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ORIGINAL PAPER

# Experimental investigation and evaluation of EDM characteristics of inconel 718 material with and without assistance of magnet

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**Abstract**

In present scenario, Inconel 718 material is widely used in various industrial applications due to their distinctive combination of mechanical and chemical properties. However, Inconel 718 material machining is most difficult by using the process of conventional machining. To overcome these problems, a noncontact electrical discharge machining process is employed. In this research work, the optimal machining parameters of dry electrical discharge machining (EDM) process on Inconel 718 material with and without assistance of magnet by using copper electrode is investigated. Initially, die-sinking EDM plasma zone coupled with magnet field for hybrid approach is to test Inconel 718 material with auxiliary copper electrode. Thereafter, an experimental study is performed based on Taguchi (L16-OA) to evaluate the compassion of EDM processing variables viz.,material removal rate (MRR) and tool wear rate (TWR) to the variation in independent parameters like peak current, pulse-duration ON ($T_{on}$), duty cycle or pulse-duration cycle OFF ($T_{off}$) and voltage. The parametric analysis, ANOVA and multi regression analysis are also considered to represent the statistical significance of the die-sinking EDM process. Finally, MOORA method is adopted for optimization of EDM process parameters with and without assistance of magnet. The result showed that an improvement in process parameters in terms of MRR and TWR with assistance of magnet as compared to without assistance of magnet and further validated using the confirmatory experiment.

**Keywords** Inconel 718 · EDM · MRR · TWR · Magnet

## 1 Introduction

As we are familiar that the commercial industries want to improve their production through put with higher quality and lower machining time and production cost. Inconel 718 nickel based super alloys full fill their industry requirements due to its grater characteristics like superior thermal properties, hardness and greater strength. These materials can be found in a variety of manufacturing environments viz., aerospace, auto mobiles, oil and, gas. However, these major drawbacks of Inconel 718 material are difficult to machine when compared to other alloys. Many of the researchers had been carried out research on the enhancement of machining performance of Inconel 718 material by both traditional and non-traditional methods. During the traditional machining process of Inconel 718, lower thermal conductivity, work hardening and higher rate of tool wear are the major effects. To overcome these effects that are presented in traditional machining approaches a non-traditional techniques are plays a vital role in current industries. Most of the non-traditional techniques are used in machining of different materials, out of which EDM is one of the most effective technique for conductive materials. Moreover, major contribution of research has been carried out on EDM process, [1]explored surface roughness and machining damage induced by EDM process on steel. The result showed that, the surface roughness is proportional to the recast layer thickness. [2] Explored the relationship between surface crack formation and EDM parameters of $D_2$ and H13 steel electrode. The result showed that, the surface crack formation is avoided when the process parameters kept at voltage of 120 V, peak current of 12–16 A and pulse-duration ON of 6–9 µs during the EDM process [3]. Investigated optimal machining parameters while using

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the die-sinking EDM process on AISI P20 tool steel by using graphite and copper electrodes. The results showed that, the combination of graphite and copper electrode with negative polarity gives higher rate of MRR and better surface finish. However, the graphite and copper electrode combination with negative polarity results in lower rate of electrode wear.

In addition to that, majority of research had been carried out on machining characterization of tool steel based material, [4] studied impact of machining variables on surface roughness of EDM process on tool steel. It is found that peak current, $T_{on}$ and duty cycles ($T_{off}$) are most influencing process variables on surface integrity. The results revealed that, the better surface integrity is obtained, peak current and pulse duration time ON at lower ranges and higher values of duty cycle [5]. Studied effect of recast layers and surface crack formation in EDM process on tool steel. The result says that the peak current directly proportional to recast layer thickness and surface roughness [6]. Investigated machining characteristics of nickel-based alloys in EDM process. It is found that positive polarity BEAM improves the machining performance [7]. Studied effect of tool rotation on MRR, TWR and surface roughness of AISI-D3 steel using rotary EDM process. The result showed that the tool rotation improves 49% MRR and 9–10% surface finish and TWR.

Moreover, sort of research had been carried out on nickel based super alloys like Inconel 718 material in this way [8] investigated effect of process variables of EDM process on Inconel 718 super alloy materials. It is found that better surface integrity is obtained at optimal cutting speed of 60 m/min during the dry EDM machining on Inconel 718 material with coated carbide tool [9]. Investigated optimal process parameters of EDM process on Inconel 718 super alloys by using copper electrodes. The results revealed that, the better values of MRR and EWR is obtained when the input variables $I_p$ and $T_{on}$ at 20–40 A and 200 µs [10]. investigated optimal machining parameters of EDM process on Inconel 825 material. The result showed that, the better values of dependent variables viz., MRR, SR, ROC and SCD obtained at optimal combination of independent variables at $I_p$ of 1A, $T_{on}$ of 10 µs and duty cycle is 75% [11]. Studied machining characteristics of Inconel 718 material by die-sinking EDM and wire EDM. The result showed that the combination of copper and silicon carbide electrode gives grater execution in terms of MRR, Ra and EWR.

Furthermore, some extent of research had been done on different types electrodes used in EDM process and assistance of magnetic field, [12] explored effect of electrode material on novel compound machining of Inconel 718 material. The study explained different kinds of tool electrodes adopted in EDM process and their characteristics. The results showed that, the tubular graphite type electrode is most suitable electrode for machining of Inconel 718 material among other type of electrodes [13]. Effect of EDM process with assistance of magnetic field of metal matrix composites. The results revealed that, the magnetic field during the machining process result in superior surface quality, good process stability and overall improvement of response parameters [14]. Studied superfast drilling of Inconel 718 material by using hybrid EDM with different electrodes. The results showed that the copper tungsten electrode is most suitable for hybrid EDM process to machine Inconel 718 material.

However, very less amount of research had been reported on machining characterization of EDM process on Inconel 718 material with assistance of magnet by using copper auxiliary electrode. In this study, the investigation of optimal machining variables of dry EDM process on Inconel 718 material with and without assistance of magnet by using copper electrode. Here, Initially, Inconel 718 material specimen with magnet and copper electrode taken for experimentation. Thereafter, an experimental study is performed based on Taguchi (L16-OA) to evaluate the compassion of EDM processing attributes [such as MRR and TWR] to the changes in independent variables like peak current, $T_{on}$, $T_{off}$ and voltage. In addition, parametric analysis, ANOVA and multi regression analysis are done to represent the statistical significance of the die-sinking EDM process. Finally, MOORA method is adopted for the optimization of EDM process variables. The confirmatory tests are conducted to verify obtained results with test results. The rest of the paper is organized as the following sections, materials and machining set-up presented in section-2, results and discussion explored in section-3, conclusions along with future scope mentioned in the section-4.

## 2 Materials & Machining setup

### 2.1 Material details

The material is selected for the investigation is Inconel 718 super alloy nickel based material of rectangular shape (120 mm height and 10 mm thickness) and kept positive polarity (i.e. work piece is positive) as shown in Fig. 1.The auxiliary electrode is a pure copper rod with a diameter of 10 mm. Die-electric fluid is EDM Oil.

### 2.2 Experimental procedure

The investigation performed on Inconel 718 material with and without assistance of magnet sample by using the die-sinking electrical discharge machine (EDM), (Machine: Electronica Elektra PlusPS 50ZNC, India) as exposed in Fig. 2. Based on the experimental equipment, a total of 16 cavities were performed on Inconel 718 material sample, using a peak current of 4, 6, 8 and 10 amps, pulse-duration ON of 10, 20, 30 and 40 µs, pulse- duration OFF or duty factor is 4, 6, 8 and 10 µs and voltage of 30, 35, 40 and 45 V[15].

**Fig. 1** Copper electrode with work piece (Inconel 718 material)

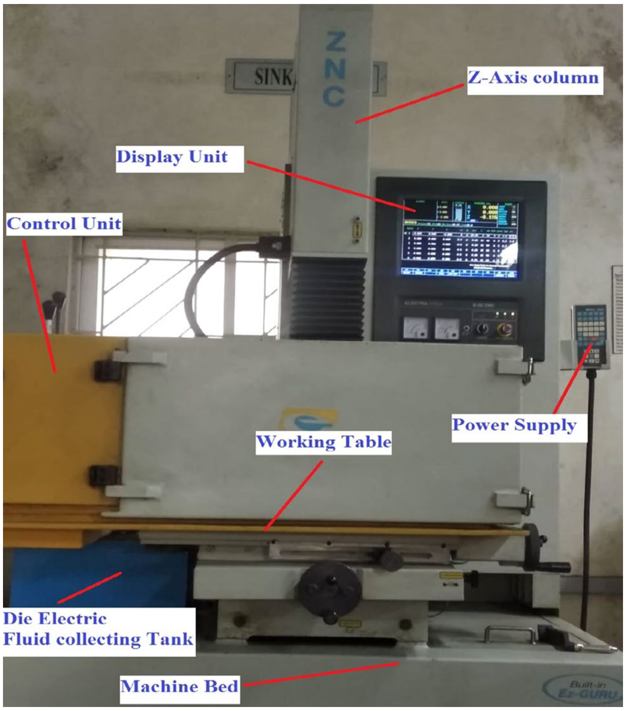

**Fig. 2** Die-sinking EDM machine set-up

According to the earlier research and existing die-sinking EDM setup, the aspects of process variables including peak current, pulse-duration ON ($T_{on}$), pulse-duration OFF ($T_{off}$) and voltage are allotted. The influences on response variables are such as material removal rate (MRR) and Tool wear ratio (TWR) of Inconel 718 material with and without assistance of magnet by the EDM process. Tables 1,2 and, 3 shows the parameter details and experimental design for the Taguchi (L16) orthogonal array.

Three process parameters [shown in Table 1] are varied during the experiment and a circular hole cavity of 10 mm is cut according to the experimental design. Every trail run is performed and the results, with the MRR and TWR averaged for analysis. [16]these trials are carried out to determine the impact of individual experimental design elements, as illustrated in Tables 2 and 3.The output parameter MRR and TWR are estimated using the following equations:

$$MRR = \frac{Material\ removed\ in\ a\ single\ spark}{Total\ Cycle\ time} \tag{1}$$

$$TWR = \frac{Mass\ of\ the\ tool\ before\ machining - Mass\ of\ the\ tool\ after\ machining}{Cycletime} \tag{2}$$

## 3 Results & Discussions

### 3.1 Parametric analysis of Inconel 718 material with copper electrode and with magnet and without magnet.

#### 3.1.1 Effect of independent variables on dependent variable MRR in case of Inconel 718 material, copper electrode with magnet

The impact of input variables such as $T_{on}$, $T_{off}$ and Voltage on response parameter MRR of Inconel 718 material with magnet is illustrated in the Fig. 3(a–c). It is clearly noticed that from Fig. 3(a) is, the process parameter $T_{on}$ gradually

**Table 1** Input parameters and their levels for EDM process

| Input parameters | Symbol | Units | Level 1 | Level 2 | Level 3 | Level 4 |
|---|---|---|---|---|---|---|
| Pulse-duration ON | $T_{on}$ | µs | 10 | 20 | 30 | 40 |
| Pulse-duration OFF | $T_{off}$ | µs | 4 | 6 | 8 | 10 |
| Voltage | voltage | Volts | 30 | 35 | 40 | 45 |
| Constant Parameters | | | | | | |
| Peak current | Peak current | Amps | 4 | 6 | 8 | 10 |
| Machine Type | Die-sinking EDM | | | | | |
| Tool material | Inconel 718 with and without assistance of magnet | | | | | |
| Die electric fluid | De-ionized water | | | | | |

**Table 2** Experimental results of EDM process with assistance of magnet

| Expt. No | current | $T_{on}$ | $T_{off}$ | Voltage | work piece | | Electrode | | Time | MRR | TWR |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | µs | µs | volts | Initial | Final | Initial | Final | Min | grm/min | grm/min |
| 1 | 4 | 10 | 4 | 30 | 172.618 | 172.39 | 30.452 | 30.341 | 116 | 0.00197 | 0.00096 |
| 2 | 4 | 20 | 6 | 35 | 172.39 | 172.002 | 30.341 | 30.238 | 52 | 0.00746 | 0.00198 |
| 3 | 4 | 30 | 8 | 40 | 172.002 | 171.614 | 30.238 | 30.162 | 30 | 0.01293 | 0.00253 |
| 4 | 4 | 40 | 10 | 45 | 171.614 | 171.268 | 30.198 | 30.139 | 14 | 0.02471 | 0.00421 |
| 5 | 6 | 10 | 6 | 40 | 171.268 | 170.939 | 30.139 | 29.989 | 90 | 0.00366 | 0.00167 |
| 6 | 6 | 20 | 4 | 45 | 170.939 | 170.607 | 30.865 | 30.725 | 57 | 0.00582 | 0.00246 |
| 7 | 6 | 30 | 10 | 30 | 170.607 | 170.245 | 30.725 | 30.603 | 23 | 0.01574 | 0.0053 |
| 8 | 6 | 40 | 8 | 35 | 170.245 | 169.865 | 30.863 | 30.762 | 22 | 0.01727 | 0.00459 |
| 9 | 8 | 10 | 8 | 45 | 169.865 | 169.605 | 30.762 | 30.641 | 51 | 0.0051 | 0.00237 |
| 10 | 8 | 20 | 10 | 40 | 169.605 | 169.388 | 30.882 | 30.877 | 21 | 0.01033 | 0.00024 |
| 11 | 8 | 30 | 4 | 35 | 169.249 | 168.892 | 30.154 | 30.011 | 48 | 0.00744 | 0.00298 |
| 12 | 8 | 40 | 6 | 30 | 168.892 | 168.577 | 30.96 | 30.845 | 29 | 0.01086 | 0.00397 |
| 13 | 10 | 10 | 10 | 35 | 168.577 | 168.228 | 29.839 | 29.688 | 32 | 0.01091 | 0.00472 |
| 14 | 10 | 20 | 8 | 30 | 168.228 | 167.92 | 30.602 | 30.47 | 30 | 0.01027 | 0.0044 |
| 15 | 10 | 30 | 6 | 45 | 167.92 | 167.812 | 28.781 | 28.733 | 32 | 0.00337 | 0.0015 |
| 16 | 10 | 40 | 4 | 40 | 167.812 | 167.479 | 30.047 | 29.887 | 31 | 0.01074 | 0.00516 |

**Table 3** Experimental results of EDM process without assistance of magnet

| Expt. No | current | $T_{on}$ | $T_{off}$ | Voltage | work piece | Electrode | | Time | | MRR | TWR |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | µs | µs | volts | Initial | Final | Initial | Final | Min | grm/min | grm/min |
| 1 | 4 | 10 | 4 | 30 | 172.375 | 172.208 | 31.17 | 31.073 | 120 | 0.00139 | 0.000808333 |
| 2 | 4 | 20 | 6 | 35 | 172.208 | 172.061 | 31.073 | 31.011 | 42 | 0.0035 | 0.00147619 |
| 3 | 4 | 30 | 8 | 40 | 172.061 | 171.701 | 30.761 | 30.667 | 40 | 0.009 | 0.00235 |
| 4 | 4 | 40 | 10 | 45 | 171.701 | 171.284 | 30.667 | 30.595 | 22 | 0.01895 | 0.003272727 |
| 5 | 6 | 10 | 6 | 40 | 171.284 | 170.983 | 31.269 | 31.125 | 101 | 0.00298 | 0.001425743 |
| 6 | 6 | 20 | 4 | 45 | 170.983 | 170.607 | 31.118 | 30.969 | 68 | 0.00553 | 0.002191176 |
| 7 | 6 | 30 | 10 | 30 | 170.607 | 170.271 | 30.548 | 30.455 | 20 | 0.0168 | 0.00465 |
| 8 | 6 | 40 | 8 | 35 | 170.271 | 169.89 | 30.455 | 30.351 | 24 | 0.01588 | 0.004333333 |
| 9 | 8 | 10 | 8 | 45 | 169.89 | 169.6 | 30.836 | 30.68 | 88 | 0.0033 | 0.001772727 |
| 10 | 8 | 20 | 10 | 40 | 169.6 | 169.232 | 30.68 | 30.524 | 23 | 0.016 | 0.006782609 |
| 11 | 8 | 30 | 4 | 35 | 169.232 | 168.913 | 30.824 | 30.688 | 69 | 0.00462 | 0.001971014 |
| 12 | 8 | 40 | 6 | 30 | 168.913 | 168.56 | 30.686 | 30.549 | 39 | 0.00905 | 0.003512821 |
| 13 | 10 | 10 | 10 | 35 | 168.56 | 168.212 | 30.154 | 29.994 | 36 | 0.00967 | 0.004444444 |
| 14 | 10 | 20 | 8 | 30 | 168.212 | 167.88 | 29.994 | 29.845 | 39 | 0.00851 | 0.003820513 |
| 15 | 10 | 30 | 6 | 45 | 167.88 | 167.564 | 30.403 | 30.292 | 41 | 0.00771 | 0.002707317 |
| 16 | 10 | 40 | 4 | 40 | 167.564 | 167.144 | 30.292 | 30.066 | 40 | 0.0105 | 0.00565 |

increases in the result with significant increase in response parameter MRR in all the cases of peak-current (4, 6, 8 and 10 amps). This is because higher $T_{on}$ causes more discharge transfer to work piece material result in higher MRR. It is also noticed that from Fig. 3(b) is, for 4 amps peak current graph shows, the independent parameter $T_{off}$ increase from 4 µs to 10 µs, the dependent parameter MRR significantly increases from 0.00196 grm /min to 0.0247 grm/min. This is because lower $T_{off}$ generates higher amount of thermal energy between work and tool results in higher vaporization and higher MRR is obtained. In case of 6, 8 and 10 amps peak current graphs shows; the input parameter $T_{off}$ increases gradually the output parameter MRR obtained moderately. This is because the initial gap between electrode (IGE) increases the amount of thermal discharge also varies the result and moderate MRR is obtained. It is also clearly observed that from Fig. 3(c), for 4 µs peak current graph shows, the independent parameter voltage raises from 30 to 45 V, the dependent parameter MRR increases significantly from 0.00197 grm /min to 0.0246 grm /min. This is

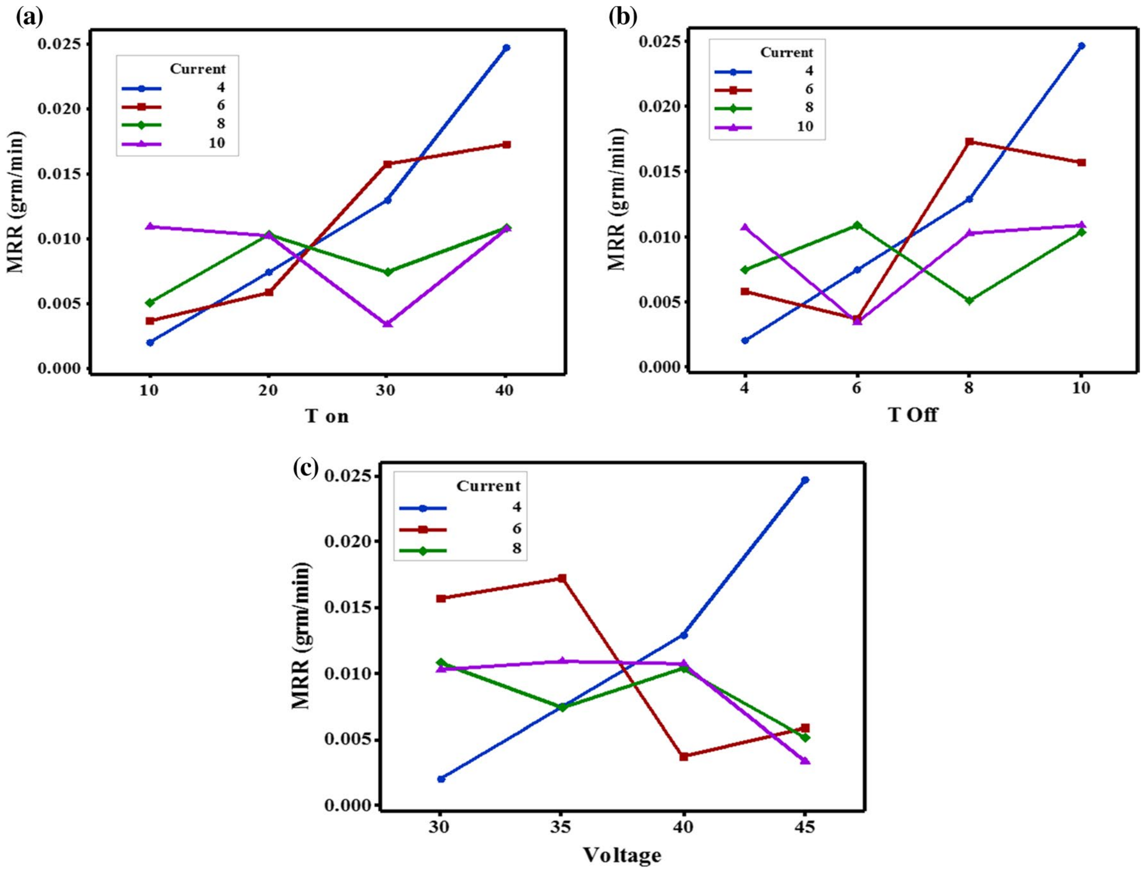

**Fig. 3** **a–c** Main effect plots for MRR for different input levels with assistance of magnet

because lower current at higher voltage produces enough sparks between electrodes results in higher MRR. Further, in case of 6,8 and 10 amps peak current graph showed that, the process parameter voltage increases the result in decreased MRR. This is why because, the higher current and voltage generates lower amount of heat in the die electric fluid result in lower MRR. It is very clearly found that the process variables $T_{on}$ and $T_{off}$ most influencing parameters on response variable MRR considering with assistance of magnet [17].

### 3.1.2 Effect of input variables on output variable MRR in case of Inconel 718 copper electrode without magnet

The impact of independent variables such as $T_{on}$, $T_{off}$ and, Voltage on dependent variable MRR of Inconel 718 material without magnet is illustrated in the Fig. 4 (a–c). It is clearly observed that from Fig. 4(a) is, for 4 amps peak current graph shows, the process parameter $T_{on}$ gradually increases result in significant increase in response parameter MRR. This is because higher $T_{on}$ causes more discharge transfer to work piece material results in higher MRR. Further, in case of 6, 8 and 10 amps peak current graphs shows that, the process variable $T_{on}$ varies from 10 μs to 40 μs, the dependent variable MRR is decreased. This is because the higher current without magnet causes uneven sparks between electrodes results in lower MRR. It is also noticed that from Fig. 4(b) is, the input variable $T_{off}$ gradually increases results in output variable MRR significantly increases in all the cases of peak current (4,6,8 and 10 amps). This is because the duty factor $T_{off}$ gradually increases without assistance of magnet creates high amount of thermal energy between electrodes results in higher vaporization takes place and, higher MRR is obtained. It is also clearly observed that from Fig. 4(c), for 4 amps peak current graph shows, the independent variable voltage raises from 30 to 45 V, the dependent variable MRR significantly raises from 0.00139 grm /min to 0.0189 grm /min. This is because lower current at higher voltage produces enough sparks between electrodes and raises heat in the dielectric fluid results in higher MRR. Further, in case of 6, 8 and 10 amps peak current graphs showed that, the process variable voltage increases result in decreased MRR. This is because at higher current and voltages generates lower amount of heat in the die electric fluid results in lower MRR. It is concluded that the process variables $T_{on}$ and $T_{off}$ are most influencing parameters on

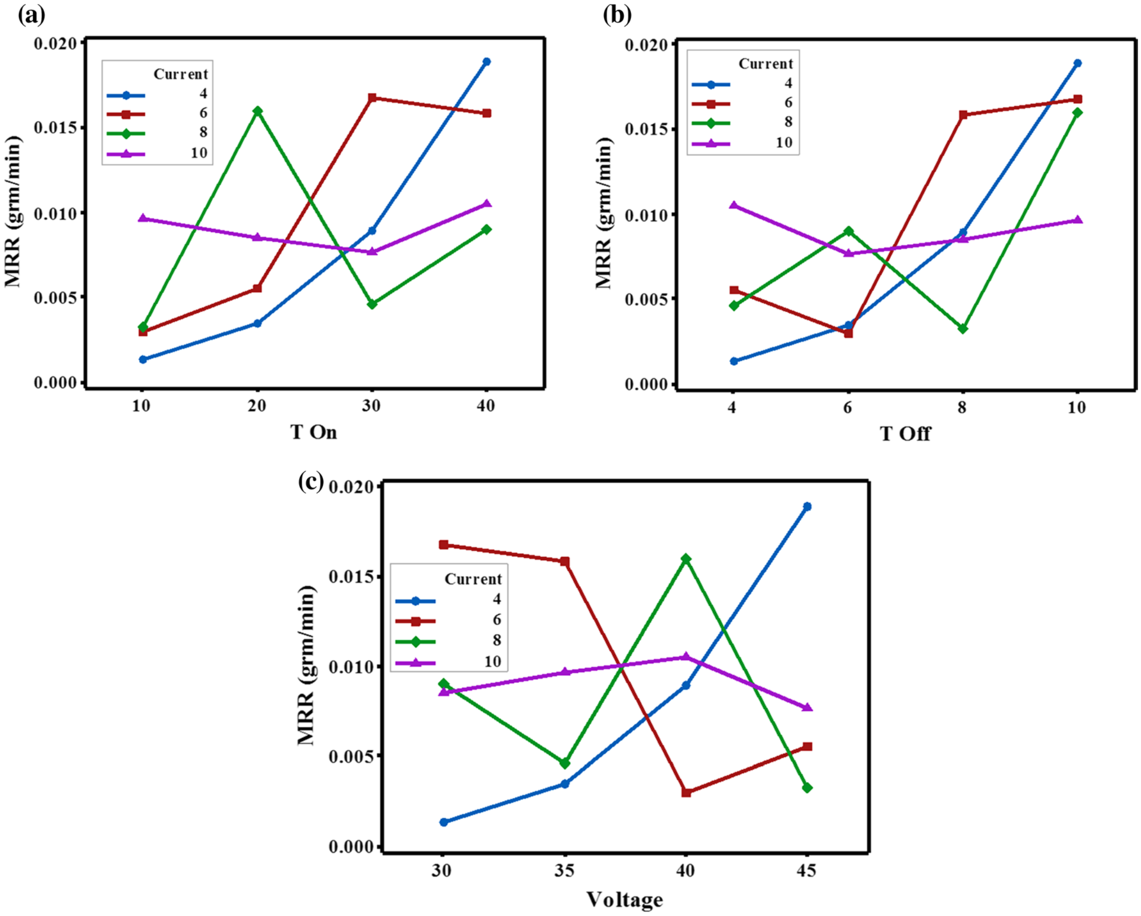

**Fig. 4** **a**–**b** Main effect plot for MRR for different input levels without magnet assistance

response variable MRR considering without assistance of magnet [18].

### 3.1.3 Effect of independent variables on dependent variable TWR in case of Inconel material with magnet

The impact of independent variables such as $T_{on}$, $T_{off}$ and, Voltage on response parameter TWR of Inconel 718 material with magnet assistance is illustrated in the Fig. 5(a–c). It is clearly observed that from Fig. 5(a) is, the input variable $T_{on}$ gradually increases the result in significant increase in response parameter TWR in all most all the cases of peak-current (4, 6, 8 and 10 amps). This is because higher $T_{on}$ causes more heat transfer between work piece and tool material results in higher TWR. It is also noticed that from Fig. 5(b) is, for 4 and 6 amps peak current graphs showed that, the independent parameter $T_{off}$ increase from 4 µs to 10 µs, the dependent parameter TWR significantly increases from 0.00095 grm /min to 0.0042 grm/min and 0.0024 grm/min to 0.0053 grm/min.

This is because lower $T_{off}$ induces high amount of thermal energy between work and tool electrode results in higher vaporization takes place and higher TWR is obtained. In case of 8 and 10 amps peak current graphs showed that, the input parameter $T_{off}$ raises from 4 µs to 10 µs, the output parameter TWR gradually decreases from the 0.0029 grm/min to 0.0002grm/min and 0.0051grm/min to 0.0047grm/min. This is because, the initial gap between electrodes (IGE) increases the amount of spark generation between tool and work piece is decreases results in lower TWR is obtained. It is also clearly observed that from Fig. 5(c), for 4 amps peak current graph shows, the independent parameter voltage raises from 30 to 45 V, the dependent parameter TWR increases significantly from 0.00095 grm /min to 0.00421 grm /min. Due to reason behind that, lower current at higher voltage produces higher discharge between electrodes and results in higher TWR. Further, in case of 6, 8 and 10 amps peak current graph showed that, the process parameter voltage increases results in decreased in TWR. This is because, the higher current and voltage generates lower amount of heat in the die electric fluid results in lesser material and is removed and lower TWR is obtained. It is clearly found that the process variables $T_{on}$ and $T_{off}$ most

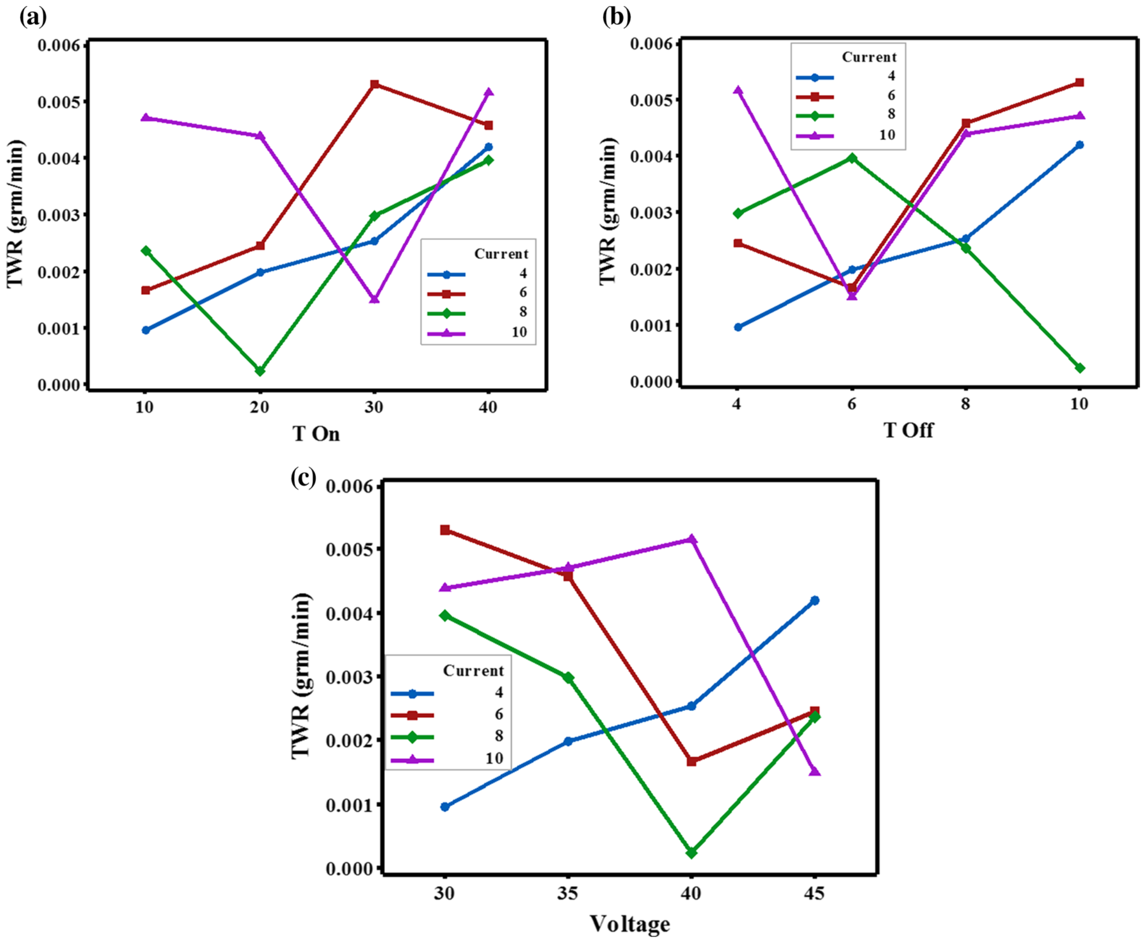

**Fig. 5** **a–c** Main effect plots for TWR for different input levels with assistance of magnet

influencing parameters on response variable TWR considering with assistance of magnet [19].

### 3.1.4 Effect of input variables on output variable TWR in case of Inconel material without magnet

The impact of independent variables such as $T_{on}$, $T_{off}$ and, Voltage on dependent variable TWR of Inconel 718 material without magnet assistance is illustrated in the Fig. 6(a–c). It is clearly observed that from Fig. 6(a) is, for 4 and 10 amps peak current graph showed that, the input variable $T_{on}$ gradually increases results in the significant increase in the response parameter TWR. This is because, higher $T_{on}$ causes more heat transfer between work piece and tool material results in higher TWR. Further, in case of 6 and 8 amps peak current graph shows, the process variable $T_{on}$ increase results in decrease in TWR. This is because, medium current at gradual increase in pulse duration time lesser material is removed and results in lower TWR. It is also noticed that from Fig. 6(b) is, for 4,6 and 8 amps peak current graphs showed that, the independent parameter $T_{off}$ increase from 4 µs to 10 µs, the dependent parameter TWR significantly increases. This is because, lower $T_{off}$ generates high amount of thermal energy between work and tool electrode results in higher vaporization takes place and higher TWR is obtained. In case of 10 amps peak current graph shows that, the input parameter.

$T_{off}$ raises from 4 µs to 10 µs, the output parameter TWR gradually decreases from the 0.00565grm/min to 0.0044grm/min. This is because, the initial gap between electrodes (IGE) increases the amount of spark generation between tool and work piece is decreased and results in lower TWR is obtained. It is also clearly identified that from Fig. 6(c), for 4 amps peak current graph shows, the independent parameter voltage raises from 30 to 45 V, the dependent parameter TWR increases significantly from 0.00080 grm /min to 0.00327 grm /min. Due to this reason, behind that lower current at higher voltage produces high discharge between electrodes results in higher TWR. Further, in case of 6, 8 and 10 amps peak current graph showed that, the process parameter voltage increases the result in decreased in TWR. This is because, the higher

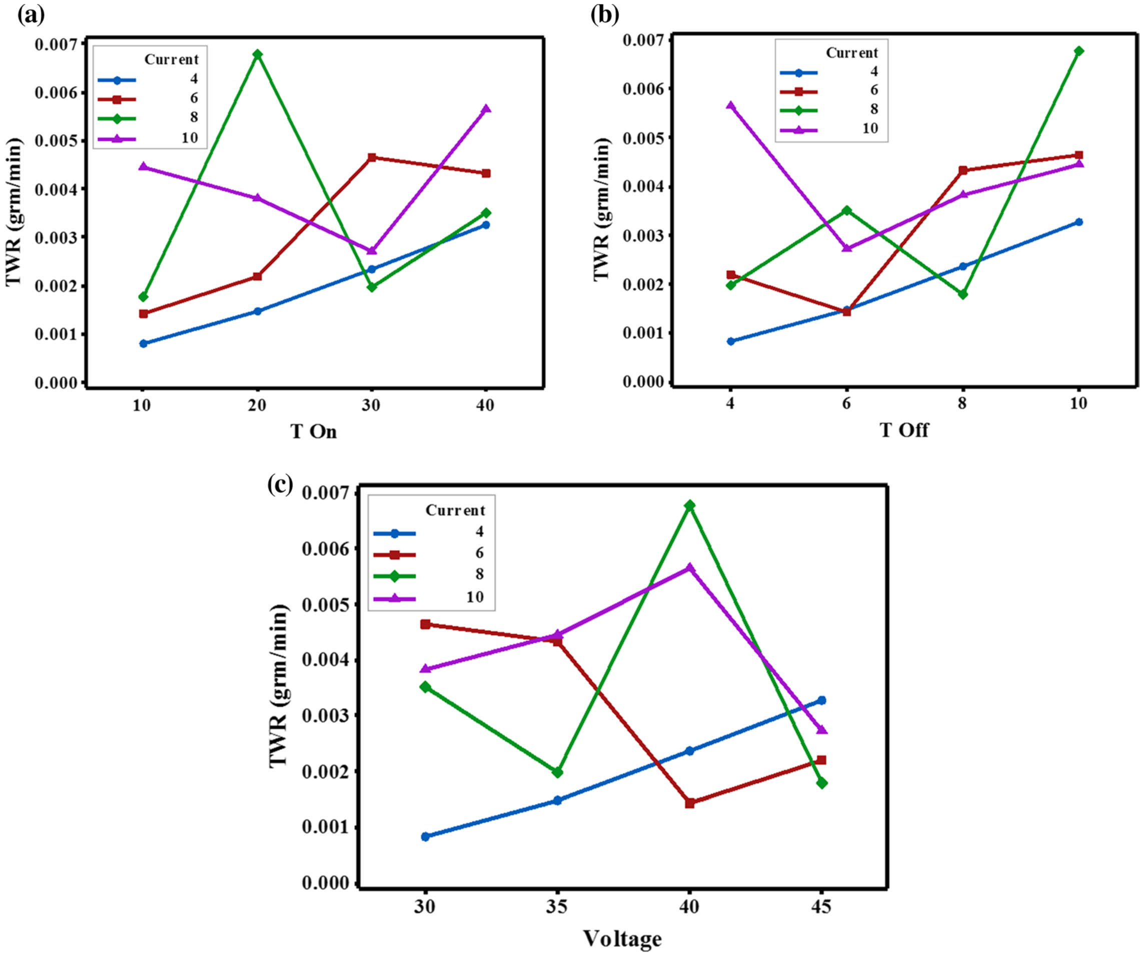

**Fig. 6** **a–c** Main effect plots for TWR for different input levels without assistance of magnet

current and voltage generates lower amount of heat in the die electric fluid results in lesser material is removed and the lower TWR is obtained. It is clearly found that the process variables $T_{on}$ and $T_{off}$ most influencing parameters on the response variable TWR considering without the assistance of magnet.[20].

## 3.2 ANOVA analysis

Analysis of variance is also called as ANOVA and is used to study the impact of machining parameters on Inconel 718 material with and without assistance of magnet while machining with EDM process. The results of the ANOVA analysis are displayed in the Tables 3, 4 and 5 by using Minitab17 version software. In an ANOVA study, the significant aspects are first identified, then insignificant values are removed from the table and the fitted quadratic model is adjusted. [21]. The parameters are said to be significant if their values are less than the P-value (probability value). Similarly, it appears that as the value of F rises, the process parameters performance characteristics changes as well. [22].

**Table 4** ANOVA for MRR for different input levels with assistance of magnet

MRR

| Source | DF | Adj SS | Adj MS | F- Value | P- Value |
|---|---|---|---|---|---|
| current | 3 | 1178.2 | 392.7 | 3.81 | 0.15 |
| $T_{on}$ | 3 | 5276.3 | 1758.8 | 17.06 | 0.022 |
| $T_{off}$ | 3 | 3895.3 | 1298.4 | 12.6 | 0.033 |
| Voltage | 3 | 324.8 | 108.3 | 1.05 | 0.484 |
| Error | 3 | 309.2 | 103.1 | | |
| Total | 15 | | | | |

$S = 0.0026979$, $R^2 = 95.77\%$, $R^2(adj) = 78.85\%$, $R^2(pred) = 0.00\%$

**Table 5** ANOVA for MRR for different input levels without assistance of magnet

| MRR | | | | | |
|---|---|---|---|---|---|
| Source | DF | Adj SS | Adj MS | F- Value | P- Value |
| current | 3 | 0.000012 | 0.000004 | 1.25 | 0.428 |
| $T_{on}$ | 3 | 0.000174 | 0.000058 | 18.98 | 0.019 |
| $T_{off}$ | 3 | 0.000251 | 0.000084 | 27.35 | 0.011 |
| Voltage | 3 | 0.00003 | 0.000001 | 0.32 | 0.811 |
| Error | 3 | 0.000009 | 0.000003 | | |
| Total | 15 | 0.000449 | | | |

$S = 0.0017492$, $R^2 = 97.96\%$, $R^2(adj) = 89.78\%$, $R^2(pred) = 41.84\%$

### 3.2.1 ANOVA for MRR in case of Inconel 718 material with assistance of magnet

The ANOVA results for the response parameter MRR depicted in Table 4, for peak current 4,6,8 and 10 amps of Inconel 718 material with assistance of magnet shows that, the input variables $T_{on}$ and $T_{off}$ are most influencing variables on the response variable MRR with larger F values and smaller P values. The value of R2is obtained for MRR is 95.77% and adjusted R2is 78.85% which indicates that the presented model is effectively fitted to the data. The results showed in the Table 4, for all the cases (4, 6, 8 and 10 amps) of peak current with assistance of magnet observed that, the input variable $T_{on}$ has higher F value and smaller P value i.e.17.06 and 0.022. Further, the F value of input variable $T_{off}$ is larger at 12.6 and the value of P is 0.033 which is less than 0.05. This indicates, the input variables $T_{on}$ and $T_{off}$ are more essential in case of MRR.

### 3.2.2 ANOVA for MRR in case of Inconel 718 material without assistance of magnet

The ANOVA results for the dependent variable MRR depicted in Table 5, for peak current 4,6,8 and 10 amps of Inconel 718 material without assistance of magnet shows that, the independent variables.

$T_{on}$ and $T_{off}$ are most significant variables on the dependent variable MRR with larger F values and smaller P values. The value of R2 obtained for MRR is 97.96% and adjusted R2 is 89.78% which indicates that the presented model is effectively fitted to the data. The results showed in the Table 5, for all the cases (4, 6, 8 and 10 amps) of peak current and without assistance of magnet observed that, the independent variable Ton has higher F value and smaller P value i.e.18.98 and 0.019. Further, the F value of independent variable $T_{off}$ is larger at 27.35 and the value of P is 0.011 which is less than 0.05. This indicates, the independent variables $T_{on}$ and $T_{off}$ are more essential in case of MRR [6].

**Table 6** ANOVA for TWR for different input levels with assistance of magnet

| TWR | | | | | |
|---|---|---|---|---|---|
| Source | DF | Adj SS | Adj MS | F- Value | P- Value |
| current | 3 | 0.00001 | 0.000003 | 4.29 | 0.131 |
| $T_{on}$ | 3 | 0.00001 | 0.000003 | 4.08 | 0.139 |
| $T_{off}$ | 3 | 0.000015 | 0.000005 | 6.3 | 0.050 |
| Voltage | 3 | 0.000005 | 0.000002 | 2.15 | 0.273 |
| Error | 3 | 0.000002 | 0.000001 | | |
| Total | 15 | 0.000042 | | | |

$S = 0.0008823$, $R^2 = 94.39\%$, $R^2(adj) = 71.95\%$, $R^2(pred) = 0.00\%$

### 3.2.3 ANOVA for TWRin case of Inconel 718 material with assistance of magnet

The analysis of variance gives the output values for the response variable TWR depicted in Table 6, for peak current 4,6,8 and 10 amps of Inconel 718 material with assistance of magnet shows that, the process variable $T_{off}$is the most influencing variable on response variable TWR with higher F value and smaller P value. The value of $R^2$ obtained for TWR is 94.39 % and adjusted $R^2$ is 71.95%which indicates that the presented model is effectively fitted to the data. The results showed in the Table 6, for all the cases (4, 6, 8 and 10 amps) of peak current with assistance of magnet observed that, the input variable $T_{off}$ has higher F value and smaller P value i.e. 6.3 and 0.050. Which is less than or equal to 0.05. This indicates, the input variable $T_{off}$ is most essential in case of TWR.

### 3.2.4 ANOVA for TWR in case of Inconel 718 material without assistance of magnet

The ANOVA output for the response variable TWR depicted in Table 7, for peak current 4,6,8 and 10 amps of Inconel 718 material without assistance of magnet shows that, the input variable $T_{off}$ is most influencing parameter on response

**Table 7** ANOVA for MRR for different input levels without assistance of magnet

| TWR | | | | | |
|---|---|---|---|---|---|
| Source | DF | Adj SS | Adj MS | F- Value | P- Value |
| current | 3 | 0.00001 | 0.000003 | 3.74 | 0.154 |
| $T_{on}$ | 3 | 0.000009 | 0.000003 | 3.63 | 0.159 |
| $T_{off}$ | 3 | 0.000014 | 0.000005 | 5.51 | 0.048 |
| Voltage | 3 | 0.000005 | 0.000002 | 1.99 | 0.293 |
| Error | 3 | 0.000003 | 0.000001 | | |
| Total | 15 | 0.000041 | | | |

$S = 0.0009286$, $R^2 = 93.70\%$, $R^2(adj) = 68.48\%$, $R^2(pred) = 0.00\%$

variable TWR with larger F value and smaller P value. The value of $R^2$ obtained for TWR is 93.70% and adjusted $R^2$ is 68.48% which indicates that the presented model is effectively fitted to the data. The results showed in the Table 7, for all the cases (4, 6, 8 and 10 amps) of peak current without assistance of magnet observed that, the input variable $T_{off}$ has higher F value and smaller P value i.e.5.51 and 0.048 which is less than 0.05. This indicates, the input variable $T_{off}$ is most essential in case of TWR [6]

## 3.3 Regression analysis

### 3.3.1 Regression analysis in case of Inconel 718 material with assistance of magnet

The empirical model graphs predict the performance response of EDM process on Inconel 718 material with assistance of magnet. These graphs are generated by using the regression analysis. The empirical model consists a set of equations comparing of independent variables such as $T_{on}$, $T_{off}$ and, Voltage and dependent variables viz., MRR and TWR [23]. Thus, the established connection of above stated parameters for the non-conventional method EDM process can be denoted by using the following equations.

$$MRR = 0.009912 + 0.00451T_{on} - 0.00342T_{off} - 0.00020Voltage \tag{3}$$

$$TWR = 0.003198 - 0.001085T_{on} - 0.000543T_{off} - 0.000000Voltage \tag{4}$$

The impact of various parameters on MRR is indicated in Eq. (3). $T_{on}$ has a positive influence on MRR, whereas $T_{off}$ and voltage have a negative effect. The independent variable $T_{on}$ is most significant independent variable. Also, in Eq. (4) variables $T_{on}$, $T_{off}$ and voltage are having negative on TWR. Additionally, the normality of residuals is plotted for analyzing normality of data points of MRR and TWR as shown in Fig. 7(a–b) respectively. The graphical representation appears that all the points of the results for MRR and TWR are closer to the linear line. Hence, it is speculated that the investigation data are normally spread [19].

### 3.3.2 Regression analysis in case of Inconel 718 material without assistance of magnet

The empirical model for predicting the values of MRR and TWR for EDM process of Inconel 718 material without assistance of magnet has been established using the following equations.

$$MRR = 0.008962 - 0.004628T_{on} - 0.003451T_{off} - 0.000023Voltage \tag{5}$$

$$TWR = 0.003249 - 0.001068T_{on} - 0.000561T_{off} + 0.000028Voltage \tag{6}$$

The impact of various parameters on MRR is indicated in Eq. (5) reveals that $T_{on}$, $T_{off}$ and, voltage have a negative effect on MRR. The independent variables not much influencing process parameter on MRR without assistance of magnet. Also, in Eq. (6) variables $T_{on}$ and $T_{off}$ have negative effect and voltage is positive effect on TWR. Additionally, the normality of residuals is plotted for analyzing normality of data points of MRR and TWR as shown in Fig. 8(a–b) respectively. The graphical representation appears that all points of the results for MRR and TWR are closer to the linear line. Hence, it is speculated that the investigation data are normally spread.

## 3.4 Optimization of EDM process parameters in case of Inconel 718 material with and without assistance of magnet.

Optimization of process variables of EDM process on machining of Inconel 718 material with and without assistance of magnet and peak current (4,6,8 and 10 amps) is performed using multi objective optimization ratio

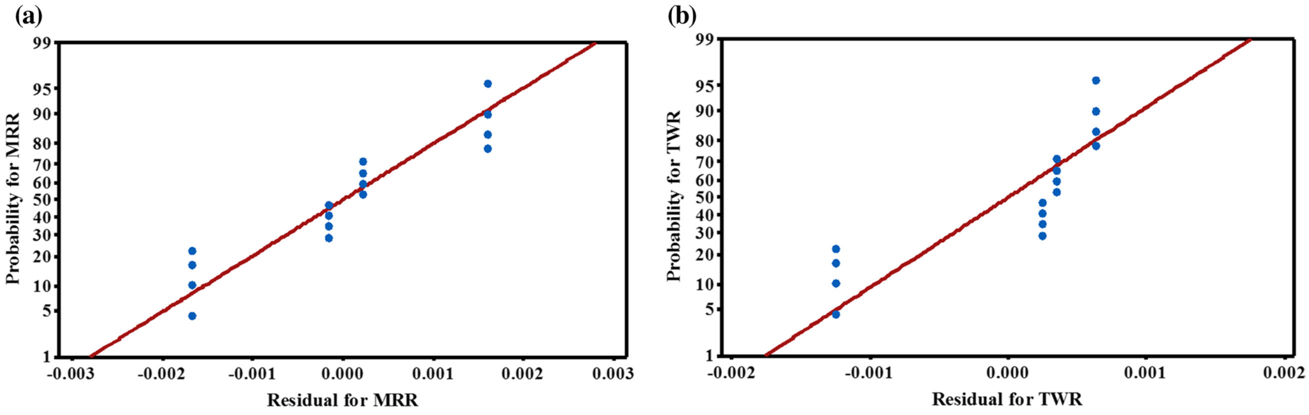

**Fig. 7** **a** Normal probability plot for MRR **b** Normal probability plot for TWR with magnet

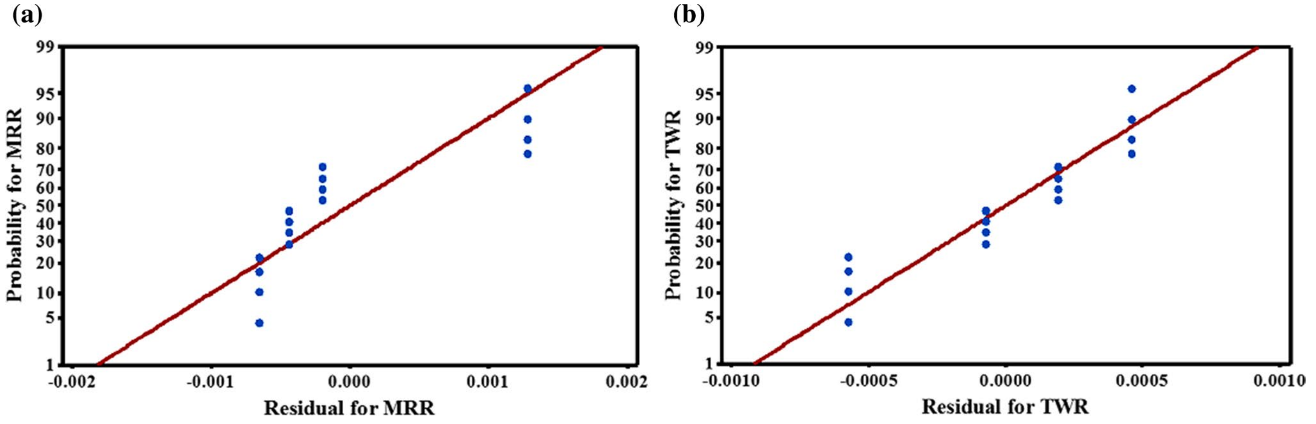

**Fig. 8** **a** Normal probability plot for MRR **b** Normal probability plot for TWR without magnet

analysis(MOORA) method([21, 24]).This technique is a multi-objective optimization technique with high usage in industrial environment for the complex decision making and it is also very simple and robust when compared to other techniques. The parameters MRR and TWR are considered as response parameters, while $T_{on}$, $T_{off}$ and voltage as process variables. In this method first, design a decision matrix is carried out based on Taguchi ($L_{16}$) using Eq. (7). The output values of decision matrix for each of the Inconel 718 material with assistance of magnet are tabulated in Table2.

$$X = \begin{bmatrix} X_{11} & X_{12} & \dots & X_{1n} \\ X_{21} & X_{22} & \dots & X_{2n} \\ \dots & \dots & \dots & \dots \\ X_{m1} & X_{m2} & \dots & X_{mn} \end{bmatrix} \tag{7}$$

where $X_{ij}$ is the performance measure of $i^{th}$ parameters on $j^{th}$ experimental runs, $m$ and $n$ are the total number of parameters and experimental runs respectively.

After the decision matrix, normalization process is done via Eq. (8) which converts the various measurement units of performance values into the comparable sequence data. Then, the overall assessment values of the responses for each of the experimental setting are evaluated using Eq. (9).This converts the multi-response optimization into the single response optimization problem. Based on the overall assessment values, ranking of the experimental setting is done([24, 25]).The experimental setting with higher assessment value yields the optimal experimental setting compare to the other and the optimized results are depicted in Tables 8 and 9.

$$N_{ij} = \frac{X_{ij}}{\left[\sum_{i-1}^{m} x_{ij}^2\right]^{1/2}} Where j = 1, 2, \dots, n \tag{8}$$

$$Y_j = \sum\nolimits_{i-1}^{m} N_{ij} - \sum\nolimits_{i=g+1}^{n} N_{ij} \tag{9}$$

**Table 8** Assessment values (Yi) values of EDM process with assistance of magnet

| Exp. No | Current | $Y_j$ values | Rank |
|---|---|---|---|
| 1 | 4.0 | 0.304 | 4 |
| 2 | | 0.937 | 3 |
| 3 | | 1.481 | 2 |
| 4 | | 2.453 | 1 |
| 1 | 6.0 | 0.432 | 4 |
| 2 | | 0.605 | 3 |
| 3 | | 2.175 | 1 |
| 4 | | 2.124 | 2 |
| 1 | 8.0 | 0.855 | 4 |
| 2 | | 1.151 | 3 |
| 3 | | 1.324 | 2 |
| 4 | | 2.084 | 1 |
| 1 | 10.0 | 1.545 | 3 |
| 2 | | 1.585 | 2 |
| 3 | | 0.721 | 4 |
| 4 | | 1.662 | 1 |

where $N_{ij}$denotes the normalized performance values of $i^{th}$ output parameters, g signifies the number of parameters to be maximized, (n-g) signifies the number of parameters to be minimized and $Y_j$ signifies the assessment values of $i^{th}$ parameters with regard to all $j^{th}$ experiment runs.

The result shows that, for all the cases i.e. 4,6,8 and 10 amps peak current of Inconel 718 material with and without assistance of magnet in EDM process, Expt.No.9 achieved highest attainment values and optimal settings obtained are $T_{on}$ (40 µs), $T_{off}$(10 µs) and voltage (30–40 V). These optimal settings provides most optimal values of parameters such as lower TWR and higher MRR for each of the peak current and improves product quality, minimizes the manufacturing costs and improving the machining efficiency of the EDM process.

**Table 9** Assessment values (Yi) values of EDM process without assistance of magnet

| Exp. No | Current | $Y_j$ values | Rank |
|---|---|---|---|
| 1 | 4.0 | 0.309 | 4 |
| 2 | | 0.814 | 3 |
| 3 | | 1.524 | 2 |
| 4 | | 2.455 | 1 |
| 1 | 6.0 | 0.395 | 4 |
| 2 | | 0.593 | 3 |
| 3 | | 2.210 | 1 |
| 4 | | 2.106 | 2 |
| 1 | 8.0 | 0.524 | 4 |
| 2 | | 2.188 | 1 |
| 3 | | 0.842 | 3 |
| 4 | | 1.647 | 2 |
| 1 | 10.0 | 1.447 | 2 |
| 2 | | 1.423 | 3 |
| 3 | | 1.098 | 4 |
| 4 | | 1.706 | 1 |

### 3.5 Confirmatory analysis

Furthermore, confirmatory tests are carried out to validate MOORA method results. The optimal setting is found during the machining of Inconel 718 material with assistance of magnet i.e. peak current levels at 4, 6, 8 and 10 amps corresponding $T_{on}$ (40 µs), $T_{off}$ (10 µs) and voltage (30 volts) and also with same peak current levels the machining of Inconel 718 material without assistance of magnet optimal parameters are $T_{on}$ (40 µs), $T_{off}$ (10µs) and voltage (40 volts) are used for confirmatory experiments and the corresponding results are shown in Tables 10 and 11. The results show that confirmatory tests results are comparable and acceptable with experimental results for the optimal setting.

## 4 Conclusions

In this research work, the study and investigation of independent variables influenced on the machining of Inconel 718 material by using die-sinking EDM process with and without assistance of magnet and auxiliary copper electrode. The MOORA technique has been adopted to find optimal process settings for the performance characteristics of EDM process. The following conclusions have been drawn from the investigation:

- From the experimental study, it is clearly observed that, the machining of Inconel 718 material by using the EDM process with magnet is most effective hybrid approach to achieve better performance results in the terms of MRR and TWR as compared to machining of Inconel 718 material without assistance of magnet. This is because, the higher rate of ionization and plasma confinement, results in higher rate of thermal energy is transferred between electrode and work pieces aids a better performance results achieved.
- The process parameters $T_{on}$, $T_{off}$ are the most influencing parameters on MRR during the EDM process of Inconel 718 material. Moreover, the higher parameter level of $T_{on}$ (40 µs) and $T_{off}$ (10 µs) values are recommended for the higher MRR during EDM process of Inconel material with assistance of magnet.
- It is clearly observed that from the investigation, the process parameters $T_{on}$, $T_{off}$ and Voltage are moderately influenced on MRR during the EDM process of Inconel 718 material without assistance of magnet. This

**Table 10** Confirmatory analysis results of Inconel 718 material with assistance of magnet

| Input positions | Response Variables | Investigation test results | Confirmatory test results |
|---|---|---|---|
| Exp.No-4: $T_{on}$ (40 µs), $T_{off}$ (10 µs) and voltage (45 V) | Peak current at 4 amps | | |
| | MRR (grm/min) | 0.02471 | 0.02109 |
| | TWR (grm/min) | 0.00421 | 0.00346 |
| Exp.No-3: $T_{on}$(30 µs), $T_{off}$(10 µs) and voltage (30 V) | Peak current at 6 amps | | |
| | MRR (grm/min) | 0.01574 | 0.01707 |
| | TWR (grm/min) | 0.0053 | 0.0047 |
| Exp.No-4: $T_{on}$(40 µs), $T_{off}$(6 µs) and voltage (30 V) | Peak current at 8 amps | | |
| | MRR (grm/min) | 0.01086 | 0.01289 |
| | TWR (grm/min) | 0.00397 | 0.00412 |
| Exp.No-4: $T_{on}$(40 µs), $T_{off}$(4 µs) and voltage (40 V) | Peak current at 10 amps | | |
| | MRR (grm/min) | 0.01074 | 0.00835 |
| | TWR (grm/min) | 0.00516 | 0.00491 |

**Table 11** Confirmatory analysis results of Inconel 718 material without assistance of magnet

| Input positions | Response variables | Investigation test results | Confirmatory test results |
|---|---|---|---|
| Exp.No-4: $T_{on}$ (40 µs), $T_{off}$(10 µs) and voltage (45 V) | Peak current at 4 amps | | |
| | MRR (grm/min) | 0.01895 | 0.01828 |
| | TWR (grm/min) | 0.003272 | 0.003905 |
| Exp.No-3: $T_{on}$(30 µs), $T_{off}$(10 µs) and voltage (30 V) | Peak current at 6 amps | | |
| | MRR (grm/min) | 0.0168 | 0.01515 |
| | TWR (grm/min) | 0.00465 | 0.00438 |
| Exp.No-2: $T_{on}$(20 µs), $T_{off}$(10 µs) and voltage (40 V) | Peak current at 8 amps | | |
| | MRR (grm/min) | 0.016 | 0.012 |
| | TWR (grm/min) | 0.00678 | 0.00428 |
| Exp.No-4: $T_{on}$(40 µs), $T_{off}$(4 µs) and voltage (40 V) | Peak current at 10 amps | | |
| | MRR(grm/min) | 0.0105 | 0.0046 |
| | TWR (grm/min) | 0.00565 | 0.00393 |

is because, the poor ionization between electrode and work piece results in the lower rate of MRR.

- The peak current at level 4 and parameters $T_{on}$(40 µs), $T_{off}$(10 µs) and voltage (30 V) are recommended for the better TWR during the EDM process of Inconel718 material with assistance of magnet.
- The optimal process parameters setting are found during EDM process of Inconel 718 material with and without assistance of magnet for higher MRR and lower TWR by using MOORA optimization method. The optimal parameter settings is found to be peak current at level 4 amps, $T_{on}$ (40 µs), $T_{off}$(10 µs) and Voltage at (30–40 V).
- The results of the confirmatory analytical test are compared and were satisfactory with the experimental results for the ideal settings.

## Declarations

**Conflict of interest** The authors declare that they have no conflict of interest.

**Ethical approval** "This chapter does not contain any studies with human participants or animals performed by any of the authors".

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