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Investigation of Machining Characteristics of nickel-based alloy with Copper Coating and Application of Magnet by using DS-EDM Process

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Abstract

Nickel based super alloy material are extensively used in various industrial applications such as aerospace, automobile etc., due to their unique mechanical and chemical properties. However, machining of such hard materials is most difficult by using traditional machining process and also increases the manufacturing time and cost as well as to reduce machine tool durability. Non-traditional machining techniques are playing a major role to resolve the issues present in traditional machining. This paper presents study and investigation of machining characteristics of a non-contacting or non-traditional machining such as die-sinking electrical discharge machining (DS-EDM) process on nickel-based alloy Inconel 718 material with copper coating and application of magnet. Further, the investigation is performed based on Taguchi L-16 orthogonal array to analyze the DS-EDM process dependent parameters like material removal rate (MRR) and tool wear rate (TWR) and corresponding independent parameters are current, pulse-ON, duty cycle and voltage. Furthermore, statistical significance analysis tools via. parametric analysis, ANOVA and 3D response is carried out to evaluate the effect of input variables on output variables of DS-EDM. The result shows that the optimal parameter setting is obtained (i.e., current at 4 amps, pulse-on at 40 µs, duty cycle at 10 µs and voltage at 40 v) by using MOORA optimization technique and achieved quality products with higher production throughput.

Key words: *Inconel-718, EDM, DS-EDM, MRR, TWR, copper coating, magnet.*

1. Introduction

In the current scenario, non-traditional machining methods are playing a vital role to produce superior quality products with minimum manufacturing time and cost. Moreover, machining of nickel based super alloy materials viz., Inconel 718 materials are bit difficult by applying conventional machining set-up due their significant mechanical and chemical properties. However, the machining of such hard materials is possible with a non-contact machining process like electrical discharge machining (EDM) to overcome the issues present in conventional machining set-up. In this regard, researchers more focused to their research on EDM process capabilities and effect of machining process parameters. Moreover some extent of work has been done on EDM technique capabilities and effect of machining parameters in this way, (Guu et al., 2003) investigated surface integrity properties and machining damage caused by EDM on steel material. The result shows that, the surface morphology is significantly depends on thickness of re-cast layers and the strength property of steel is drastically decreases (Khan, 2008). studied machining characterization of EDM process with copper and brass electrodes on aluminum and mild steel materials. The result shows that, the better results obtained in terms of MRR and TWR while machining of EDM with copper electrode. (Kiyak and Çakir, 2007) study and evaluation of EDM process parameters on machining of tool steel material. The results showed that, the process parameters viz., peak current, voltage, pulse-ON and duty cycle are most significantly influencing variables on surface roughness. (Rajendran et al., 2013) explored re-cast layers and crack formation caused by EDM process of tool steel material. The results revealed that, the peak current is most influencing parameter to produce re-cast layers and crack formation.

Furthermore some extent of work has been carried out machining characteristics of EDM process on nickel based super alloy materials, in this regard (Ahmad and Lajis, 2013) study and investigation of EDM process parameters of Inconel 718 super alloy material by using copper electrode. The results shows that, the independent parameters peak current at 20-40 amps and pulse-ON time at 200 µs gives better machining results in terms of MRR and TWR. (Mohanty et al., 2014) investigated optimal process parameters setting of WEDM process on Inconel 825 super alloy material. The results show that, the optimal process parameters setting i.e., peak current at 1 amp, pulse-ON time at 10 µs and duty cycle is at 75% gives better response parameters viz., MRR, SR, radial over cut (ROC) and surface crack density (SCD).

Moreover, (Torres et al., 2015) investigated EDM machining characteristics of Inconel 600 by using graphite electrode. The result shows that, the negative polarity gives better results in terms of MRR whereas positive polarity gives good surface finish. (Archana et al., 2018) studied machining response in WEDM of Inconel 625 material. The results revealed that, the optimal process parameters settings are found to improve the response parameters i.e. MRR, SR, and EWR. (Kumar and Maity, 2018) study and comparison of machining characteristics of Inconel 625, Inconel 718 and Monel 400 in hot milling operation. The results showed that, the three kinds of nickel based super alloy materials compared hot milling results with room temperature results, it is found that heating significantly affect the machining characteristics of all three kinds of nickel-based materials.

Apart from the machining characteristics of super alloy materials, very less amount of research work is to be reported on machining characteristics of super alloy materials by using EDM technique with application of magnet and coated electrodes, (Singh Bains et al., 2016) investigated and found that, the overall improvement in response parameters of EDM technique while machining of the metal matrix composite by application of magnet. (Teimouri and Baseri, 2012) studied effect of magnetic field and rotary tool in EDM process. The results raveled that, the significant improvement in the response parameters is obtained when the magnet is rotates around the machining zone.

In addition, (Maher et al., 2015) explored EDM process improvements and effect of different coated electrodes. The results showed that various coated electrodes are used EDM process like copper, brass, and zinc, still there is a challenge to develop an electrode with coating and having good conductivity, eco-friendly and superior machinability properties. (Dhale and Kulkarni, 2016) studied the behavior of Inconel 718 varying electrode coating using EDM. The result shows that, the better material removal and surface finish is obtained with coated electrode. (Kuppan et al., 2017) studied performance and evaluation of electrode materials in EDM of Inconel 718 material. The results revealed that, the copper electrode is recommended for better MRR and SR as compared to copper tungsten and graphite electrode.

Moreover, (Dong et al., 2017) explored and investigation of micro-EDM process with auxiliary electrode on beryllium copper alloy material. In this work, study and evaluation of optimal machining set-up parameters and effects of hole end surfaces of beryllium copper alloy material by micro-EDM process with and without auxiliary electrode. The results showed that, auxiliary electrode improves the surface morphology on work piece and effectively protect the hole end surfaces from stray-current corrosion. And also, auxiliary electrode can be fixed on different radii of curvature surface. However more research work has been carried out by using copper material as an electrode in DS-EDM process, but copper electrode having low melting point, less durability, more tool wear rate, high cost as compared to graphite electrode. In this paper, graphite electrode with copper coating act as auxiliary electrode to avoid issues present in copper electrode.

Despite of machining characteristics of Inconel718 super alloy materials, very limited work has been addressed on machinability characterization of Inconel 718 material by using DS-EDM process with copper coating and application of magnet. In this paper presents, study and evaluation of machining characteristics of DS-EDM process with copper coating and copper coating with application of magnet. Initially the investigation is performed based on Taguchi L-16 orthogonal array to analysis and impact of DS-EDM process dependent parameters like material removal rate (MRR) and tool wear rate (TWR) and corresponding independent parameters are current, pulse-ON, duty cycle and voltage. Furthermore, statistical significance analysis tools via. parametric analysis, ANOVA and 3D response is carried out to evaluate the significant levels of independent parameters. At last, the optimal process parameters setting is determined by using MOORA technique. The results are validated through confirmatory tests. The remaining portion of the article is segregated into several sections like material and experimental details, result and discussion and conclusions.

2. Material and Experimental procedure

2.1. Material and coating details

The selection of materials for this study is nickel-based materials such as Inconel 718 material of having rectangular cross section (100 mm height and 10 mm thickness) and considered as an anode shown in Figure 1. The deposition of copper coating on Inconel 718 by sputtering machine as shown in Figure 2. The input values of sputtering machine are working pressure of 3 mTorr (0.39996 Pascal), dc power 200 watts and substrate temperature 100^0C is to be considered. The obtained copper layer thickness on the material is determined by wave length dispersive X-ray fluorescence (WDXRF) method. The copper coating on work piece acts as auxiliary electrode to improve material removal rate and surface morphology. EDM oil is used as a die-electric fluid (Chakraborty et al., 2015).

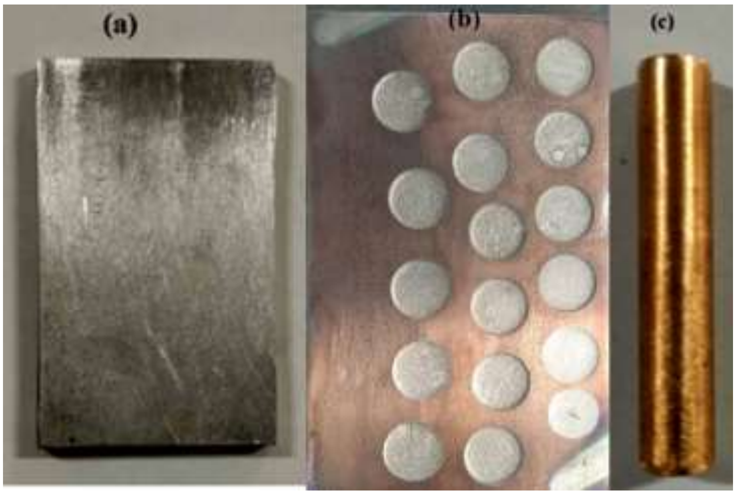

Figure 1. (a) work piece before machining and copper coating (b) work piece with coating after machining (c) copper electrode

Figure 2. Sputtering machine

2.2. Experimental procedure

The experimentation is conducted on nickel-based alloy Inconel 718 material with copper coating and application of magnet by DS-EDM process, (Machine: Electronica ElektraPlusPS 50ZNC, India) as shown in Figure 3. According to DS-EDM set-up, there are 16 operations are performed on the work piece based on the process variable levels depicted in the Table 1. The impact of input variables on output variables of nickel-based alloy with copper coating and application of magnet by DS-EDM process details incorporated in the Table 2 and Table 3 (Das et al., 2016).

Figure 3. DS-EDM machine set-up

Table 1 process variables and their levels for DS-EDM process

No. of Levels	Current (amps)	Pulse-ON (μs)	Duty-cycle (μs)	Voltage (Volts)
Level-1	4	10	4	30
Level-2	6	20	6	35
Level-3	8	30	8	40
Level-4	10	40	10	45

Table 2 Test results of DS-EDM process with copper coating on Inconel 718 material.

Expt. No	Current	Pulse-ON	Duty cycle	Voltage	MRR	TWR
	Amps	μs	μs	volts	mm^3/min	mm^3/min
1	4	10	4	30	1.436	0.827
2	4	20	6	35	4.623	0.981
3	4	30	8	40	12.083	1.233
4	4	40	10	45	14.414	2.114
5	6	10	6	40	2.556	0.667
6	6	20	4	45	3.75	1.156
7	6	30	10	30	12.722	3.304
8	6	40	8	35	16.457	4.191
9	8	10	8	45	3.7	1.273
10	8	20	10	40	10.736	0.238
11	8	30	4	35	6.105	3.979
12	8	40	6	30	13.114	4.966
13	10	10	10	35	6.962	2.719
14	10	20	8	30	12.333	3.4
15	10	30	6	45	4.187	4.1
16	10	40	4	40	12.502	5.161

Table 3 Test results of DS-EDM process with copper coating and application of magnet on Inconel 718 material

Expt. No	Current	Pulse-ON	Duty cycle	Voltage	MRR	TWR
	Amps	μs	μs	volts	mm^3/min	mm^3/min
1	4	10	4	30	1.700862	0.892
2	4	20	6	35	6.04225	1.481
3	4	30	8	40	12.50833	1.883
4	4	40	10	45	19.56429	3.164
5	6	10	6	40	3.105833	1.167
6	6	20	4	45	4.787456	2.806
7	6	30	10	30	14.23044	3.304
8	6	40	8	35	16.86477	4.391
9	8	10	8	45	4.399167	1.823
10	8	20	10	40	10.53452	2.238
11	8	30	4	35	6.771479	3.479
12	8	40	6	30	11.98793	4.466
13	10	10	10	35	8.934375	3.719
14	10	20	8	30	11.3	3.9
15	10	30	6	45	3.78125	4.8
16	10	40	4	40	11.62177	5.161

There are four independent variables considered (shown in Table 1) during the investigation and performed 16 circular trail runs on the work piece and the results of MRR and TWR is averaged for evaluation (Dong et al., 2017). The response parameters MRR and TWR are determined by using the following relations:

$$MRR = \frac{MRSS}{TCT} \quad \text{----------------------- (1)}$$

$$TWR = \frac{MT_{before\ machining} - MT_{after\ machining}}{TCT} \quad \text{------------------------ (2)}$$

Where MRSS represents material removal in a single spark, TCT indicates total cycle time and MT represents mass of the tool.

3. Result and Discussion

3.1. Parametric Analysis

3.1.1. Parametric analysis of process parameters on MRR of DS-EDM process with copper coating on Inconel 718 material.

The influence of input parameters on output parameter MRR of nickel-based alloy Inconel 718 material with copper coating by using DS-EDM process as shown in Figure 4. The copper coating on the work material act as an auxiliary electrode and make the process is smooth and obtained superior surface morphology. The input parameters pulse-ON and duty cycle are significantly influence on out parameter MRR of DS-EDM process of nickel-based alloy Inconel 718. This is due to fact that, the parameter pulse-ON and duty cycle increases, rate of plasma also increases between electrodes then the huge amount of thermal energy is generated within the dielectric fluid result in high amount of MRR is attained. However, the input parameters current and voltage are influenced moderately. This trend is obtained due to increase of current and voltage then the initial gap between electrodes varied and result in moderate MRR is obtained. The parameters pulse-ON and duty cycle are most effecting variables on MRR of DS-EDM process of nickel based alloy Inconel 718 material with copper coating (Joshi et al., 2011).

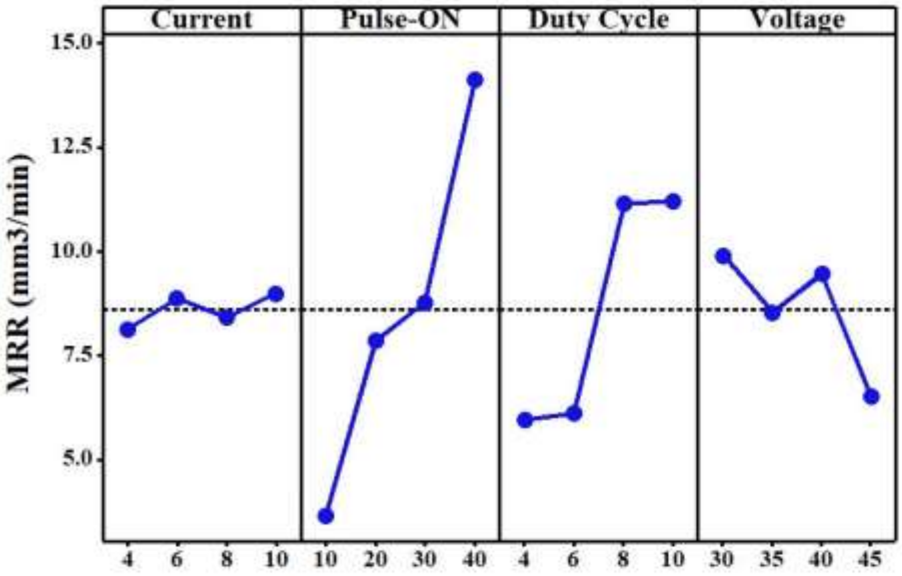

Figure 4. Main effect plots for MRR for various independent variables with copper coating on Inconel 718 material

3.1.2. Parametric analysis of process variables on TWR of DS-EDM process with copper coating on Inconel 718 material.

The process parameters current and pulse-On are the most significant effecting parameters on TWR of DS-EDM process with copper coating on nickel-based alloy Inconel 718 as shown in Figure 5. The trend is occurred due to the fact that, the parameters such as current and pulse-ON increases, more sparks are generated between electrodes (work piece and copper electrode) result in higher TWR is obtained. Moreover, the reduced trend is observed when the parameters duty cycle and voltage are increases gradually. This is because the distance between electrodes were increases, reduces the impact of sparks on the work pieces result in lower amount of TWR is attained during the machining of nickel-based alloy Inconel 718 material with copper coating by DS-EDM process. It is noted that the input parameters current, pulse-on, duty cycle and voltage are most impact parameters on TWR of DS-EDM process of nickel-based alloy Inconel 718 material with copper coating.

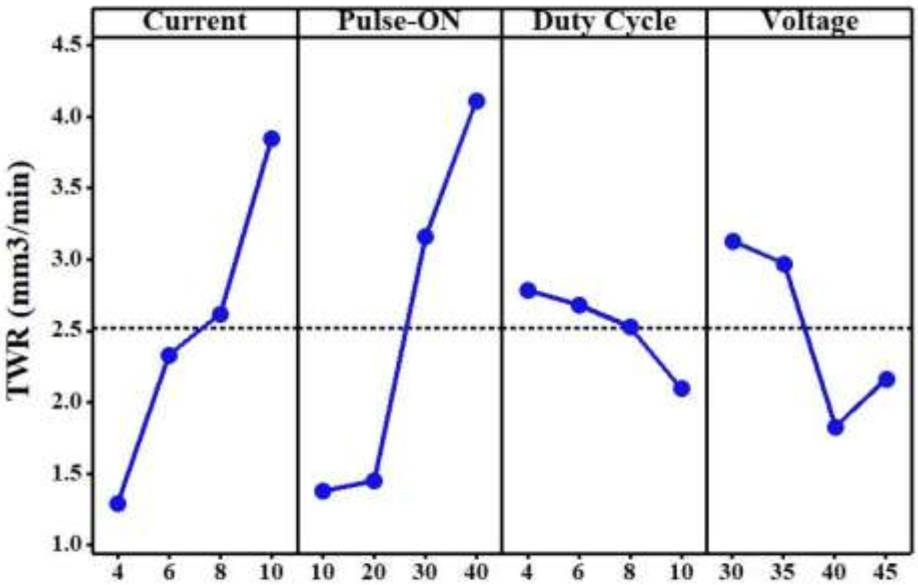

Figure 5. Main effect plots for TWR for various independent variables with copper coating on Inconel 718

3.1.3. Parametric analysis of input variables on MRR & TWR with copper coating and application of magnet.

The effect of process variables such as pulse-On and duty cycle are most influencing variables on output parameter MRR of DS-EDM process on nickel-based alloy Inconel 718 material with copper coating and application of magnet as shown in Figure 6. This is due to fact that, the copper coating act as an auxiliary electrode and magnet creates constructive plasma pressure and density between anode and cathode then the high number of sparks strikes on the work material result in high MRR is obtained.

However, there is a negative trend is observed while the process variables current and voltage increases simultaneously. This is because the process variables current and voltage increases, the distance between electrodes also increases then the intensity of plasma and density decreases in the work zone result in lower MRR is reported while machining of DS-EDM process on nickel based alloy Inconel 718 material with copper coating and application of magnet (Ahmed et al., 2018).

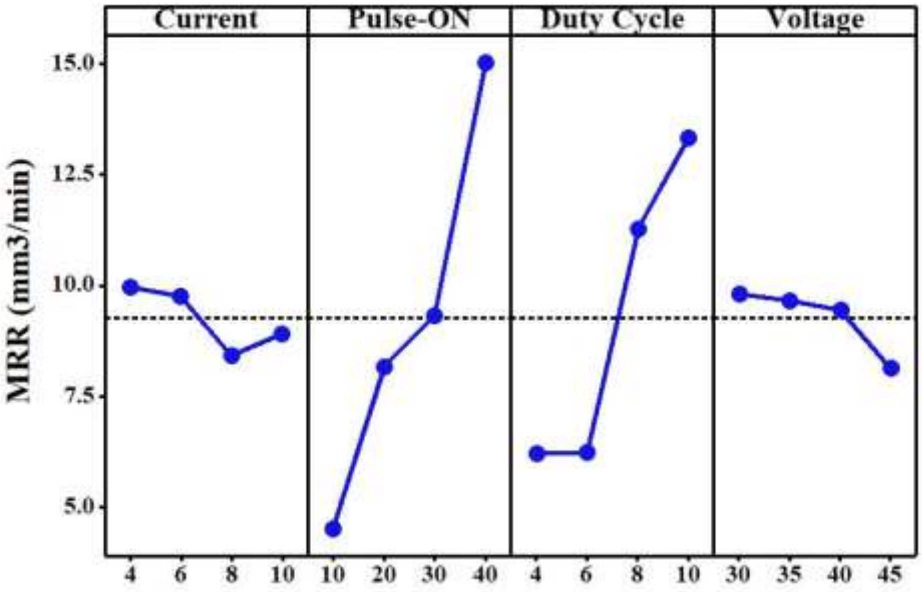

Figure 6. Main effect plots for MRR for various independent variables with copper coating and application of magnet on Inconel 718

The input variables current and pulse-ON effects significantly on response variable TWR of DS-EDM process on nickel-based alloy Inconel 718 material with copper coating and application of magnet as shown in Figure 7. The reason due to fact that, the magnetic field and copper coating creates constrained plasma pressure and density in between tool and work piece when the input variables current and Pulse-ON increases gradually result in higher rate of TWR is obtained. Moreover, the process parameters duty cycle and voltage increase gradually then the response variable TWR is obtained moderately. This is because coating and magnetic field produces constrained plasma, but in case of higher values of duty cycle and voltage the intensity of plasma is scattered result in moderate TWR is achieved. Based on the results it is noticed that the independent variables current and pulse-ON most influencing variables of DS-EDM process on nickel-based alloy Inconel 718 material with copper coating and application of magnet (Teimouri and Baseri, 2012).

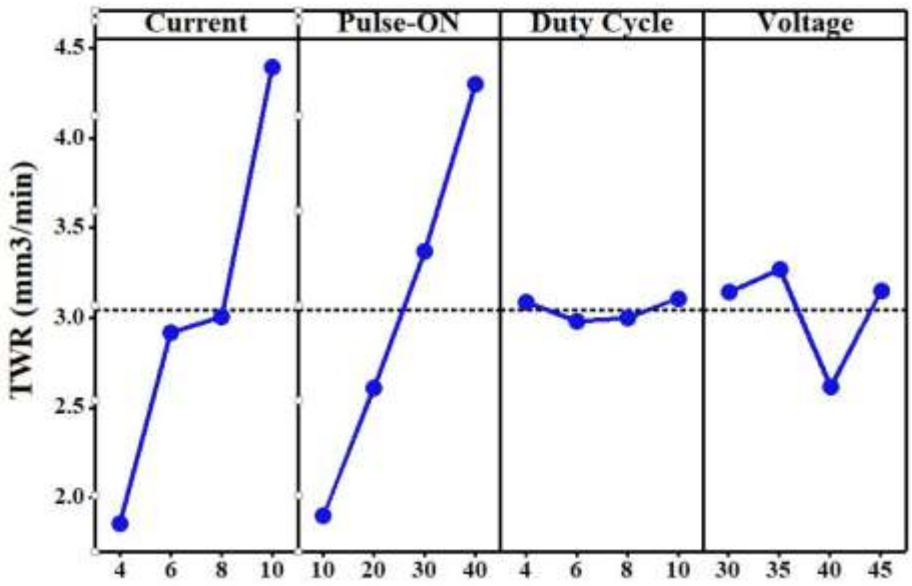

Figure 7. Main effect plots for TWR for various independent variables with copper coating and application of magnet on Inconel 718

3.2. ANOVA analysis

Analysis of variance is also termed as ANOVA is a collection of statistical models and their associated estimation procedure used to analyze the influence of DS-EDM process with copper coating and copper coating with application of magnet machining variables on nickel-based alloy Inconel 718 material. The output values of ANOVA analysis are depicted in the Table (4-7) by using Minitab 17 version software. In this study, identify the significant aspects from the output values and remove the insignificant values from the table, and the fitted quadratic model is adjusted (Rao and Kalyankar, 2014). When the P-value is less than a certain threshold, the parameters are considered significant (probability value). As the Fisher value (F) increases, it appears that the performance characteristics of the process parameters alter as well (Kechagias et al., 2012).

3.2.1. ANOVA results for MRR and TWR of DS-EDM process on nickel-based alloy Inconel 718 material with copper coating.

The statistical analysis tool ANOVA is adopted to find the statistical significance of input parameters on out parameter MRR of DS-EDM process on nickel-based alloy Inconel 718 material with copper coating results depicted in the Table (4). The results showed that, the process parameters pulse-ON, duty cycle and voltage are most significant parameters on response parameter MRR having higher results of F and lower values of P (i.e., less than 0.05). The corresponding R2 and adjusted R2 values are 99.54% and 97.72% for MRR, it shows that the investigation data is well suited for current model. This indicates, the independent variables pulse-ON, duty cycle and voltage are plays most significant role to achieve better values of MRR while DS-EDM process with copper coating on nickel-based alloy Inconel 718.z

Table 4 ANOVA results of MRR for various independent levels with copper coating on Inconel 718.

MRR					
Source	**DF**	**Adj SS**	**Adj MS**	**F- Value**	**P- Value**
Current	3	1.910	0.6367	1.17	0.450
Pulse-ON	3	221.744	73.9145	135.87	0.001
Duty cycle	3	105.818	35.2726	64.84	0.003
Voltage	3	27.237	9.0791	16.69	0.022
Error	3	1.632	0.5440		
Total	15	358.341			
S= 0.737575, R^2 = 99.54% , R^2(adj) = 97.72% , R^2(pred)= 87.06%					

The Table (5) shows that, ANOVA results for response variable TWR of DS-EDM process with copper coating on Inconel 718 material; it is clearly found that P value of independent variable current is smaller, i.e., 0.004 and F value is larger with 56.52. Also, P value for pulse-ON is 0.002 and F value is 92.04. Further, the independent variable voltage P value is 0.017 and corresponding F value is 20.07. This mentioned P values are smaller than 0.05. This is due to fact that, the input parameters current, pulse-ON and voltage most significant parameters for TWR. The values of R^2 attained for TWR is 99.43%, and adjusted R^2 is 97.13%, this value represents that the data well suited for present model.

Table 5 ANOVA results of TWR for various independent levels with copper coating on Inconel 718.

TWR					
Source	**DF**	**Adj SS**	**Adj MS**	**F- Value**	**P- Value**
Current	3	13.2669	4.4223	56.52	0.004
Pulse-ON	3	21.6043	7.20142	92.04	0.002
Duty cycle	3	1.0993	0.36642	4.68	0.118
Voltage	3	4.7112	1.57041	20.07	0.017
Error	3	0.2347	0.07824		
Total	15	40.9164			
S= 0.279718, R^2 = 99.43%, R^2(adj) = 97.13%, R^2(pred)= 83.68%					

3.2.2. ANOVA results for MRR and TWR of DS-EDM process on nickel-based alloy Inconel 718 material with copper coating and application of magnet.

The results of ANOVA tabulated in Table 6 for dependent variable MRR of DS-EDM process with copper coating and application of magnet on nickel-based alloy Inconel 718 material observed that, the input values pulse-ON and duty cycle are found to be more significant process variables because of higher results of F values and lower results of P i.e., 27.48, 18.90 and 0.011, 0.019 (i.e., $P < 0.05$). It represents that the input parameters pulse-ON and duty cycle are significant variables for MRR. The obtained R^2 and adjusted R^2 values are 98.56% and 90.34% which shows that the present model fits the data is very well.

Table 6 ANOVA results of MRR for various independent levels of Inconel 718 with copper coating and application of magnet.

MRR					
Source	**DF**	**Adj SS**	**Adj MS**	**F- Value**	**P- Value**
Current	3	6.168	2.056	0.75	0.591
Pulse-ON	3	226.339	75.446	27.48	0.011
Duty cycle	3	155.628	51.876	18.9	0.019
Voltage	3	7.019	2.34	0.85	0.551
Error	3	8.235	2.745		
Total	15	403.388			
S= 1.65682, R^2 = 98.56%, R^2(adj) = 90.34%, R^2(pred)= 41.93%					

The table (7) shows that, ANOVA results for response variable TWR of DS-EDM process with copper coating and application of magnet on Inconel 718 material; it is clearly found that P value of independent variable current is smaller, i.e., 0.004 and F value is larger with 58.5. Also, P value for pulse-ON is 0.004 and F value is 56.94. This mentioned P values are smaller than 0.05. This is because independent variables current and pulse-ON are most significant variables for TWR. The values of R^2 attained for TWR is 99.18%, and adjusted R^2 is 95.88%, this value represents that the data well suited for present model.

Table 7 ANOVA results of TWR for various independent levels of Inconel 718 with copper coating and application of magnet.

TWR					
Source	**DF**	**Adj SS**	**Adj MS**	**F- Value**	**P- Value**
Current	3	13.0274	4.34246	58.5	0.004
Pulse-ON	3	12.6801	4.22671	56.94	0.004
Duty cycle	3	0.0472	0.01573	0.21	0.883
Voltage	3	1.0261	0.34204	4.61	0.121
Error	3	0.2227	0.07423		
Total	15	27.0035			
S= 0.272459, R^2 = 99.18%, R^2(adj) = 95.88%, R^2(pred)= 76.54%					

3.3. 3D surface analysis

3.3.1 3D surface analysis of nickel-based alloy Inconel 718 material with copper coating

The 3D surface response plot of independent variables such as current, pulse-ON, duty cycle and voltage for MRR shown in Figure 8 (a-f) for the DS-EDM process of nickel-based alloy Inconel 718 material with copper coating. The Figure 8 (a-f) indicates that higher MRR is obtained when the independent variables current at lower levels and pulse-ON, duty cycle and voltage at higher levels. This is because higher levels of pulse-on, duty cycle and voltage transfer more discharge between electrodes result in higher MRR is attained (Pradhan, 2013). Therefore, higher values of pulse-ON, duty cycle and voltage and lower values of current is recommended for higher MRR in case of nickel-based alloy Inconel 718 material machining in DS-EDM process with copper coating.

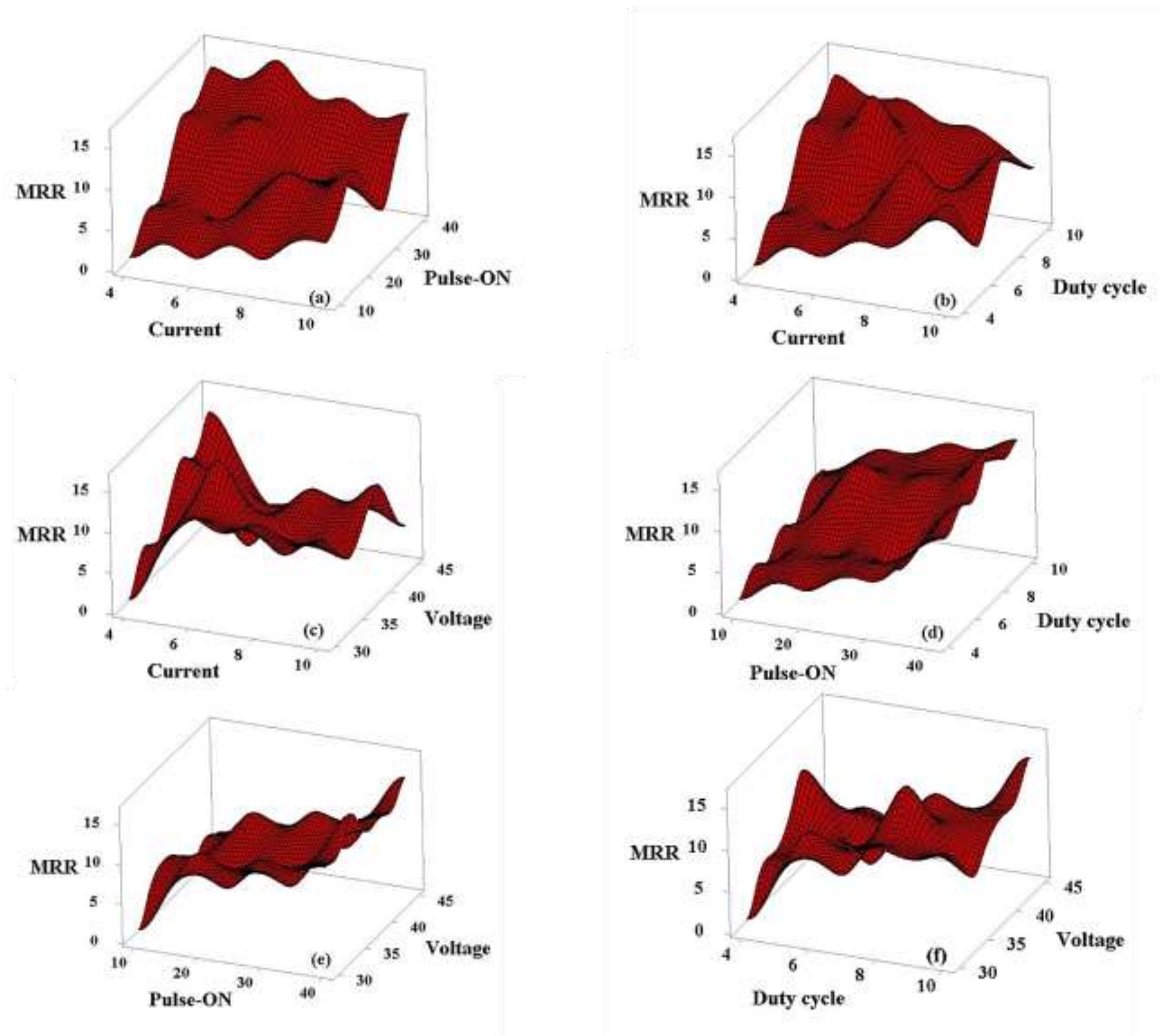

Figure 8 (a-f) 3D response plot of current, pulse-ON, duty cycle and voltage for MRR

Additionally, the 3D surface response plot is also carried out based on the ANOVA analysis for Inconel 718 material of DS- EDM with copper coating. The surface interaction plots for TWR are represented in Figure 9 (a-f). In case of larger values of current and pulse-ON as shown in Figure 9(a) represents more tool wear is attained. This is because high discharge is transfer between tool and work piece causes more sparks are induced result in higher TWR is obtained. On the other hand, the moderate values of TWR are achieved while increasing the independent variables as shown in Figure 9 (b-f). This is because the distance between anode and cathode varying results in moderate TWR is obtained in case of nickel-based alloy Inconel 718 machining in DS-EDM with copper coating. Hence, inter mediate values of independent variables are desirable for better results of TWR.

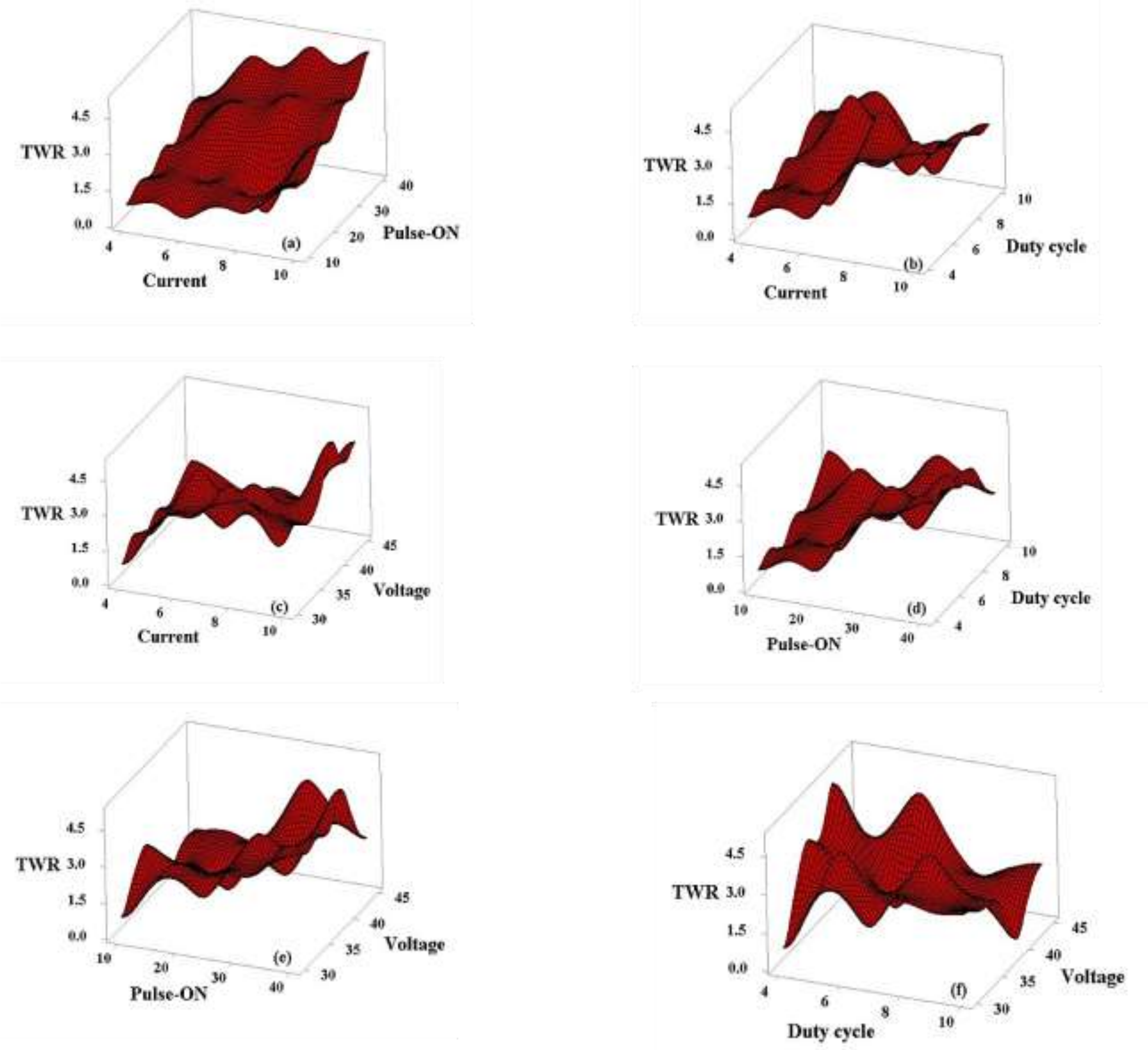

Figure 9 (a-f) 3D response plot of current, pulse-ON, duty cycle and voltage for TWR

3.3.2 3D surface analysis of nickel-based alloy Inconel 718 with copper coating and application of magnet.

The 3D surface interaction plot of input variables such as current, pulse-ON, duty cycle and voltage for MRR shown in Figure 10 (a-f) for the DS-EDM process of nickel-based alloy Inconel 718 with copper coating and application of magnet. The interaction between current and other input variables are shown in the Figure 10 (a-c) is that, higher MRR is obtained when the independent variable current, pulse-ON, and voltage at lower levels. This is because lower levels of current, duty cycle, pulse-on and voltage transfer enough sparks between tool and work piece with copper coated electrode (act as an auxiliary electrode) and application of magnet increases the plasma pressure intensity and density result in higher MRR is obtained. And also, the interaction between pulse-ON, duty cycle and voltage variables of 3D response is represented in Figure 10 (d-f) that, the values of pulse-on, duty cycle and voltage at higher levels result in better MRR is obtained. This is because the higher values of pulse-ON, duty cycle and voltage provide constructive plasma intensity and density between anode and cathode result in higher MRR is achieved. Thus, the DS-EDM process with copper coating and application of magnet on nickel-based alloy Inconel 718 material, the independent variables at smaller ranges of current and higher values of pulse-ON, duty cycle and voltage most significant variables to achieve higher MRR.

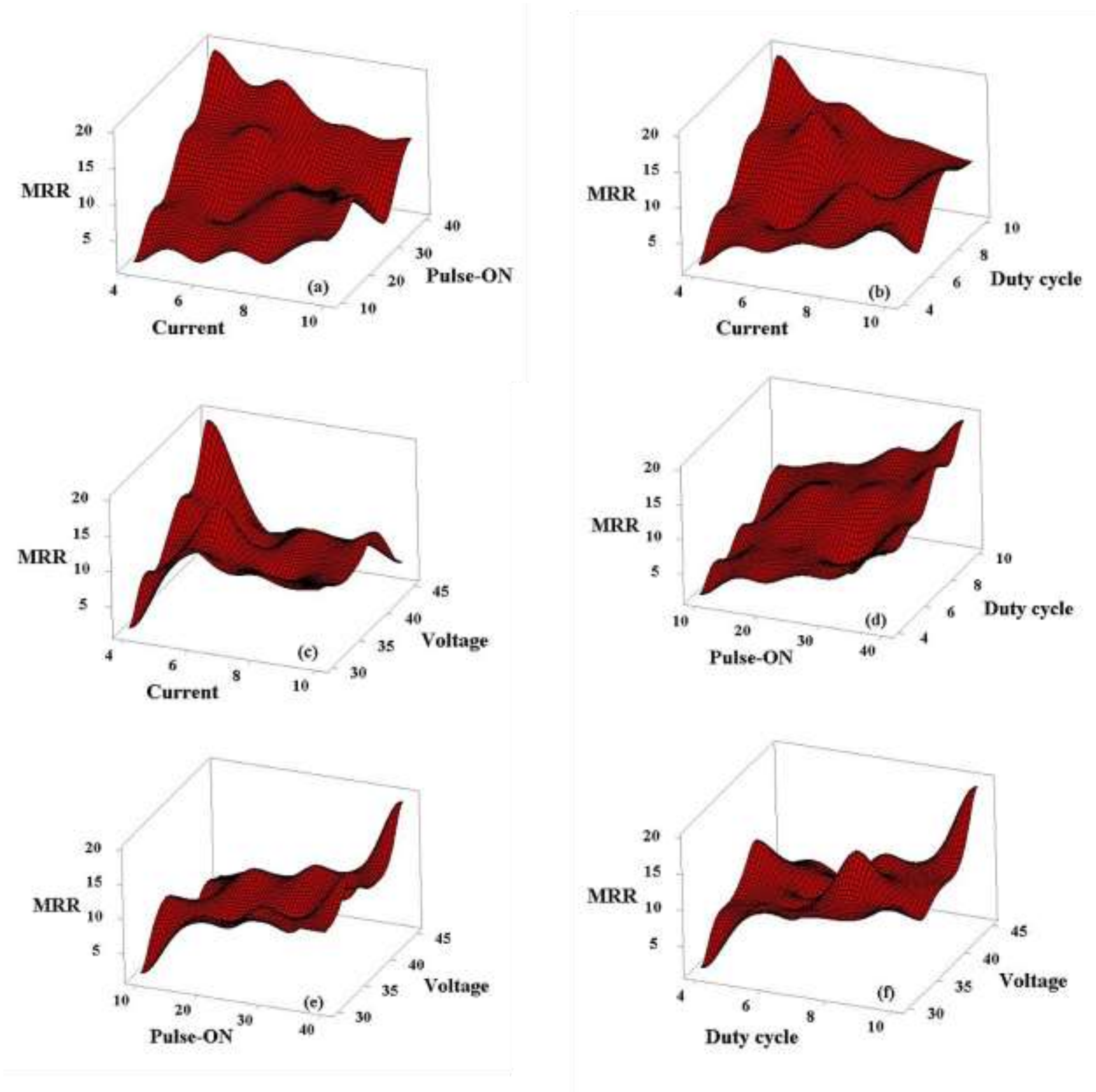

Figure 10 (a-f) 3D response plot of current, pulse-ON, duty cycle and voltage for TWR

Moreover, the 3D surface interaction plot is also carried out based on the ANOVA analysis for Inconel 718 material of DS-EDM with copper coating and application of magnet. The surface interaction plots for TWR are represented in Figure 11 (a-f). The interaction between current and other independent variables response as shown in Figure 11(a-c) shows that, higher rate of tool wear is identified when the independent variables at higher values. This is due to fact that, the plasma pressure intensity and density increases, high amount of spark is discharges in between anode and cathode result in higher TWR is obtained. On the other hand, the intermediate results of TWR are achieved while increasing the independent variables as shown in Figure 11 (d-f). This is due to fact that, the distance between electrodes changes similarly the plasma pressure intensity and density also varying results in moderate TWR is obtained in case of nickel-based alloy Inconel 718 machining in DS-EDM with copper coating and application of magnet. Hence, inter mediate values of independent variables are most desirable variables for better results of TWR.

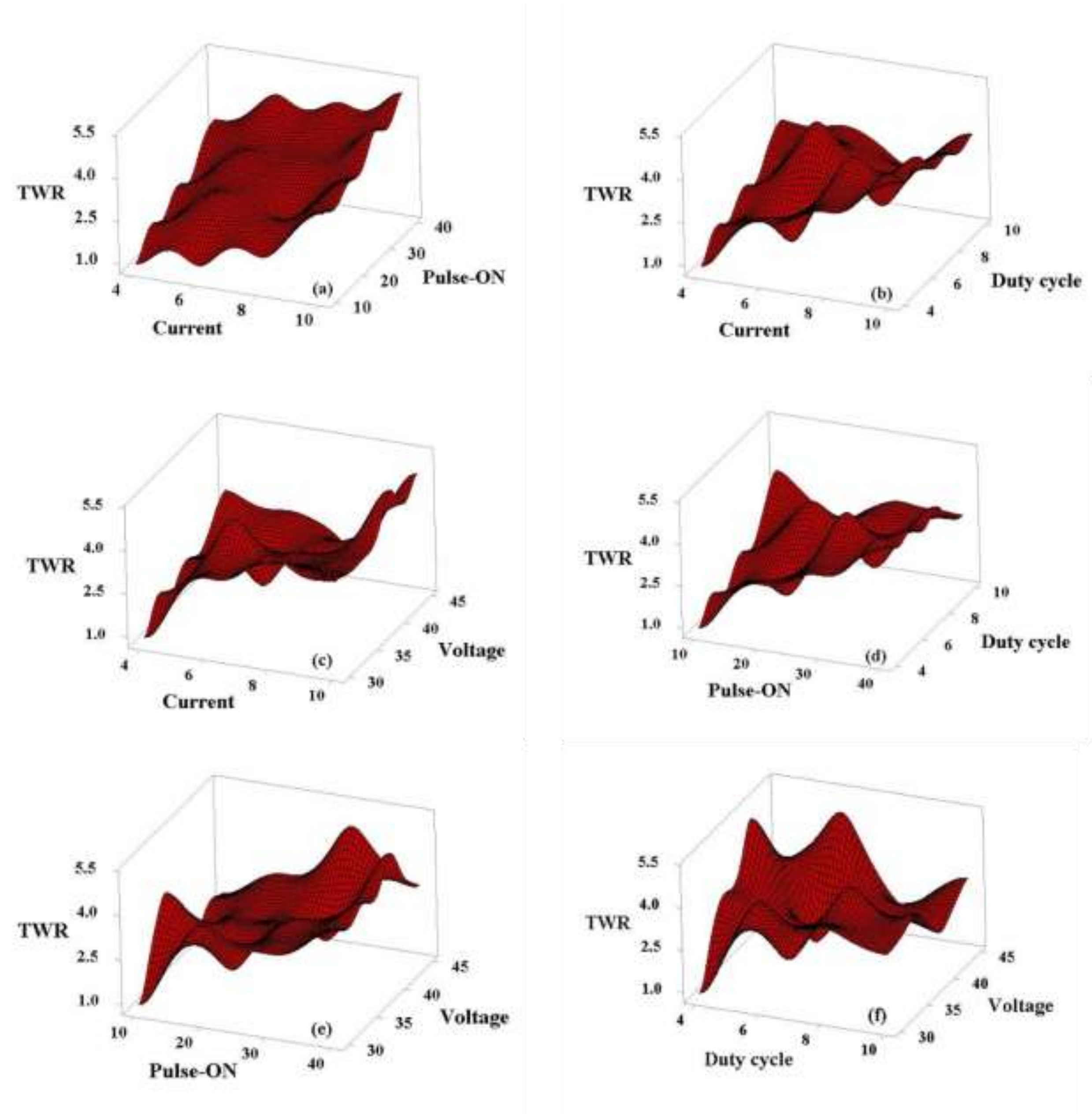

Figure 11 (a-f) 3D response plot of current, pulse-ON, duty cycle and voltage for TWR

3.4 Optimization

Optimization of independent variables of DS-EDM process with copper coating and copper coating with application of magnet on nickel based super alloy material Inconel 718 is carried out using multi objective optimization ratio analysis(MOORA) method (Trych-Wildner and Wildner, 2017). The variables MRR and TWR are considered as dependent variables, whereas current, pulse-ON, duty cycle and voltage treated as independent parameters. Initially, the decision matrix is calculated by using the following equation.

$$X = \begin{bmatrix} X_{11} & X_{12} & \ldots & X_{1n} \\ X_{21} & X_{22} & \ldots & X_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ X_{m1} & X_{m2} & \ldots & X_{mn} \end{bmatrix} \qquad \text{----------------------------------- (7)}$$

Where X_{ij} represents decision index of ith variable of jth trail, n and m are indicates number of variables and investigation trails.
The Eq. (8), which normalizes the different performance measurement units into equivalent sequence data, is used after the decision matrix. After that, Eq. (9) evaluates the overall assessment values of the results for each of the experimental setting.

Multi-response optimization becomes a single-response optimization as a result of this transformation. The test context is ranked based on its overall evaluation scores. The best experimental setting is the one with the highest assessment value, and the optimized results are shown in the Table 8 and Table 9.

$$N_{ij} = \frac{X_{ij}}{\left[\sum_{i=1}^{m} x_{ij}^{2}\right]^{1/2}} \text{ Where= } 1, 2, \ldots n \qquad \text{----------------------} \qquad (8)$$

$$y_j = \sum_{i=1}^{g} N_{ij} - \sum_{i=g+1}^{n} N_{ij} \qquad \text{----------------------} \qquad (9)$$

where, N_{ij} represents normalized performance values of i^{th} dependent variables, g represents the No. of variables to be maximized, (n-g) indicates the No. of variables to be minimized, y_j denotes assessment values of i^{th} variables with respect to the all *j*th exp. trails.

Table 8 Test assessment results (Yi) of DS-EDM process with copper coating on Inconel 718.

Exp. No	Current	Y_i values	Rank
1	4	0.88172	4
2		1.42248	3
3		2.17821	2
4		**2.63747**	**1**
1	6	1.20705	4
2		1.35259	3
3		2.06612	2
4		**2.31232**	**1**
1	8	1.45232	3
2		**2.14391**	**1**
3		1.39705	4
4		1.97723	2
1	10	1.54383	4
2		1.76677	2
3		1.55390	3
4		**1.90935**	**1**

Table 9 Test assessment results (Yi) of DS-EDM process with copper coating and application of magnet

Exp. No	Current	Y_i values	Rank
1	4	0.88399	4
2		1.42458	3
3		2.06127	2
4		**2.68594**	**1**
1	6	1.20339	4
2		1.31769	3
3		2.10315	2
4		**2.28347**	**1**
1	8	1.46438	4
2		**2.03693**	**1**
3		1.46554	3
4		1.95473	2
1	10	1.60062	3
2		1.69682	2
3		1.49548	4
4		**1.87196**	**1**

The result showed that, DS- EDM process with copper coating and copper coating with application of magnet on nickel-based alloy Inconel 718 material, to obtained the optimal settings are Pulse-ON (**40µs**), duty cycle (**10µs**) and voltage (**40 v**). These optimal settings provide most optimal values of variables such as higher MRR and lower TWR for nickel-based alloy Inconel 718 with superior quality, higher throughput and less machining cost and time of DS-EDM process with copper coating and copper coating with application of magnet.

3.5 Confirmatory test analysis

Moreover, the confirmatory test result shows that, the optimal parameter setting (i.e., pulse-ON 40 µs, duty cycle 10 µs and voltage at 40 volts) is found for DS-EDM process on nickel-based alloy Inconel 718 material with copper coating and copper coating and application of magnet, the optimal values are used for confirmatory experiments and the corresponding results are shown in Table 10 & Table 11. The results show that confirmatory tests results are comparable and acceptable with experimental results for the optimal setting.

Table 10 Confirmatory test results of DS-EDM process on nickel-based Inconel 718 material with copper coating

Independent Variables	Dependent Parameters	Experimentation Results	Confirmatory Test Results
Exp. No-4 : Pulse-ON (40 µs), duty cycle (10 µs) and voltage (45 volts)	Current at **4** amps		
	MRR (mm^3/min)	14.414	15.419
	TWR (mm^3/min)	2.114	2.315
Exp. No-4 : Pulse-ON (40 µs), duty cycle (8 µs) and voltage (35 volts)	Current at **6** amps		
	MRR (mm^3/min)	16.457	17.291
	TWR (mm^3/min)	4.191	3.625
Exp. No-2 : Pulse-ON (20 µs), duty cycle (10 µs) and voltage (40 volts)	Current at **8** amps		
	MRR (mm^3/min)	10.736	10.308
	TWR (mm^3/min)	0.238	0.105
Exp. No-4 : Pulse-ON (40 µs), duty cycle (4 µs) and voltage (40 volts)	Current at **10** amps		
	MRR (mm^3/min)	12.502	10.274
	TWR (mm^3/min)	5.161	4.256

Table 11 Confirmatory test results of DS-EDM process on nickel-based alloy Inconel 718 material with copper coating and application of magnet

Independent Variables	Dependent Parameters	Experimentation Results	Confirmatory Test Results
Exp. No-4 : Pulse-ON (40 µs), duty cycle (10 µs) and voltage (45 volts)	Current at **4** amps		
	MRR (mm^3/min)	19.564	20.583
	TWR (mm^3/min)	3.164	4.155
Exp. No-4 : Pulse-ON (40 µs), duty cycle (8 µs) and voltage (35 volts)	Current at **6** amps		
	MRR (mm^3/min)	16.864	18.555
	TWR (mm^3/min)	4.391	5.047
Exp. No-2 : Pulse-ON (20 µs), duty cycle (10 µs) and voltage (40 volts)	Current at **8** amps		
	MRR (mm^3/min)	10.534	11.696
	TWR (mm^3/min)	2.238	3.181
Exp. No-4 : Pulse-ON (40 µs), duty cycle (4 µs) and voltage (40 volts)	Current at **10** amps		
	MRR (mm^3/min)	11.621	11.874
	TWR (mm^3/min)	5.161	6.506

4 Conclusions

In this study presents machinability characteristics of DS-EDM process on nickel-based alloy Inconel 718 material with copper coating and application of magnet. Initially the investigation is performed based on Taguchi (L16) orthogonal array to analyze the machining attributes of DS-EDM process. The impact of input parameters on output parameters of DS-EDM process of Inconel 718 with copper coating and application of magnet are analyzed by using various statistical models like parametric analysis, ANOVA analysis and 3D surface response. Furthermore, the DS-EDM optimal process parameters setting is determined by using MOORA technique. The following observations have been noted during the machining process.

- Based on the investigational study, superior machinability characterization is obtained while machining of DS-EDM process on nickel-based alloy with copper coating and application of magnet as compared to work material only with copper coating. The reason due to fact that, the copper coating act as an axillary electrode whereas magnet provides constructive plasma intensity and density between work and tool, result in good surface quality and desirable dependent parameters like MRR and TWR is achieved.
- The input parameters current and pulse-ON are the most influencing parameters on response parameters MRR and TWR

of DS-EDM process in both the cases. However, the process parameters duty cycle and voltage effects moderately on output parameters of DS-EDM process.

- The optimal process parameters setting (i.e., pulse-On **40 µs**, duty cycle at **10 µs** and voltage at **40 volts**) of DS-EDM process on nickel-based alloy in both the cases identified by using MOORA optimization technique.
- At last, confirmatory test analysis were conducted to validate optimized results with test results, it is found that optimized results were comparable and acceptable with the test results.

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