.83	0.088443	7.943
8.	200	70	10	11.3231	0.065432	5.607
9.	150	60	6	4.9845	0.01412	5.411
10.	150	80	6	3.1222	0.013588	5.472
11.	150	60	10	14.2844	0.107068	6.664
12.	150	80	10	7.4872	0.05433	5.606
13.	150	70	8	8.1556	0.048379	7.738
14.	150	70	8	8.123	0.042844	7.152
15.	150	70	8	8.1341	0.044124	6.9321

3. Results and Discussions

The result obtained through the set of experiments is to be analyzed for ensuring the fitness of model. This is done by doing a significance test. The test for goodness of fit and lack of fit is also done.

MINITAB 17 is used to analyze the experimental data and get the best possible result and analysis of variance is done to sum up the above test.

3.1 Response Surface Methodology

Response surface methodology (RSM) is a collection of mathematical and statistical technique for empirical model building. RSM is mainly used to get the optimize result for different inputs. RSM is generally used to find the significance of several input parameters on one or more output parameters.

An ordinary second order model is given by:

$$f = a_0 + \sum_{i=1}^n a_i x_i + \sum_{i=1}^n a_{ii} x_i^2 + \sum_{i < j}^n a_{ij} x_i x_j + \epsilon \quad (1)$$

where, a_{ii} denotes the quadratic effect of x_i , a_i denotes the linear effect of x_i and a_{ij} denotes the line to line interaction between x_i and x_j and x_i and x_j are the design variables. This quadratic model allows to locate the region of optimality besides investigating entire factor space.

The important data for response surface models is collected with the help of design of experiments, with the adoption of Box-Behnken Design.

The final response equations are as follows:

$$\begin{aligned} MRR = & 8.334 - 2.226 \times 10^{-1} T_{on} - 1.7998 V_g + 3.0312 I_p + 2.26 \times 10^{-1} T_{on}^2 - \\ & 2.335 V_g^2 + 4.18 \times 10^{-1} I_p^2 - 3.95 \times 10^{-1} T_{on} V_g - 6.12 \times 10^{-1} T_{on} I_p - 9.7 \times 10^{-2} V_g I_p \end{aligned} \quad (2)$$

$$\begin{aligned} MRR_{CRYO} = & 8.1376 + 2.5589 \times 10^{-1} T_{on} - 2.15726 V_g + 3.40710 I_p - 4.879 \times 10^{-1} T_{on}^2 - \\ & 6.969 \times 10^{-1} V_g^2 + 2.88 \times 10^{-2} I_p^2 - 5.291 \times 10^{-1} T_{on} V_g + 6.9 \times 10^{-3} T_{on} I_p - 1.2337 V_g I_p \end{aligned} \quad (3)$$

$$\begin{aligned} TWR = & 1.9683 \times 10^{-1} + 3.31 \times 10^{-3} T_{on} - 1.422 \times 10^{-2} V_g + 6.203 \times 10^{-2} I_p \\ & - 8.953 \times 10^{-2} T_{on}^2 - 4.776 \times 10^{-2} V_g^2 - 3.38 \times 10^{-3} I_p^2 - 2.59 \times 10^{-3} T_{on} V_g \\ & - 3.62 \times 10^{-3} T_{on} I_p - 2.322 \times 10^{-2} V_g I_p \end{aligned} \quad (4)$$

$$\begin{aligned} TWR_{CRYO} = & 4.512 \times 10^{-2} - 5.46 \times 10^{-3} T_{on} - 7.15 \times 10^{-3} V_g + 3.429 \times 10^{-2} I_p - 8.49 \times 10^{-3} T_{on}^2 - \\ & 2.99 \times 10^{-3} V_g^2 + 5.15 \times 10^{-3} I_p^2 + 1.241 \times 10^{-2} T_{on} V_g - 7.28 \times 10^{-3} T_{on} I_p - 1.305 \times 10^{-2} V_g I_p \end{aligned} \quad (5)$$

$$\begin{aligned} R_a = & 7.143 + 8.6 \times 10^{-1} T_{on} + 2.162 \times 10^{-1} V_g + 1.0337 I_p - 3.49 \times 10^{-1} T_{on}^2 + \\ & 1.101 V_g^2 + 5.1 \times 10^{-2} I_p^2 - 1.15 \times 10^{-1} T_{on} V_g - 2.05 \times 10^{-1} T_{on} I_p + 1.25 \times 10^{-1} V_g I_p \end{aligned} \quad (6)$$

$$\begin{aligned} R_a_{CRYO} = & 7.272 - 1.178 T_{on} - 4.18 \times 10^{-1} V_g + 5.95 \times 10^{-1} I_p - 3.68 \times 10^{-1} T_{on}^2 - \\ & 5.12 \times 10^{-1} V_g^2 - 9.73 \times 10^{-1} I_p^2 + 6.01 \times 10^{-1} T_{on} V_g + 8.8 \times 10^{-2} T_{on} I_p - 2.8 \times 10^{-1} V_g I_p \end{aligned} \quad (7)$$

3.2 Analysis of Variance (ANOVA)

The ANOVA for MRR, TWR and R_a has been found out for both normal and cryogenically cooled electrode. F-value is used to check the significance of values. The probability of F-value which exceeds the calculated F-value due to the noise is given by the P-value. If P value is more than 0.05 then the term is insignificant and lacks fit. An insignificant term is required as it indicates the left out term not significant and hence the develop model fits together. The value of coefficient of determination (R^2) and $adj.R^2$ are found to be 0.9979 and 0.9942 with normal electrode and 1.0000 and 0.9999 with cryogenically cooled electrode respectively. A normality test is further checking, by plotting the results. It is clear from the Figure 3 and Figure 4 that the residuals are normally distributed as they fall on a straight line. The plot of residual versus fit denotes the variance to be constant and linearity is maintained. The histogram data shows that the data is not skewed. Also, the systematic effect of order or time is found to be in good agreement in the residual versus order plot.

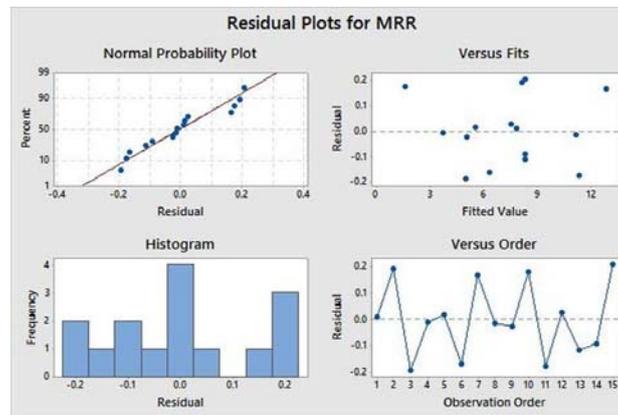


Figure3. Residual plots for MRR with normal electrode

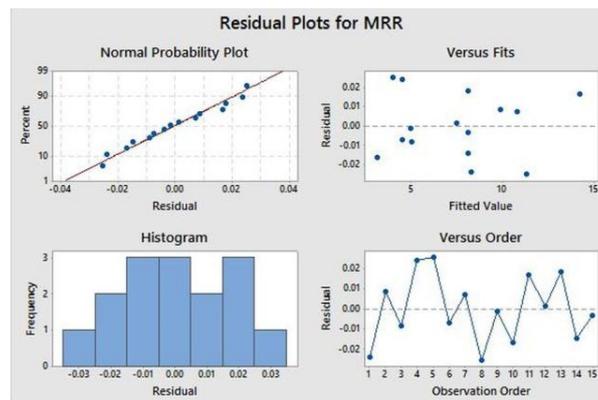


Figure4. Residual plots for Material Removal Rate with cryogenic electrode

3.3 Surface Plots

Surface plot for material removal rate is shown in Figure 5 and Figure 6 for normal and cryogenic electrode. From the graph, it can be seen that maximum value of material removal rate of 13.0155 mm³/min is achieved with normal electrode when $I_p=10.00\text{A}$, $T_{on}=100\mu\text{s}$ and $V_g=70\text{V}$ and maximum MRR of 14.28 mm³/min is achieved with cryogenically cooled electrode when pulse on time is 150 μs , gap voltage is 60 V and peak current is 10 A. It can be seen that MRR increase with increase in peak current and decrease with increase in gap voltage.

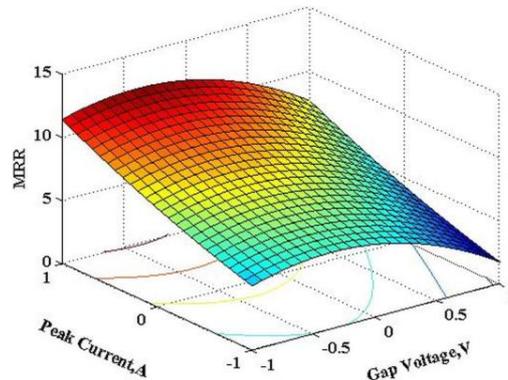


Figure5. Response Plot for V_g and I_p for MRR for normal electrode

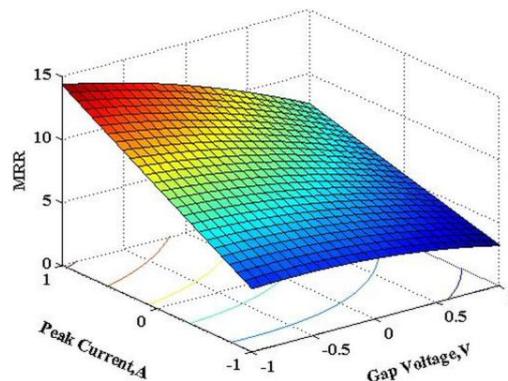


Figure6. Response Plot for V_g and I_p for MRR for cryogenic electrode

Surface plot for TWR and surface roughness is found out in the same for both the normal and cryogenic cooled electrode.

3.4 Multi Objective Optimization of Responses

Multi objective optimization of response is used to find out the best input setting for which we can get the best result for the output parameters. Here, we are looking for input which gives us maximum MRR, minimum TWR and minimum surface roughness. Figure 7 and Figure 8 shows the

optimization plot for normal and cryogenically cooled electrode. From the figure, we can see the best condition for normal electrode is when pulse on time is 100 μ s, gap voltage is 66.4646 V and peak current is at 6.7273 A. Also, we can see the best condition for cryogenic electrode is when pulse on time is 200 μ s, gap voltage is 60 V and peak current is at 7.737 A. [12,13]

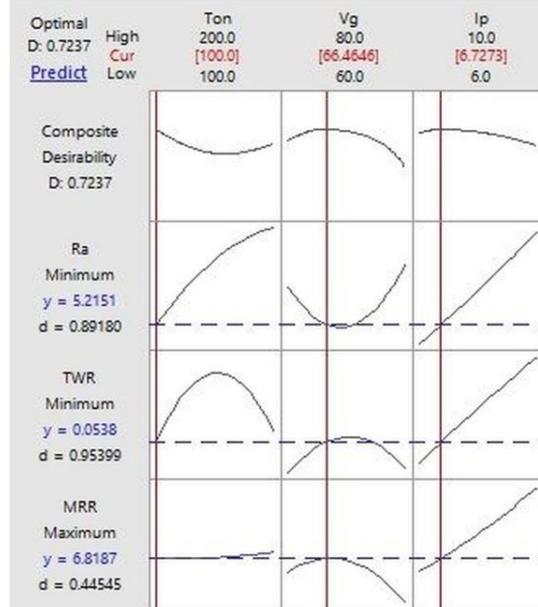


Figure7. Response Optimization Plot for Normal Electrode

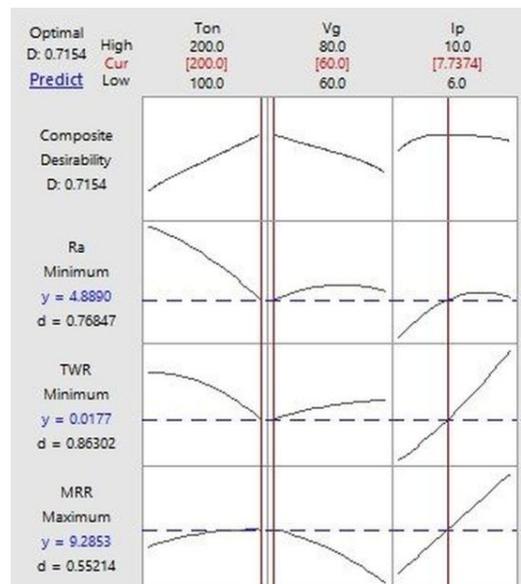


Figure8. Response Optimization Plot for Cryogenically Cooled Electrode

3.5 Comparative Study

A comparative graph is shown in Figure 9, Figure 10 and Figure 11 for results obtained from machining without the use of cryogenic treated copper electrode and with use of cryogenic treated copper electrode in EDM with Inconel 601 as workpiece. Figure 9 is the comparison of MRR of workpiece. In the graph, it can be seen that maximum MRR is achieved in experiment number 11 in cryogenic process. Similarly, Figure 10 is the comparison of TWR and it shows that the least or minimum tool wear is achieved in experiment number 5 in cryogenic process. The comparison of surface roughness of the machined surface is shown in Figure 11. Experiment number 6 shows the lowest surface roughness which is of cryogenic process.

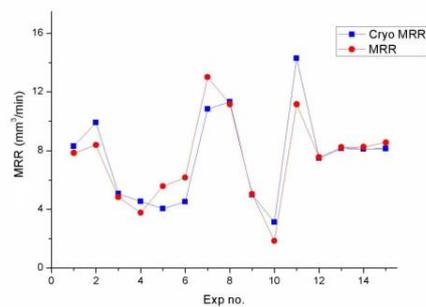


Figure9. Comparison of MRR in workpiece with an without use of Cryo-cooled electrode

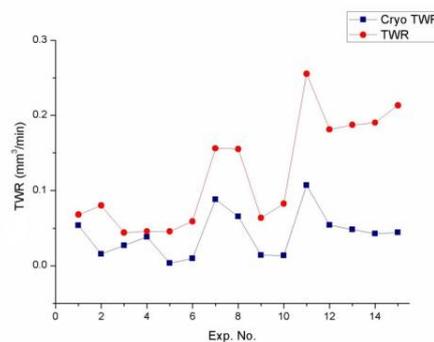


Figure10. Comparison of TWR in tool with an without use of Cryo-cooled electrode

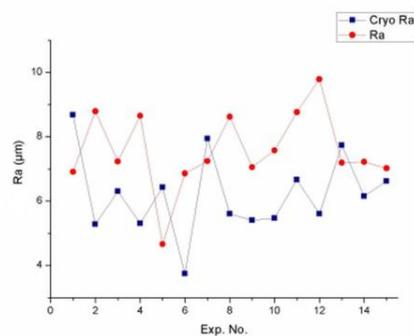


Figure 11. Comparison of R_a in workpiece with an without use of Cryo-cooled electrode

It is clear from the above graphs that the use of cryogenic cooling shows significant improvement in MRR, TWR and R_a . It simply means that cryogenic cooling helps in improving the machining response parameters.

4. Conclusion

Results from the experiment carried out in the work are as such that the ANOVA results are in good agreement with the reprised models.

Current is the most important factor among all for all the three output. TWR and MRR is inversely proportional to voltage. TWR is more at lower pulse on time and decreases with increase in pulse on time. Surface roughness varies directly with current. Cryogenic cooling helps in improving the machining response parameters. Cryogenic treatment of electrode enhances the surface hardness of the materials.

Cryogenic cooling improves the MRR by 1.36 times as compared to normal electrode. In cryogenic cooling, tool wear rate is 33% as that of normal electrode. Cryogenic cooling also improves the surface roughness by 6%.

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