Experimental Study and Determination of the Effect of Drilling EDM Parameters for Incoloy 800 Alloy

R. ARUNBHARATHI*, P. ASHOKA VARTHANAN†, R. JAYASURYA‡, S.V.KAVIN‡, S. JAYASURIYA‡

1Department of Mechanical Engineering, Sri Krishna College of Engineering and Technology, Coimbatore 641008, India.

*Email: arunbharathi@skcet.ac.in

Abstract This work involves the experimental study of drilling EDM parameters for Incoloy 800 alloy. Material erosion rate and tool wear rate has been considered as the response characteristics. Design of experimental runs were framed using CCD based response surface methodology. The experiments are performed in random manner with different combination of pulse current, spark duration, voltage and pulse interval and the results obtained are analyzed using Analysis of Variance (ANOVA). Various 3D plots are generated by using Design Expert software in this work. Discharge current and spark duration were found as the dominant variables for MRR and EWR and the effect is high on these two responses relative to other variables.

Keywords: Incoloy 800, RSM, DEDM

1. Introduction:

In recent years, processing of nickel-based super alloys was found to be a dynamic amount of research in various engineering applications attributable to the expanding request of this class of material and also due to the difficulties associated with their processing. In this present work, iron-nickel-based super alloy called Incoloy 800 was chosen as the workpiece material due to its inherent properties comprising, resistance to chloride stress-corrosion cracking, possessing high strength and excellent resistance to oxidation, carburization and sulfidation at elevated temperatures. These attractive features cause them to widely use in many applications, namely aircraft turbine engines, chemical and petrochemical processing equipment, automotive, heat treating equipment, land-based gas turbine engines and spacecraft structural components [1]. These commonplace applications require tight dimensional resistances in the machined products. However, some physical and metallurgical characteristics of these super alloys, such as high strength, low thermal diffusivity, high work solidifying, presence of profoundly grating carbide particles and solid inclination to cling to the device face to form developed edge, make them difficult to machine in acceptable tolerance limits using conventional techniques like turning, milling and drilling operations[2].
Prevalently, when large scale or miniature size gaps of high perspective proportion in nickel based super composites are machined by EDM operation, bore is uneffectively broken and machining effectiveness is low as result of low strength nature and hard to empty the wrecked drill from the hole [3–5]. To overcome the above limitations, electrical discharge machining (EDM) is one of the most suitable non-conventional and widely accepted manufacturing processes for machining difficult-to-machine materials like super alloys, composites, ceramics, etc., [6–8]. EDM is an cost-effective method and provides more flexibility in terms of hole geometry and hole placement on electrically conductive materials regardless of their hardness and strength with good dimensional accuracy [9]. In EDM measure, as there is no immediate contact between the tool and the workpiece, the harmful effects such as chatter, vibration and mechanical stresses normally present in traditional machining are eliminated. Moreover, the spiral follows obtained by ordinary drilling processing are totally disposed in EDM process.

The material removal in EDM is through electric-thermal erosion process by applying a series of rapidly recurring controlled discrete sparks across a small gap between the tool electrodes in the presence of dielectric fluid, which results in extremely high temperature in the range of 8,000°C to 12,000°C causing melting and vaporization of the material at the point of discharge.

Some of the important machining performance measures of the EDM drilling process are the surface quality, productivity and electrode wear, which are influenced by a few cycle parameters, e.g., release current and time, open release voltage, workpiece polarity, duty factor, materials used as dielectric fluid, etc. Surface quality from boring cycle clearly explains about surface harshness, opening size, normal white layer thickness and actuated remaining pressure gets affected because of addition of current and spark length. Proper selection of the drilling EDM measure boundaries can guarantee that the cycle would be exceptionally proficient and yield a great machined surface. As a result, a comprehensive study of the effects of EDM parameters on the machining characteristics is of great significance. Therefore in this study most dominating electrical parameters such as pulse current, discharge duration, voltage and spark off time were considered and its influence was measured in terms of EWR of copper electrode and MRR of Incoloy 800.

2. Materials and Methods

2.1 Work piece material

Incoloy 800 alloy plate of dimensions (120 mm x 60 mm x 10 mm) was used as the work piece material as shown in figure 1(a). This alloy is characterized by its high strength and good resistance to oxidation and carburization at elevated temperature and pressure. These looked-for individualities made it a very apt material in the industries like medical, chemical, aerospace and electric power generation due to its superior performance under severe conditions [10]. The top face of the work piece were ground before drilling actions so as to remove any surface irregularities as shown in figure 1(b). The chemical formation of Incoloy 800 alloy are elucidated in Table 1.
Figure 1(a) Incoloy 800 plate ‘as received’

Figure 1(b) Prepared work piece for experimentation

Table 1 Chemical elements of Incoloy 800

| Element | C  | Cr  | Mn | Al | Mo | Ni  | Fe  | Ti | W  | V  | Co |
|---------|----|-----|----|----|----|-----|-----|----|----|----|----|
| Wt %    | 0.073 | 21.10 | 0.74 | 0.28 | 0.22 | 33.59 | 42.19 | 0.33 | 0.11 | 0.014 | 0.12 |

2.2 Tool electrode material

When drilling of small holes in high strength alloys using electrical discharge drilling, electrolytic copper electrode is preferred as the suitable cathode material because of higher melting point, high temperature and electrical conductivity, easy machinability as well as lower disintegration rate, which leads to greater efficiency compared to other materials. A cylindrical tubular copper (CU) electrode of 2 mm in circumferential and 100 mm longitudinal dimension was used as the tool electrode material. Figure 2 shows few CU electrodes used in the experimental runs.

Figure 2 Copper Electrodes

2.3 Machine tool

The designed experimental runs were carried out using SPARKONIXDSH-II EDM drill machine on Incoloy 800 alloy depicted in Figure 3. The deionized water with specific gravity of 1.0 and boiling point of 100°C is used as the dielectric fluid medium and it is injected through the tubular electrode at a constant flushing pressure of 0.3 kg/cm² to avoid overheating of the electrode and also to remove the eroded particles from the hole that is being drilled to prevent disruptions in the process. In EDM drilling, the electrode polarity selection is very important as
it impacts the machining qualities during the EDM cycle and hence the electrodes polarity is selected first. The desired performances viz., higher material removal rate, lower tool wear rate and better surface finish is obtained generally with tool electrode as negative[11]. Hence, direct mode of polarity was selected to complete the experimental work.

Figure 3 EDM Machine

2.4 Process parameters and its levels

Adequacy of any exploration relies exceptionally upon the suitable choice of variable ranges and their values. As EDM drilling is an electro thermal erosion process, it is necessary to control the electrical input conditions to achieve the desired performance measures. Hence, the electrical factors such as current, discharge interval, spark on time and Gap Voltage which have straight impact on the outcome of the edm drilling process and also the accuracy of the features produced was considered for the present work. Other factors such as electrode speed, flushing pressure were kept constant during the experimentation. Determination of the scope of parameter value settings is made subsequent by some pilot tests inside the steady space of the machining variables. The levels of chosen dependent parameters are shown in Table 3.

Table 3. Selected Process parameters and its levels

| Factors                  | Units | Levels |
|--------------------------|-------|--------|
| Discharge current (A)    | A     | -2     |
|                          |       | -1     |
|                          |       | 0      |
|                          |       | 1      |
|                          |       | 2      |
| Pulse-on time (B)        | µs    | 2      |
|                          |       | 4      |
|                          |       | 6      |
|                          |       | 8      |
|                          |       | 10     |
| Pulse-off time (C)       | µs    | 2      |
|                          |       | 4      |
|                          |       | 6      |
|                          |       | 8      |
|                          |       | 10     |
| Gap voltage (D)          | V     | 20     |
|                          |       | 27     |
|                          |       | 34     |
|                          |       | 41     |
|                          |       | 48     |
2.5 Response Measurements:

Experiments were designed based on central composite design of RSM. Based on number of factors chosen for experimental study, 30 runs are generated with different combination of process variables. For each experimental run responses such as MRR and TWR were determined using Eq. 1-2 respectively[13].

\[
MRR = \frac{\pi (R_{top}^2 + R_{bottom}^2 + R_{top}R_{bottom}) \times T}{t}
\]  
(1)

Where,
- \( R_{top} \) = Entrance radius of the hole, \( R_{bottom} \) = Exit radius of the hole, \( T \) = workpiece thickness.
- \( t \) = time taken for drilling a through hole

\[
TWR = \frac{\pi d^2 T_f}{4t}
\]
(2)

Where, \( d \) = Tool diameter, \( T_f \) = Frontal wear of the electrode

Through gaps of 10 mm cavity were penetrated in all the investigations. The time taken for machining a gap was recorded utilizing an electronic timer. The experimental runs along with responses are shown in table 4.

### Table 4 Experimental trials and responses

| Run | A: Current | B: Ton | C: Toff | D: Voltage | MRR  | TWR  |
|-----|------------|--------|---------|------------|------|------|
| 1   | 14         | 8      | 8       | 27         | 0.5581| 0.6775|
| 2   | 18         | 2      | 6       | 34         | 0.6362| 1.1652|
| 3   | 14         | 4      | 4       | 27         | 0.4629| 0.6449|
| 4   | 14         | 4      | 4       | 20         | 0.4843| 0.7475|
| 5   | 18         | 6      | 6       | 34         | 0.8072| 1.1643|
| 6   | 22         | 8      | 4       | 41         | 1.6785| 1.5244|
| 7   | 18         | 6      | 6       | 34         | 0.7775| 1.1655|
| 8   | 22         | 4      | 4       | 38         | 1.1224| 1.536 |
| 9   | 18         | 6      | 6       | 34         | 0.6714| 1.1652|
| 10  | 22         | 4      | 4       | 41         | 1.209 | 1.5344|
| 11  | 22         | 4      | 8       | 41         | 1.0401| 1.5244|
| 12  | 10         | 6      | 6       | 20         | 0.3428| 0.4418|
| 13  | 14         | 8      | 8       | 4          | 0.5077| 0.6482|
| 14  | 22         | 8      | 8       | 41         | 1.4609| 1.5499|
| 15  | 22         | 8      | 4       | 41         | 1.7643| 1.5244|
| 16  | 18         | 6      | 6       | 34         | 0.7221| 1.1659|
| 17  | 22         | 4      | 8       | 41         | 1.1717| 1.5244|
| 18  | 18         | 6      | 6       | 34         | 0.8652| 1.1658|
| 19  | 18         | 6      | 6       | 34         | 0.9872| 1.1659|
| 20  | 24         | 6      | 6       | 48         | 2.1771| 1.9087|
| 21  | 18         | 6      | 10      | 34         | 0.7656| 1.1655|
| 22  | 18         | 10     | 6       | 41         | 0.8807| 1.1656|
| 23  | 14         | 8      | 8       | 27         | 0.5847| 0.7912|
3. Results and Discussion

3.1 Significance of dependent Process variables on MRR

The Regression condition for the material expulsion rate as an element of four process factors was created by utilizing test information and is given below,

\[
MRR = +0.86785 +0.35239 \times \text{Current} -0.13408 \times \text{Ton} +0.39203 \times \text{Toff} -0.30237 \times \text{Voltage} +0.014508 \times \text{Current} \times \text{Ton} -0.041678 \times \text{Current} \times \text{Toff} +0.030095 \times \text{Current} \times \text{Voltage} -0.010025 \times \text{Ton} \times \text{Toff} -1.04025 \times 10^{-003} \times \text{Ton} \times \text{Voltage} +0.013036 \times \text{Toff} \times \text{Voltage} -0.032131 \times \text{Current}^2 -3.28896 \times 10^{-004} \times \text{Ton}^2 -2.00857 \times 10^{-003} \times \text{Toff}^2 -4.11880 \times 10^{-003} \times \text{Voltage}^2
\]

Table 5 Analysis of variance table [Material erosion rate]

| Source  | Sum of Squares | df | Mean Square | F Value | p-value | Prob > F |
|---------|----------------|----|-------------|---------|---------|----------|
| Model   | 5.16           | 14 | 0.37        | 26.99   | < 0.0001 | Significant |
| A-Current | 0.11            | 1  | 0.11        | 7.84    | 0.0135  |           |
| B-Ton   | 4.783E-005     | 1  | 4.783E-005  | 3.505E-003 | 0.9536  |           |
| C-Toff  | 0.034          | 1  | 0.034       | 2.46    | 0.1379  |           |
| D-Voltage | 0.029           | 1  | 0.029       | 2.11    | 0.1672  |           |
| AB      | 0.035          | 1  | 0.035       | 2.57    | 0.1301  |           |
| AC      | 0.081          | 1  | 0.081       | 5.92    | 0.0279  |           |
| AD      | 0.092          | 1  | 0.092       | 6.78    | 0.0200  |           |
| BC      | 0.015          | 1  | 0.015       | 1.07    | 0.3174  |           |
| BD      | 6.903E-004     | 1  | 6.903E-004  | 0.051   | 0.8251  |           |
| CD      | 0.035          | 1  | 0.035       | 2.58    | 0.1292  |           |
| A^2     | 0.079          | 1  | 0.079       | 5.81    | 0.0292  |           |
| B^2     | 3.272E-005     | 1  | 3.272E-005  | 2.398E-003 | 0.9616  |           |
| C^2     | 1.724E-003     | 1  | 1.724E-003  | 0.13    | 0.7272  |           |
| D^2     | 0.035          | 1  | 0.035       | 2.60    | 0.1277  |           |
| Residual| 0.20           | 15 | 0.014       |         |         | 0.9618   |

R- Squared = 0.9618  Adj R-Squared = 0.9262  Adeq Precision = 21.888
From the ANOVA table 5, it is found that the A, AC, AD and A² terms are significant factors (Prob>F is <0.05000) on the material removal rate.

![Fig 5a: Effect of Current on MRR](image1)

![Fig 5b: Effect of Ton on MRR](image2)

From Figure 5a the material evacuation rate is found to have an expanding pattern with the expansion of current. As intensity of spark is increased which results in high material removal. Figure 5b shows that the material expulsion rate is found to have an expanding pattern with increment in spark release duration due to the fact discharge energy is increased.

### 3.2 Significance of dependent Process variables on TWR

The Regression condition for the tool erosion rate as an element of four Input measure factors was created by utilizing exploratory information and it is given below,

\[
TWR = -0.71148 + 0.26428 \times \text{Current} + 0.057033 \times \text{Ton} + 0.049545 \times \text{Voltage} - 6.25104E-003 \times \text{Current} \times \text{Ton} - 0.011114 \times \text{Current} \times \text{Toff} + 0.011420 \times \text{Current} \times \text{Voltage} - 1.37295E-003 \times \text{Ton} \times \text{Toff} + 3.14475E-003 \times \text{Ton} \times \text{Voltage} + 5.24109E-003 \times \text{Toff} \times \text{Voltage} - 0.013103 \times \text{Current}^2 - 3.90310E-003 \times \text{Ton}^2 - 1.37945E-003 \times \text{Toff}^2 - 2.05946E-003 \times \text{Voltage}^2
\]
Table 6 Analysis of variance table [Tool wear rate]

| Source   | Sum of Squares | df | Mean Square | F Value | p-value | Prob > F |
|----------|----------------|----|-------------|---------|---------|----------|
| Model    | 3.86           | 14 | 0.28        | 134.02  | < 0.0001| Significant |
| A-Current| 0.020          | 1  | 0.020       | 9.52    | 0.0075  |           |
| B-Ton    | 5.909E-003     | 1  | 5.909E-003  | 2.87    | 0.1108  |           |
| C-Toff   | 5.566E-003     | 1  | 5.566E-003  | 2.70    | 0.1208  |           |
| D-Voltage| 7.436E-003     | 1  | 7.436E-003  | 3.61    | 0.0067  |           |
| AB       | 6.498E-003     | 1  | 6.498E-003  | 3.16    | 0.0958  |           |
| AC       | 5.746E-003     | 1  | 5.746E-003  | 2.79    | 0.1154  |           |
| AD       | 0.013          | 1  | 0.013       | 6.47    | 0.0225  |           |
| BC       | 2.737E-004     | 1  | 2.737E-004  | 0.13    | 0.7204  |           |
| BD       | 6.308E-003     | 1  | 6.308E-003  | 3.07    | 0.1004  |           |
| CD       | 5.685E-003     | 1  | 5.685E-003  | 2.76    | 0.1172  |           |
| A^2      | 0.013          | 1  | 0.013       | 6.41    | 0.0230  |           |
| B^2      | 4.607E-003     | 1  | 4.607E-003  | 2.24    | 0.1553  |           |
| C^2      | 8.130E-004     | 1  | 8.130E-004  | 0.40    | 0.5391  |           |
| D^2      | 8.872E-003     | 1  | 8.872E-003  | 4.31    | 0.0555  |           |
| Residual | 0.031          | 15 | 2.058E-003  |         |         |           |

R- Squared = 0.9921  Adj R-Squared = 0.9847
Pred R-Square = 0.8696  AdeqPrecision= 46.591

Fig 6a: Effect of Current on TWR
From Figure 6a and 6b the electrode erosion rate is found to have an expanding style with increment in current and voltage because of the fact that the size of the material removed is coarser. This is owing to higher release energy. Those removed particles dissolve and resolidify at the edge of the miniature openings and it gets hard to eliminate them from the machined zone. Accordingly, the machining cycle becomes unsteady and the overall measure of material expulsion from the tool increments.

**Conclusion**

The present study develops a regression model for MRR and TWR involving four input parameters ejection current, spark release time, pulse interval, gap voltage. The developed regression model was validated with analysis of variance to find the significant input parameters that affects the response.

- ANOVA result shows for MRR discharge current term are significant and increase in discharge energy, intensity of spark likewise expanded and brings about high Material expulsion.

- Tool wear rate is found to have an increasing with increase in current and voltage because the size of the removed material gets coarser because of higher release energy. Hence, the machining cycle becomes insecure and the general measure of material expulsion from the electrode rises.

**References**

[1] N.K. Jain, A. Potpelwar, S. Pathak, N.K. Mehta, Investigations on geometry and productivity of micro-holes in Incoloy 800 by pulsed electrolytic jet drilling, Int. J. Adv. Manuf. Technol. 85 (2016) 2083–2095. doi:10.1007/s00170-016-8342-9.

[2] S. Suresh Kumar, M. Uthayakumar, S. Thirumalai Kumaran, P. Parameswaran, E. Mohandas, Electrical discharge machining of Al (6351) alloy: Role of electrode shape, Int. J. Mater. Prod. Technol. 53 (2016) 86–97. doi:10.1504/IJMPT.2016.076378.
[3] M. Ay, U. Caydaş, A. Hasçalik, Optimization of micro-EDM drilling of inconel 718 superalloy, Int. J. Adv. Manuf. Technol. 66 (2013) 1015–1023. doi:10.1007/s00170-012-4385-8.

[4] Dhayachandhran K S, Jothilakshmi M, Tholkapiyan M, Mohan A, “Performance Evaluation and R-Value for Thermally Insulated Wall With Embedding Fluted Sheets”, Materials Today : Proceedings, ISSN: 1904-4720 , Volume 22, 912-919, 2020.

[5] S. Dhanabal, K. Sivakumar, C.S. Narayanan, Analysis of form tolerances in electrical discharge machining process for inconel 718 and 625, Mater. Manuf. Process. 29 (2014) 253–259. doi:10.1080/10426914.2013.852213.

[6] A. Mohan, V. Saravana Karthika, J. Ajith, Lenin dhal, M. Tholkapiyan, “Investigation on ultra high strength slurry infiltrated multiscale fibre reinforced concrete”, Materials Today : Proceedings, ISSN: 1904-4720 , Volume 22, 904-911, 2020.

[7] A. Mohanty, G. Talla, S. Gangopadhyay, Experimental Investigation and Analysis of EDM Characteristics of Inconel 825, Mater. Manuf. Process. 29 (2014) 540–549. doi:10.1080/10426914.2014.901536.

[8] A. Torres, C.J. Luis, I. Puertas, Analysis of the influence of EDM parameters on surface finish, material removal rate, and electrode wear of an INCONEL 600 alloy, Int. J. Adv. Manuf. Technol. 80 (2015) 123–140. doi:10.1007/s00170-015-6974-9.

[9] R. Gopalakrishnan, VM Sounthararajan, A. Mohan, M. Tholkapiyan, “The strength and durability of flyash and quarry dust light weight foam concrete”, Materials Today : Proceedings, ISSN: 1904-4720 , Volume 22, 1117-1124, 2020.

[10] D.R. Unune, H.S. Mali, Parametric modeling and optimization for abrasive mixed surface electro discharge diamond grinding of Inconel 718 using response surface methodology, Int. J. Adv. Manuf. Technol. 93 (2017) 3859–3872. doi:10.1007/s00170-017-0806-z.

[11] P. Kuppan, S. Narayanan, A. Rajadurai, M. Adithan, Effect of EDM parameters on hole quality characteristics in deep hole drilling of Inconel 718 superalloy, Int. J. Manuf. Res. 10 (2015) 45–63. doi:10.1504/IJMR.2015.067617.

[12] Srividhya K., Mohan A, Tholkapiyan M, Arunraj A, “Earth Quake Mitigation (EQDM) Through Engineering Design", Materials Today : Proceedings, ISSN:1904-4720 , Volume 22, 1074-1077, 2020.

[13] M.H. Abidi, A.M. Al-Ahmari, U. Umer, M.S. Rasheed, Multi-objective optimization of micro-electrical discharge machining of nickel-titanium-based shape memory alloy using MOGA-II, Meas. J. Int. Meas. Confed. 125 (2018) 336–349. doi:10.1016/j.measurement.2018.04.096.