Influence of Cryogenically Treated Cupro-Nickel Electrode on Electric Discharge Machining of Inconel 718 Super Alloy

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Abstract: This paper describes a study on the cooling effect on cupronickel electrode while electric discharge machining of nickel based super alloy Inconel 718 workpiece. To evaluate material removal rate (MRR), electrode wear rate (EWR) and average surface roughness values (SR) were the three responses observed. Peak current, pulse on time, voltage gap and duty cycle were the controllable process parameters. Taguchi experimental design of L9 orthogonal has been applied to investigate the optimal process parameters for maximum material removal rate (MRR), minimum electrode wear rate (EWR) and surface roughness (SR). The ANOVA analysis also been applied to investigate influencing parameters which effects response obtained from experimentation. The conclusions made from this study are optimum value combination of process parameters for optimum material removal rate (MRR) when using C.T cupronickel as electrode is Ip = 10 A, Ton = 300 µs, Vg = 50 V and Tau = 15.The optimum value combination of process parameters for optimum electrode removal rate (EWR) when using C.T cupronickel as electrode is Ip = 6 A, Ton = 100 µs, Vg = 70 V and Tau = 10.The optimum value combination of process parameters for optimum surface roughness (SR) when using C.T cupronickel as electrode is Ip = 6 A, Ton = 100 µs, Vg = 70 V and Tau = 15.This treatment majorly improves the tool wear rate and material removal rate as compared to surface roughness. From the experiments performed and the analysis carried out it can be concluded that cryogenically treated cupronickel is the best electrode as compared to non-treated electrode The C.T. cupronickel electrode produces improvement in electrode wear rate (6.611%), material removal rate (4.00%) and surface roughness (0.305%) as compare to Cupronickel electrode. Cryogenic treatment of tool electrodes result into reduction in electrode wear rate and material removal rate. Relatively lesser influence of the same has been observed on surface roughness.

Keywords— **Electrical discharge machining, Cryogenic treatment, Inconel 718 super alloy, Cupronickel (90/10), Regression analysis**

I. INTRODUCTION

Toughened and high strength-to-weight ratio super alloys find diversified range of applications in aerospace, automobile, chemical plant, power generation, oil and gas extraction, surgical instruments and other major industries. However, it is difficult to machine these alloys with conventional machining processes due to high temperature generation at tool tip resulting in change in mechanical properties of both the tool and work piece. Therefore, non-conventional machining processes like electrical discharge machining (EDM) is normally recommended for the purpose [16]. Electrical-discharge machining (EDM) is an unconventional, non-contact machining process where metal removal is based on thermal principles. In this process, the material removal mechanism uses the electrical energy and turns it into thermal energy through a series of discrete electrical discharges occurring between the electrode and workpiece immersed in an insulating dielectric fluid. The thermal energy generates a channel of plasma between the cathode and anode at a temperature in the range of 8000–12,000 ◦C, initializing a substantial amount of heating and melting of material at the surface of each pole. When the direct current supply is turned off, the plasma channel breaks down [1]. This causes a sudden reduction in the temperature allowing the circulating dielectric fluid to implore the plasma channel and flush the molten material from the pole surfaces in the form of microscopic debris [10]. EDM does not make direct contact between the electrode and the workpiece whereby it can eliminate mechanical stresses, chatter and vibration problems during machining. Despite all the advantages, the EDM process is not free from drawbacks. One of the major drawbacks is the slow rate of material removal [5]. Other drawback includes high rate of electrode wear, surface and subsurface damage and creation of thin and brittle heat-affected zone. In light of these defects, researchers have developed new techniques using ultrasonic, gas based method, dry EDM, near dry EDM etc., where they tried to overcome the above limitations.

Electrical discharge machining also known as EDM has been proven as an alternative process for machining complex and intricate shapes from the conductive ceramic composition. It is a non-conventional machining method. In electrical discharge machining process electrical energy is used to cut the material to final shape and size. Efforts are made to utilize the whole energy by applying it at the exact spot where the operation needs to be carried out [8] .There is no mechanical pressure existing between work piece and electrode as there is no direct contact. Any type of conductive material can be machined using EDM irrespective of the hardness or toughness of the material. The selection of EDM parameters for optimum output characteristics require large experimental work. A super alloy, or high-performance alloy, is an alloy that exhibits several key characteristics [7] [15], excellent mechanical strength, resistance to thermal creep deformation, good surface stability and resistance to corrosion or oxidation. Super alloys are the alloys which possess comparatively higher mechanical and thermal strength in comparison to individual metals. These properties of the super alloys make them eligible for the purpose where in high strength to weight ratio of a material is expected [17].

II. DETAILS OF WORK AND TOOL MATERIAL

Commercially available Inconel 718 alloy plates of size 150×100×3 mm and Cupro-nickel (90/10) rods of diameter 10 mm and length 150 mm are chosen as work and tool material respectively as shown in figure 1, because of their lower electrical and thermal conductivity with an objective to improve their mechanical properties through cryogenic treatment. The details of size, physical and mechanical properties of work and tool material are given below.

Fig. 1 pictorial view work and tool material

Inconel 718 is an austenitic nickel-base superalloy which is used in applications requiring high strength to approximately 1400°F (760°C) and oxidation resistance to approximately 1800°F (982°C). In addition, the alloy exhibits excellent tensile and impact strength even at cryogenic temperatures. High strength at room and elevated temperatures is developed by a precipitation heat treatment at 1325°F (718°C) with cooling and a hold of 1150°F (621°C). The relatively slow response to precipitation hardening permits repair welding of the alloy even in the aged condition [18]. The nominal chemical composition and properties of Inconel 718 is given in table 1 and table 2.

Table 1: The nominal chemical composition of Inconel 718 [18]

Sr. no.	Elements	Weight %	Sr. no.	Elements	Weight %
1	Carbon (C)	0.08	9	Columbium (Nb)	4.75-5.50
2	Manganese (Mn)	0.35	10	Titanium (Ti)	065-1.15
3	Phosphorous (P)	0.015	11	Aluminum (Al)	0.20-0.80
4	Sulphur (S)	0.015	12	Cobalt (Co)	1.00
5	Silicon (Si)	0.35	13	Boron (B)	0.006
6	Chromium (Cr)	17.00-21.00	14	Copper (Cu)	0.30
7	Nickel (Ni)	50.00-55.00	15	Tantalum (Ta)	0.05
8	Molybdenum (Mo)	2.80- 3.30	16	Iron (Fe)	Balance

Table 2: Properties of Inconel 718 alloy [18]

Sr. no.	Properties	Value
1	Density	8.19 g/cm3
2	Tensile Strength	1241 MPa
3	Yield Strength (0.2% offset)	1034 MPa
4	Elongation in 2 ln. , %	12
5	Hardness	Rc 36 or 382 VHN
6	Melting Point	1260-1360 0C
7	Thermal conductivity	6.7 W/m-K @30 0C

Commercially available 90/10 Cupro-nickel is chosen as tool material which is an alloy of 90% copper and 10% nickel that contains small but important addition of iron and manganese that enhance the overall strength and corrosion resistance. Traditionally, 90/10 is used in marine environments as it offers inherent resistance to bio-fouling, low rates of corrosion in seawater and brackish water, high resistance to ammonia stress corrosion cracking, good pitting, resistance and excellent resistance to crevice corrosion and stress corrosion. In addition, 90/10 has high resistance to hydrogen embrittlement and retains its mechanical properties from elevated temperatures down to cryogenic temperatures as low as -149 ^{0}C [19]. The nominal chemical composition and properties of cupronickel are given in table 3 and table 4.

Table 3: Chemical composition [19]

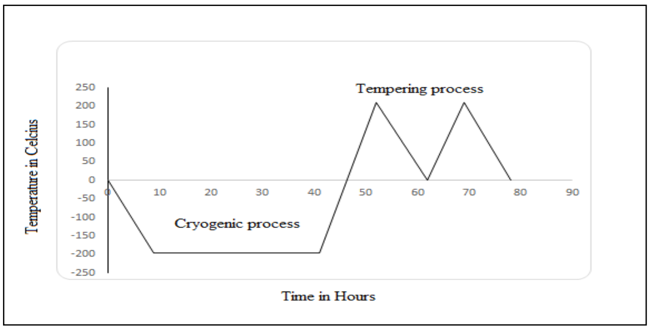
Element	Copper (Cu)	Nickel (Ni)	Iron (Fe)	Manganese (Mn)
Weight %	87.25	10.5	1.5	0.75

Table 4: Properties of cupronickel (90/10) alloy [19]

Sr. no.	Properties	Value
1	Density	8.94 g/cm3
2	Ultimate Tensile Strength	300 MPa
3	Yield Strength (0.2% offset)	105 MPa
4	Elongation in 2 ln.	30 %
5	Hardness	250 BHN
6	Melting Point	1099 ^{0}C
7	Thermal conductivity	46 W/m-K @30 0C

III. CRYOGENIC TREATMENT

A cupronickel electrode of 10 mm diameter was subjected to deep cryogenic treatment which consist of cool down rate of (1 ^{0}C/min) from room temperature to cryogenic temperature at -184 ^{0}C and electrode was kept in cryogenic processor for about 30 hours and then temperature was gradually increased to room temperature, then electrode was subjected to two tempering cycles at the temperature of +184 ^{0}C to incur the stresses induced by cryogenic treatments and cool down to room temperature slowly at the rate of 0.5 ^{0}C/min as shown in figure 1(a). This treatment is done to improve the wear, hardness, toughness, thermal and electrical properties of tool electrode [8].



(a)

(b)

Fig. 1 (a) Cryogenic treatment process (b) Pictorial view of cryogenic processor

IV. EXPERIMENTAL DETAILS

The choice of points where experiments are performed has very large affecting the accuracy of the response surface. The method for selecting a good set of points for carrying out experiments is known as design of experiments. According to Design of Experiments (DOE) methodology, experiments are designed in which design domain is bounded by upper and lower limits of the factor. It is an effective and systematic approach to experimentation that considers all the factors simultaneously and predicts response over a wide range of values. DOE provides information about the interaction of factors and the way the total system works, something not obtainable by testing one factor at a time (OFAT) while holding other factors constant. Another advantage of DOE is that it shows how interconnected factors respond over a wide range of values, without requiring the testing of all the possible combinations of the factorial values directly. Thus, it drastically reduces the number of experiments to be conducted. Most of the experiments were done by using this method because it reduces the time and money consuming experiments. The input parameters and generation of DoE using Taguchi method L9 array is shown in table 5 and table 7. Following parameters were kept constant during the experiments:

a) Work Material: Inconel 718
b) Electrode material: C.T. cupronickel, N.C.T cupronickel.
c) Electrode Polarity: Positive
d) Work material polarity: Negative
e) Spark voltage: 50 V, DC.
f) Flushing type: Submerged in dielectric.
g) Machining depth: 1.00 mm.
h) Dielectric: EDM oil (Grade 30)

Table 5: Input parameter

Parameter	Levels		
	1	2	3
Peak Current (I_p)	6	8	10
Pulse on Time (T_{on})	100	200	300
Voltage gap (V_g)	50	60	70
Duty cycle (τ)	10	15	20

Table 7: Generation of DOE by using Taguchi Method L9 Array is as below

Run No.	Peak Current (I_p)	Pulse on Time (T_{on})	Voltage gap (V_g)	Duty cycle (τ)
1	6	100	50	10
2	6	200	60	15
3	6	300	70	20
4	8	100	60	20
5	8	200	70	10
6	8	300	50	15
7	10	100	70	15
8	10	200	50	20
9	10	300	60	10

V. RESULTS AND DISCUSSIONS

MRR versus Ip, Ton, Vg, Tau:

The material removal rate (MRR) is larger the better type quality characteristics. Thus, the taguchi methodology using larger is better approach has been employed. The mean of three S/N ratios for MRR, each for 9 experiments, were calculated. The results obtained from taguchi analysis for material removal rate (MRR) are summarized in table 8.

Table 8: MRR response table for S/N ratios of C.T electrode (Larger is better)

Level	Ip	Ton	Vg	Tau
1	11.006	4.850	12.044	12.247
2	11.638	13.439	12.033	12.777
3	11.744	16.099	10.312	9.364
Delta	0.738	11.248	1.732	3.413
Rank	4	1	3	2

The higher the delta value, the higher the contribution of parameter on response and rank shows their relative importance effect on MRR. From table 8, it is clear that pulse on time (Ton), pulse duty factor (Tau), voltage gap (Vg) and peak current (Ip) affect the process performance in order of significance. In the present study, the main effect plot (S/N ratios) for MRR, as shown in fig. 2, clearly depicts that the largest value of S/N ratio (Larger is better) for MRR is obtained at combination Ip3Ton3Vg1Tau2. In other word, the optimum condition for MRR is at level 3 (10 A) of peak current (Ip), level 3 (300 µs) of pulse on time (Ton), level 1 (10 V) of voltage gap (Vg) and level 2 (15) of pul48se duty factor (Tau).

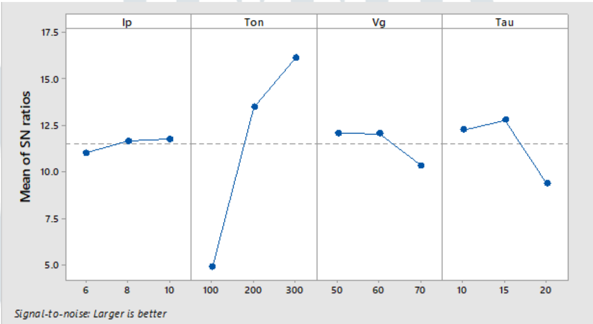


Fig. 2 MRR main effect plot for SN ratio – C.T cupronickel

The ANOVA analysis was performed, neglecting interaction effect of various parameters. From table 10, it was found that pulse on time (Ton) most significantly affect the performance characteristic MRR and least affected by peak current in case of C.T electrode at 95% of confidence level of significance.

It is quite evident from analysis of the results that the peak current affects the MRR, most predominantly. During the understanding of mechanism of material removal the following observations were noted. The reason behind the exhibited trend of MRR is the spark energy which depends upon the peak current. The more spark energy is conducted into the gap, with the increasing peak current. Moreover, while studying the effect of pulse duration on MRR, an increasing trend was seen to be suddenly reversed after 300 µs due to the behaviour of the formation of the discharge channel between the electrodes. At lower pulse duration, the movement of electrons and ions starts channelizing until it attains a peak level to form an optimum discharge channel causing highest MRR, after this level, if the pulse duration is further increased the constituent electrons and ions start colliding with each other which results in lesser focused channel and thus, lesser MRR is attained.

Table 10: Analysis of variance for transformed response (MRR) of C.T electrode

Source	DF	Seq. SS	Contribution	Adj. SS	Adj. MS	F-Value	P-Value
Regression	4	2.55387	89.65%	2.55387	0.63847	8.66	0.030
Ip	1	0.02202	0.77%	0.02202	0.02202	0.30	0.614
Ton	1	2.26937	79.66%	2.26937	2.26937	30.79	0.005
Vg	1	0.08561	3.01%	0.08561	0.08561	1.16	0.342
Tau	1	0.17688	6.21%	0.17688	0.17688	2.40	0.196
Error	4	0.29482	10.35%	0.29482	0.07370		
Total	8	2.84869	100.00%				

EWR versus Ip, Ton, Vg, Tau:

The electrode wear rate (EWR) is smaller the better type quality characteristics. Thus, the taguchi methodology using smaller is better approach has been employed. The mean of three S/N ratios for EWR, each for 9 experiments, were calculated. The results obtained from taguchi analysis for electrode wear rate (EWR) are summarized in table 9.

Table 9: EWR response table for S/N ratios of C.T electrode (Smaller is better)

Level	Ip	Ton	Vg	Tau
1	15.805	11.466	8.596	10.088
2	7.209	5.457	7.326	5.079
3	2.146	8.236	9.237	9.993
Delta	13.659	6.009	1.911	5.009
Rank	1	2	4	3

The higher the delta value, the higher the contribution of parameter on response and rank shows their relative importance effect on EWR. From table 9, it is clear that peak current (Ip), pulse on time (Ton), pulse duty factor (Tau) and voltage gap (Vg) affect the process performance in order of significance. In the present study, the main effect plot (S/N ratios) for EWR, as shown in fig. 3, clearly depicts that the largest value of S/N ratio (Smaller is better) for EWR is obtained at combination Ip1Ton1Vg3Tau1. In other word, the optimum condition for EWR is at level 1 (6 A) of peak current (Ip), level 1 (100 µs) of pulse on time (Ton), level 3 (20 V) of voltage gap (Vg) and level 1 (10) of pulse duty factor (Tau).

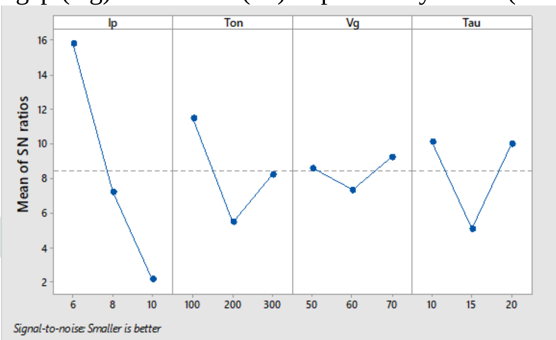


Fig. 3 MRR main effect plot for SN ratio – C.T cupronickel

The regression analysis results using Box-Cox transformation for electrode wear rate (EWR) shown table 10. The ANOVA analysis was performed, neglecting interaction effect of various parameters. From table 10, it was found that peak current (Ip) most significantly affect the performance characteristic EWR and least affected by pulse duty factor (Tau) in case of C.T electrode at 95% of confidence level of significance.

Table 10: Analysis of variance for EWR of C.T electrode

Source	DF	Seq. SS	Contribution	Adj. SS	Adj. MS	F-Value	P-Value
Regression	4	0.558634	86.73%	0.558634	0.139659	6.54	0.048
Ip	1	0.517518	80.35%	0.517518	0.517518	24.22	0.008
Ton	1	0.025455	3.95%	0.025455	0.025455	1.19	0.336
Vg	1	0.015626	2.43%	0.015626	0.015626	0.73	0.441
Tau	1	0.000035	0.01%	0.000035	0.000035	0.00	0.970
Error	4	0.085453	13.27%	0.085453	0.021363		
Total	8	0.644087	100.00%				

It is very much evident from the results that the peak current affects the EWR to the greatest extent. This may be due to the directly proportional relation of the temperature of the tool with the peak current and thus the high melting and vaporization leads to high EWR. Nozzle flushing has been observed to put a positive effect on the EDM performance, by reducing the tool wear. This happens due to the assistance provided by nozzle flushing to clear the debris, reduce the metal deposition on the electrodes and avoid any clogging between the electrodes

VI. CONCLUSION

In this study the electrode which gave the optimum values of process parameters for machining the Inconel 718 is suggested by performing the experiment on the EDM using cryogenic treated (C.T) cupronickel and non-cryogenic treated (N.C.T) cupronickel electrode. Using the Minitab 18 first the SN ratio is calculated and the mean values of the performance parameters were recorded. The predicted values were checked with experimental results and a good agreement was found. The optimum values of the process parameters are the one which take the highest value in the SN ratio graph. The conclusions made from this study are:

The optimum value combination of process parameters for optimum material removal rate (MRR) when using C.T cupronickel as electrode is Ip = 10 A, Ton = 300 µs, Vg = 50 V and Tau = 15. The optimum value combination of process parameters for optimum electrode removal rate (EWR) when using C.T cupronickel as electrode is Ip = 6 A, Ton = 100 µs, Vg = 70 V and Tau = 10. The optimum value combination of process parameters for optimum surface roughness (SR) when using C.T cupronickel as electrode is Ip = 6 A, Ton = 100 µs, Vg = 70 V and Tau = 15. This treatment majorly improves the tool wear rate and material removal rate as compared to surface roughness. From the experiments performed and the analysis carried out it can be concluded that cryogenically treated cupronickel is the best electrode as compared to non-treated electrode The C.T. cupronickel electrode produces improvement in electrode wear rate (6.611%), material removal rate (4.00%) and surface roughness (0.305%) as compare to Cupro-Nickel electrode Cryogenic treatment of tool electrodes result into reduction in electrode wear rate and material removal rate. Relatively lesser influence of the same has been observed on surface roughness.

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