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COMPARATIVE ANALYSIS USING ELECTRICAL DISCHARGE MACHINING TO DETERMINE THE IMPACT OF POWDER PARTICLES ON INCONEL-800

Inconel-800 is often used across different industries because of its unique properties, especially its ability to withstand very high temperatures. However, machining Inconel-800 can be quite challenging to conventional machining processes due to its distinctive properties. This paper reports the comparative evaluation of electric discharge machining and powder-mixed electrical discharge machining for machining Inconel-800 using a graphite electrode. FERROLAC 3M EDM Oil and boron carbide powder particles mixed with FERROLAC 3M EDM Oil were used as dielectric for electrical discharge machining and powder-mixed electrical discharge machining, respectively. Similar specifications of work specimens and machining combinations were used for conducting experiments by electric discharge machining and powder-mixed electrical discharge machining. Peak current 'I_P', pulse-on-time 'T_{on}', and pulse-off-time 'T_{off}' were chosen as variable parameters for conducting experiments according to Taguchi L_9 (3^3), and each experimental run was used for EDM and PMEDM for machining of Inconel-800 to perform the comparative evaluation in terms of material removal rate and tool wear rate. The research findings of this study showed that, in comparison to the electric discharge machining process, the powder-mixed electrical discharge machining process significantly increases the material removal rate and decreases the tool wear rate. The results of this study were further confirmed by confirmation tests. A scanning electron microscope and energy dispersive spectrograph were used to analyze the microstructural analysis and elemental composition of the work specimens.

Keywords: Taguchi Methodology; Microstructure; Crater & Debris

1. Introduction

In the past, the aerospace sector played a key role in the development of the high-performance superalloy Inconel-800. Novel materials possessing high strength-to-weight ratios between those of aluminum and iron were desperately needed at that time. Inconel-800's outstanding properties have made it valuable across several emerging fields, including nuclear power, biomedical, chemical, automotive, and aerospace industries. However, fabricating parts and components for these industries requires precise design and close tolerances. Machining Inconel-800 to meet acceptable tolerance limits with standard methods is difficult because of its unique properties [1]. The excellent toughness, high hardness, and poor thermal conductivity of this alloy make it extremely difficult to process with traditional machining methods. Advanced machining processes, such as electric discharge machining (EDM), are employed to overcome the challenges associated with machining Inconel 800 [2-5]. EDM is a versatile and precise machining process, but it does have several limitations such as (i) a lower material removal rate compared to traditional machining methods, (ii) frequent replacements or adjustments of tool electrodes due to tool wear, (iii) sometimes limitations on the complex features in terms of the depth-to-width ratio and the intricacy of internal features, (iv) alter the material properties and affect the performance of the finished part due to generation of heat affected zone 'HAZ', (v) often require of post machining process such as polishing to meet desired specifications of EDM machined parts, and (vi) may require specialized EDM techniques for machining of some extremely hard or highly conductive materials. The abovementioned limitations have restricted the use of EDM. In EDM, the dielectric fluid which is usually an insulating fluid plays a crucial role in the overall process and enhances the machining performance. Its main functions are (i) acting as an insulator between the electrode and the workpiece to prevent short circuits during the EDM process, (ii) acting

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as a coolant by dissipating the heat generated by the electrical discharges, (iii) flushing away the debris from machining zone and thus maintaining the machining efficiency as well as improve the surface finish, (iv) reducing tool wear by avoiding abrasion or clogging of debris on tool surface, (v) ensure safety as well as generation of controlled sparks and narrow down the risk of fire and other hazards EDM using metallic powder-mixed dielectric, known as powder-mixed EDM (PMEDM) can be employed to overcome the limitations of EDM [6-9]. PMEDM is a hybrid technique used to enhance the machining process. This method involves adding metal powder to EDM oil. By mixing the metal powder into the EDM oil, the insulating properties of the oil are reduced. As a result, the workpiece can be more effectively removed during machining, increasing the overall efficacy of the EDM process. A brief summary of past studies on EDM and PMEDM is given in the following paragraphs.

In order to improve performance metrics for machining aluminum matrix composites, Tahsin et al. [10] investigated the efficacy of abrasive powder mixed electrical discharge machining (PMEDM). Their results showed that adding powder to the dielectric greatly increases the erosion rate. Further, graphite powder was added to the EDM fluid to increase the machining rate in another study [11]. Three different types of titanium alloys were machined using three different electrode materials in another study. A combination of machine input parameters and a mixed dielectric fluid containing powdered tungsten and manganese were used to optimize the process. The results showed that the electrode material had a significant impact on the roughness of the machined surface [12-15]. The impact of different additives combined with kerosene on the surface quality of machined workpieces during EDM machining was examined by Kumar et al. [16]. Their research findings revealed that the additions of additives combined with kerosene greatly improved the material removal rate (MRR) and decreased the tool wear rate (TWR) and surface roughness. This suggests that the additives increase the machining process's overall durability and efficiency in addition to improving the surface quality [16]. Therefore, it was concluded that the additives not only improved the surface quality but also improved the overall efficiency and durability of the machining process [16]. The use of different dielectric fluids in EDM was examined in other studies [17-20]. The study's findings indicate that adding powders like silicon carbide (SiC) and aluminum (Al) to the kerosene dielectric fluid greatly enhances the surface roughness of machined parts. Compared to aluminum, it was found that a kerosene dielectric combined with silicon carbide yields a deeper material removal rate. This recommends that silicon carbide works better than other materials to improve surface quality and machining efficiency during the EDM process [17-20]. In their study, Singh and Yeh [21] compared the performance of PMEDM and EDM by evaluating the surface finish of the machined surface. They concluded that PMEDM a better surface finish can be achieved by PMEDM than EDM. Kumar et al. [22] used a thin electrode and a rotating disc electrode for machining by PMEDM. Other past work suggested adding tungsten carbide powder to the dielectric as an additive to alter the surface characteristics of machined parts; the experimental findings revealed that this method forms a tungsten carbide layer 150 µm thick on carbon steel, which has a Vickers hardness of 1600 Hv [23-26]. Electrical discharge machining with powder mix dielectric was studied by Furutani et al. [27]. It was found that adding conductive powders to the EDM dielectric minimizes its insulating abilities, which promotes a more stable machining process and increases the effectiveness of the electrical discharge. Thus, the machining results become more consistent and of higher quality when these powders are added. Some past work revealed the application of multi-objective algorithms to investigate how PMEDM process parameters impact critical performance measures. In order to determine the ideal machining combinations, the study used the NSGA-II multi-objective optimization algorithm in MATLAB and examined Pareto frontiers. To choose the optimal machining parameters based on the specified objective functions, the LINMAP method was also applied [28-31]. The aforementioned past work indicates that research on PMEDM specifically for Inconel-800 is limited. Few studies have explored the machinability of Inconel-800 when combined with boron carbide as a powder additive. While previous studies have examined the machinability of various materials and powders, this research aims to fill the gap by comparing the effects of machining Inconel-800 with and without the addition of boron carbide powder particles with FERROLAC 3M EDM Oil in terms of MRR and TWR. The goal is to evaluate how the presence or absence of the boron carbide powder additives impacts the machining process and the resulting response characteristics.

2. Materials and Methods

The experimental runs were conducted on a CNC-based EDM (Model: OSCARMAX S 645 CMAX; Manufacturer: OSCAR EDM Co. Ltd.; Origin: Taichung, Taiwan) at the Central Institute of Hand Tools, Jalandhar, Punjab, India. Figs. 1(a) and, 1(b) show the experimental setup used for experimentation. In this study, FERROLAC 3M EDM oil, supplied by OSCARMAX EDM Company, was used as a dielectric. The workpiece used in this study was Inconel-800, a high-performance superalloy known for its excellent mechanical properties and resistance to extreme environments. A rectangular plate with dimensions of 150 mm in length, 15 mm in width, and 6 mm in thickness was used as the workpiece. Figs. 1(c) and 1(d) depicted the workpiece, before and after machining, respectively. As a tool electrode, a graphite (Gr) rod with a diameter of 12 mm was utilized. Boron carbide (B4C) with a particle size ranging from between 1-10 µm was selected as the metal additive to mix with EDM oil (i.e. FERROLAC 3M). Prior to the experiments, the workpiece and the tool electrode were carefully machined and polished using different grades of emery paper to ensure uniform shape, size, and perfectly flat bottom surface. Then electrode and workpiece were cleaned with acetone. The machine setup

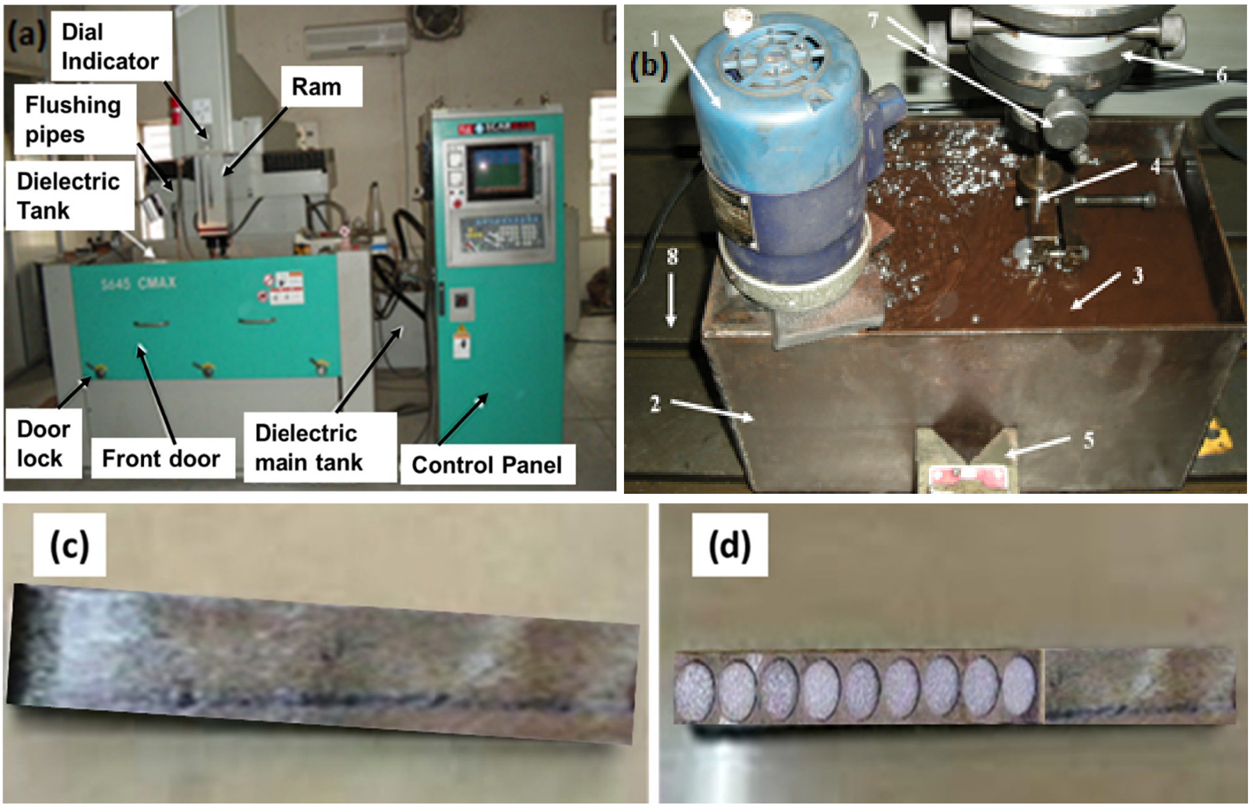

Fig. 1. EDM machine and specimen used in this study: (a) during machining by EDM; (b) pictorial view of used EDM machine; (c) specimen before machining; and (d) specimen after machining

is configured with a 350 mm × 200 mm × 200 mm tank for mixing the powder with the EDM oil. The tank had a stirring mechanism to prevent powder particles from settling, ensuring a consistent mixture throughout the machining process. Trial experiments on EDM and PMEDM were conducted using the one factor at a time (OFAT) approach to determine the levels, range, and fixed parameters based on machining time for a comparative analysis of EDM and PMEDM in terms of material removal rate '*MRR*' and tool wear rate '*TWR*'. OFAT is a systematic experimental approach where only one variable is changed at a time while keeping all other variables constant. It helps identify the influence of each specific variable on the response measures. Three EDM parameters namely peak current 'I_P', pulse-on-time 'T_{on}', and pulse-off-time 'T_{off}' were chosen as variable parameters and were varied according to Taguchi L_9 (3^3) to identify their impact on *MRR* and *TWR*. TABLE 1 shows the details of variable parameters, constant parameters, responses under consideration, and chemical composition of workpiece material (i.e.

TABLE 1

Details of experimentation

<table>
<tr><th colspan="2">Details</th><th colspan="6">Variable Process Parameters</th><th colspan="2">Others</th></tr>
<tr><th colspan="2">Symbols</th><th colspan="2">A</th><th colspan="2">B</th><th colspan="2">C</th><th colspan="2">Dielectric</th></tr>
<tr><td colspan="2">Parameters</td><td colspan="2">Pulse-on-time 'T_{on}' (µs)</td><td colspan="2">Pulse off-time 'T_{off}' (µs)</td><td colspan="2">Peak current 'Ip' (A)</td><td>Dielectric</td><td>Additives</td></tr>
<tr><td rowspan="3">Levels</td><td>1</td><td colspan="2">60</td><td colspan="2">30</td><td colspan="2">4</td><td rowspan="4">EDM oil</td><td rowspan="4">Boron carbide (B_4C)</td></tr>
<tr><td>2</td><td colspan="2">90</td><td colspan="2">45</td><td colspan="2">8</td></tr>
<tr><td>3</td><td colspan="2">120</td><td colspan="2">60</td><td colspan="2">12</td></tr>
<tr><td colspan="2">Units</td><td colspan="2">µs</td><td colspan="2">µs</td><td colspan="2">A</td></tr>
<tr><th colspan="10">Constant Parameters</th></tr>
<tr><td colspan="10">Tool electrode material: Graphite; Tool shape and size: 40 mm length, 12 mm diameter; Workpiece material: Inconel 800;
Workpiece shape: Rectangular; Polarity: Electrode: +ve, Workpiece: –ve; Flushing Method: Side jet flushing;
Flushing Pressure: 0.5 Kg/cm^2; Depth of Cut: 0.5 mm; Powder Concentration in Dielectric: 6 g/liter; Input Voltage: 40V</td></tr>
<tr><th colspan="10">Considered Responses or Performance Measures</th></tr>
<tr><td colspan="10">Material removal rate 'MRR' (mm^3/min) and Tool wear rate 'TWR' (mm^3/min)</td></tr>
<tr><th colspan="10">Chemical composition of specimen Inconel-800</th></tr>
<tr><th colspan="2">Element</th><td>Ni</td><td>Fe</td><td>Cr</td><td>C</td><td>MO</td><td>S</td><th>Si</th><th>Cu</th></tr>
<tr><th colspan="2">Weight (%)</th><td>Base</td><td>39.5</td><td>20.5</td><td><0.1</td><td>1.11</td><td><0.015</td><td><1</td><td><0.75</td></tr>
</table>

Inconel 800). Numbers 1-8 in Fig. 1(b) indicate 1 – motorized stirrer, 2 – small tank, 3 – powder mixed dielectric, 4 – electrode holder, 5 – magnetic block, 6 – lower part of ram, 7 – electrode adjusting screws, 8 – machine table (dielectric tank).

2.1. Measurements of performance measures

Material Removal Rate (MRR) in EDM is a key performance metric that measures the efficiency of the machining process. It indicates the amount of material extracted from the workpiece in a given time and measured in mm^3/min. The material removal rate (MRR) is a critical factor in determining how well an EDM process can remove material from a workpiece in order to shape and size it to the desired result. On the other hand, the rate at which material is removed from the tool electrode during machining is referred to as the tool wear rate (TWR). It is an indicator of how fast the electrical discharges cause the electrode to deteriorate. MRR and TWR are significant performance measures to evaluate the effectiveness of the EDM because they directly affect the productivity, accuracy, cost, and overall performance of the EDM process. MRR and TWR can be calculated by Eq. 1. Whereas, Eqs. 3 and 4 are used to evaluate the MRR and TWR separately in this study.

$$MRR\ or\ TWR = \frac{Volume\ of\ Material\ Removed}{Machining\ Time} \tag{1}$$

$$MRR = \frac{Weight\ of\ worpiece\ \left(befor\ machining - After\ Machining\right)}{Density\ of\ workpiece \times Machining\ Time} \tag{2}$$

$$TWR = \frac{Weight\ of\ tool\ electrode\ \left(befor\ machining - After\ Machining\right)}{Density\ of\ tol\ electrdoe \times Machining\ Time} \tag{3}$$

In this study, a precision weighing machine with an accuracy of 0.1 mg was used to measure the weight of both the workpiece and the tool electrode.

3. Result and Discussions

Taguchi L_9 orthogonal array (3^3) was used for planning machining combination to conduct the experiments accordingly to compare the performance of EDM and PMEDM for machining rectangular Inconel 800 specimens in terms of material removal rate '*MRR*' and tool wear rate '*TWR*'. Experiments were performed by varying the peak current 'I_P', pulse-on-time 'T_{on}', and pulse-off-time 'T_{off}' and keeping other parameters constant during experimentation. Each machining combination was applied to the EDM and PMEDM machining of Inconel-800 in order to compare the results in terms of *MRR* and *TWR*. The experimental matrix and related results for MRR and TWR,

TABLE 2

Experimental runs, their corresponding results, and statistical analysis of experimental results using ANOVA and S/N ratio for material removal rate

MRR (mm^3/min) for PMEDM								
Exp. No	**Parametric combinations**			**Material Removal Rate 'MRR' (mm^3/min)**				**S/N Ratio**
	A	**B**	**C**	R_1	R_2	R_3	**Avg. value**	
1	1	1	1	1.887	1.901	1.887	1.892	5.537
2	1	2	2	7.819	7.777	7.819	7.805	17.847
3	1	3	3	7.304	7.304	7.304	7.304	17.271
4	2	1	2	2.926	2.963	2.963	2.951	9.398
5	2	2	3	20.647	20.609	20.532	20.596	26.276
6	2	3	1	1.777	1.772	1.777	1.775	4.986
7	3	1	3	19.244	19.286	19.244	19.258	25.692
8	3	2	1	1.666	1.67	1.666	1.667	4.440
9	3	3	2	8.318	8.283	8.318	8.306	18.388
Mean values of MRR and S/N ratio							**7.95**	**14.42**
S = 4.55343; R^2 = 99.2%; $Adj\ R^2$ = 96.90%; Predicted R^2 = 98.61%								
MRR (mm^3/min) for EDM								
1	1	1	1	1.254	1.268	1.268	1.263	2.030
2	1	2	2	6.516	6.539	6.539	6.531	16.300
3	1	3	3	6.967	6.918	6.918	6.934	16.820
4	2	1	2	8.379	8.354	8.354	8.362	18.447
5	2	2	3	11.735	11.735	11.735	11.735	21.390
6	2	3	1	1.264	1.279	1.279	1.274	2.103
7	3	1	3	13.587	13.587	13.587	13.587	22.662
8	3	2	1	1.233	1.218	1.223	1.225	1.760
9	3	3	2	6.991	7.039	6.991	7.007	16.911
Mean values of MRR and S/N ratio							6.435	13.15
S = 4.55343; R^2 = 75.76%; $Adj\ R^2$ = 61.21%; Predicted R^2 = 24.69%								

respectively, are shown in TABLES 2 and 3. These results are based on findings from three repetitions of each combination, including the S/N ratio. ANOVA results for experimental data obtained from machining Inconel-800 specimens by EDM and PMEDM involve analyzing the significance of variable parameters and their impact on MRR and TWR. The total mean of MRR is 6.435 mm^3/min and 7.950 mm3/min for EDM and PMEDM, respectively. For MRR, the mean signal-to-noise ratio is 14.42 for PMEDM and 13.15 for EDM. For (PMEDM) MRR, the values of R^2 and R^2 adj. are 99.2% and 96.9%, respectively. Whereas, for EDM, these values are 75.76% and 61.21%. The total mean of TWR is 1.269 mm^3/min and 0.548 mm^3/min for EDM and PMEDM, respectively. Similarly, the mean of the S/N ratio is 6.437 and -0.407 for PMEDM and EDM, respectively. For TWR, the values of R^2 and R^2 adj. are 96.0% and 84.0%, respectively. Whereas, for EDM, these values are 82.9% and 31.7%. Eqs. 4-7 depict the prediction models obtained from the regression analyses for PMEDM and EDM, respectively. TABLES 2 and 3 display the values of R^2 and R^2 (adj.) for both scenarios. Average TWR values are displayed in TABLE 3 together with the S/N ratio, both with traditional and hybrid methods.

$$MRR\left(PMEDM\right) = -8.75 + 0.068T_{on} - 0.08T_{off} + 1.74I_P \quad (4)$$

$$MRR\left(EDM\right) = -6.75 + 0.055T_{on} - 0.08T_{off} + 1.74I_P \quad (5)$$

TABLES 2 and 3 show that incorporating boron carbide (B_4C) powder into the dielectric improves the average S/N ratio compared to standard EDM. This suggests that adding B_4C powder to the EDM oil increases MRR. While using a dielectric mixed with boron carbide or PMEDM significantly reduces the mean TWR, it also lowers the mean S/N ratio. Additionally, for PMEDM, both R^2 and adjusted R^2 values are higher compared to those for EDM. TABLE 4 presents the ANOVA analysis for MRR and TWR. The following conclusions were drawn from this analysis.

For MRR:

- Peak current has a significant impact on MRR compared to pulse-on time and pulse-off time.
- For EDM, the P value indicates that pulse-off time is a non-significant parameter while, all variable parameters are significant for PMEDM.
- In PMEDM, P values indicate residual errors for MRR decreased from 24.24% to 5.91% but slightly increased for TWR.
- Developed prediction models for MRR using regression equations.

For TWR:

- Peak current has a significant impact on TWR compared to pulse-on time and pulse-off time.
- P value indicates that peak current is significant only for PMEDM.
- Developed prediction models for MRR using regression equations.

TABLE 3

Experimental runs, their corresponding results, and S/N ratio for tool wear rate

Exp. No	Parametric combinations			Material Removal Rate *'TWR'* (mm^3/min)				S/N Ratio
TWR (mm^3/min) for PMEDM								
	A	B	C	R_1	R_2	R_3	Avg. value	
1	1	1	1	0.228	0.254	0.203	0.228	12.829
2	1	2	2	0.73	0.73	0.657	0.706	3.028
3	1	3	3	0.764	0.764	0.849	0.792	2.022
4	2	1	2	0.345	0.259	0.345	0.316	9.997
5	2	2	3	1.069	1.069	1.069	1.069	–0.580
6	2	3	1	0.191	0.191	0.191	0.191	14.379
7	3	1	3	0.582	0.582	0.727	0.630	4.009
8	3	2	1	0.466	0.417	0.417	0.433	7.264
9	3	3	2	0.563	0.563	0.563	0.563	4.990
Mean values of TWR and S/N ratio							**0.548**	**6.437**
S = 4.55; R^2 = 96%; $Adj\ R^2$ = 84%; Predicted R^2 = 98.61%								
TWR (mm^3/min) for EDM								
1	1	1	1	0.973	0.997	0.95	0.973	0.235
2	1	2	2	2.347	2.428	2.347	2.374	–7.510
3	1	3	3	1.877	1.791	1.877	1.848	–5.336
4	2	1	2	2.083	2.17	2.083	2.112	–6.494
5	2	2	3	1.253	1.127	1.253	1.211	–1.663
6	2	3	1	0.65	0.632	0.65	0.644	3.822
7	3	1	3	1.366	1.366	1.366	1.366	–2.709
8	3	2	1	0.246	0.246	0.246	0.246	12.181
9	3	3	2	0.922	0.09	0.922	0.645	3.813
Mean values of TWR and S/N ratio							1.269	–0.407
S = 4.55343; R^2 = 82.9%; $Adj\ R^2$ = 31.7%; Predicted R^2 = 24.69%								

TABLE 4

ANOVA analysis for material removal rate

Control Factors	DOF	Adj. SS	Adj. MS	F-value	P-value	% PC	Remarks
ANOVA analysis for MRR (EDM)							
Regression	3	323.984	107.995	5.21	0.054	75.75	x
T_{on} (μs)	1	24.933	24.933	1.2	0.323	5.83	x
T_{off} (μs)	1	7.514	7.514	0.36	0.573	1.75	x
I_P (μs)	1	291.537	291.537	14.06	0.013	68.17	**
Error	5	103.669	20.734			24.24	
Total	8	427.653					
ANOVA analysis for MRR (PMEDM)							
Regression	3	154.358	51.453	26.49	0.002	94.08	
T_{on} (μs)	1	8.377	8.377	4.31	0.092	5.1	x
T_{off} (μs)	1	10.66	10.66	5.49	0.066	6.49	x
I_P (μs)	1	135.321	135.321	69.66	0.001	82.47	***
Error	5	9.713	1.943			5.91	
Total	8	164.071					
ANOVA analysis for TWR (EDM)							
Regression	3	2.821	0.94	3.43	0.109	67.26	
T_{on} (μs)	1	1.439	1.439	5.24	0.071	34.31	x
T_{off} (μs)	1	0.287	0.287	1.05	0.353	6.84	x
I_P (μs)	1	1.094	1.094	3.98	0.102	26.08	x
Error	5	1.372	0.274			32.71	
Total	8	4.194					
ANOVA analysis for TWR (PMEDM)							
Regression	3	0.47	0.157	4.21	0.078	71.63%	
T_{on} (μs)	1	0.001	0.001	0.04	0.842	0.25%	x
T_{off} (μs)	1	0.022	0.022	0.61	0.469	3.48%	x
I_P (μs)	1	0.447	0.447	11.96	0.018	67.89%	*
Error	5	0.187	0.037			28.37%	
Total	8	0.659				100%	

TABLE 5 provides a comprehensive overview of the response values corresponding to the S/N ratio across different levels of the variable parameters under consideration. It serves to highlight how varying these factors affects the quality or performance metrics being measured. It illustrates how changes in these parameters impact the responses being evaluated. TABLE 5 also shows the specific values and rankings of the factors being examined. These rankings clarify which levels of each parameter have the foremost positive or negative impact on the measured responses. For MRR, the delta value of the peak current is higher when the powder is mixed with dielectric. In contrast, TWR shows a contrasting result under similar conditions.

3.1. Influence of variable parameters on responses

Figs. 2 and 3 depict variable parameters' influence on MRR and TWR, respectively. Figs. 2(a) and 2(b) depict the variable parameters influencing MRR for the machining of Inconel 800 by EDM and PMEDM, respectively. Similarly, Figs. 3(a)

TABLE 5

Ranking of variable parameters for MRR and TWR

Delta/Rank for MRR (EDM)				**Delta/Rank for TWR (EDM)**			
Level	T_{on}	T_{off}	I_P	**Level**	T_{on}	T_{off}	I_P
1	13.55	13.54	4.98	1	5.95	8.94	11.49
2	13.55	16.18	15.21	2	7.93	3.23	6.00
3	16.17	13.54	23.08	3	5.42	7.13	1.81
Delta	2.62	2.64	18.09	**Delta**	2.51	5.70	9.67
Rank	3	2	1	**Rank**	3	2	1
Delta/Rank for MRR (PMEDM)				**Delta/Rank for TWR (PMEDM)**			
1	11.717	14.38	1.96	1	–4.20	–2.98	5.41
2	13.98	13.15	17.21	2	–1.44	1.00	–3.39
3	13.77	11.94	20.29	3	4.42	0.76	–3.23
Delta	2.26	2.43	18.32	**Delta**	8.63	3.99	8.8
Rank	3	2	1	**Rank**	2	3	1

and 3(b) depict the influence of variable parameters on TWR after machining of Inconel 800 by EDM and PMEDM, respectively. Figs. 2 and 3 show that peak current has the most impact on MRR and TWR compared to pulse-on time and pulse-off time. MRR and TWR increase with the increase in peak current. For EDM, MRR increases with the increase in pulse-on time whereas for PMEDM, MRR increases with the increase in pulse-on time from 90 µs to 120 µs after that it becomes stable. It can be observed in Fig. 2 that higher MRR can be achieved by varying peak currents in PMEDM compared to EDM. This fact can be explained by the fact that the addition of conductive powders to the dielectric fluid (often EDM oil) improves the efficiency of material removal by modifying the properties of the dielectric fluid. By mixing conductive powders into the EDM oil, the insulating properties of the oil are modified, allowing stronger and more frequent electrical discharges between electrode gaps. As the peak current is increased, these discharges become more powerful, leading to a greater rate of material removal as well as tool wear rate. High discharge energy leads to higher melting temperatures, which in turn causes increased evaporation and generates more impulsive forces acting on the machine surface. This results in a higher MRR [30,31]. Thus, MRR increases in direct proportion to the increase in discharge energy due to higher peak currents. It was found that A3B1C3 is the optimal parametric combination for achieving the highest MRR when using conductive powder additives. Fig. 3 shows that in EDM, peak current has a more pronounced effect on Tool Wear Rate (TWR) compared to PMEDM. In EDM, TWR increases continuously as the current rises from 4 amps to 12 amps. However, in PMEDM, TWR initially increases from 4 amps to 8 amps but then decreases as the current increases from 8 amps to 12 amps.

Figs. 4 and 5 depict the graphs of the normal percentage probability plot of residuals drawn for MRR and TWR, respectively. A strong correlation between experimental results and predicted values is indicated by these graphs, which show a small difference between observed and fitted values. Moreover, the normal probability plot confirms that the response is influenced by the input parameters and that the data follow a normal distribution. Conversely, the residuals versus fitted values plot indicates a nonlinear relationship, implying that the model might not fully account for the data's inherent complexity. The residual graphs of MRR for PMEDM and EDM are shown in Figs. 4(a) and 4(b), respectively. Whereas, the residual graphs of TWR for PMEDM and EDM, are shown in Figs. 5(a) and 5(b), respectively. Figs. 4(a) and 5 (a) revealed that most residuals are normally distributed, as they cluster around a straight line. In contrast, Figs. 4(b) and 5(b) indicate that 5 to 10% of the data do not align with the mean line. In PMEDM, the histogram plot of residuals shows a regular distribution. However, in EDM, a missing bar indicates that the residuals are not normally distributed. A similar pattern is observed in Fig. 5 for TWR.

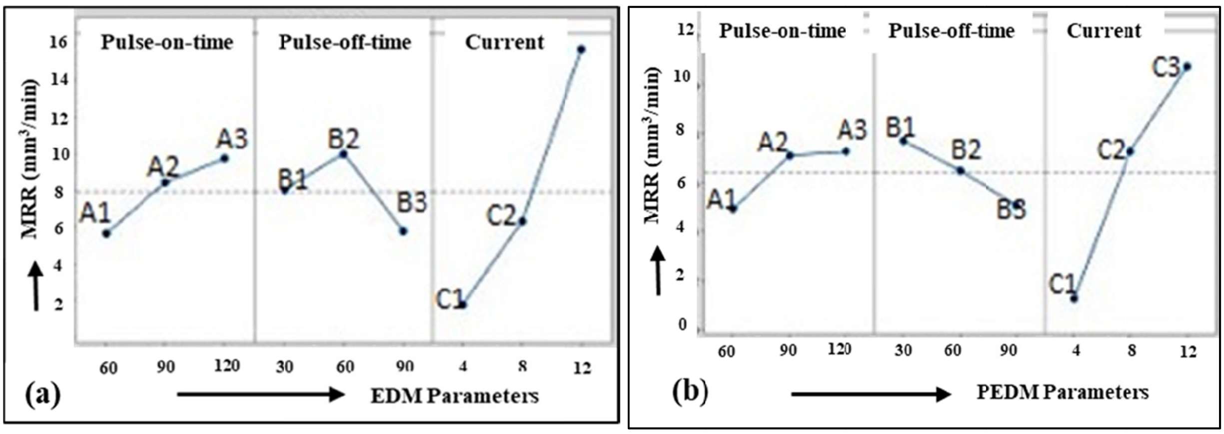

Fig. 2. Influence of variable parameters on MRR: (a) for EDM; and (b) PMEDM

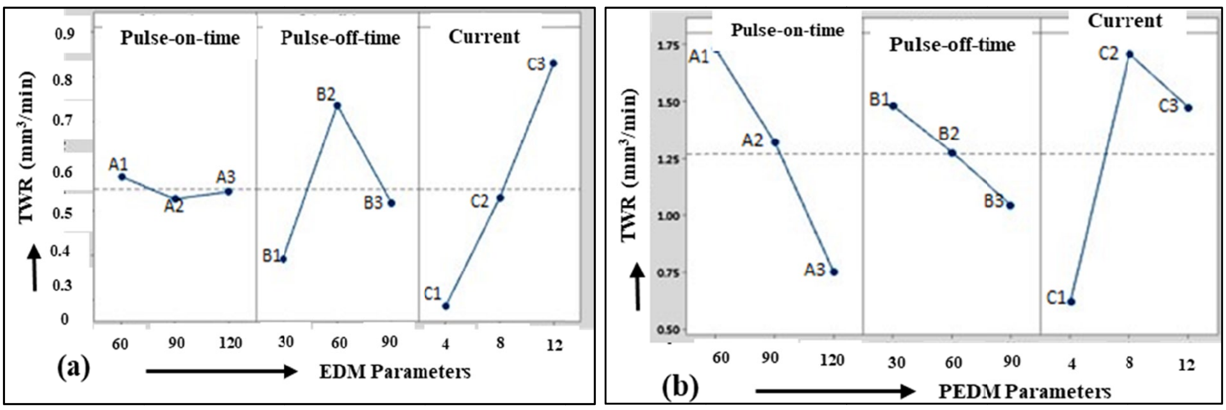

Fig. 3. Influence of variable parameters on TWR: (a) for EDM; and (b) PMEDM

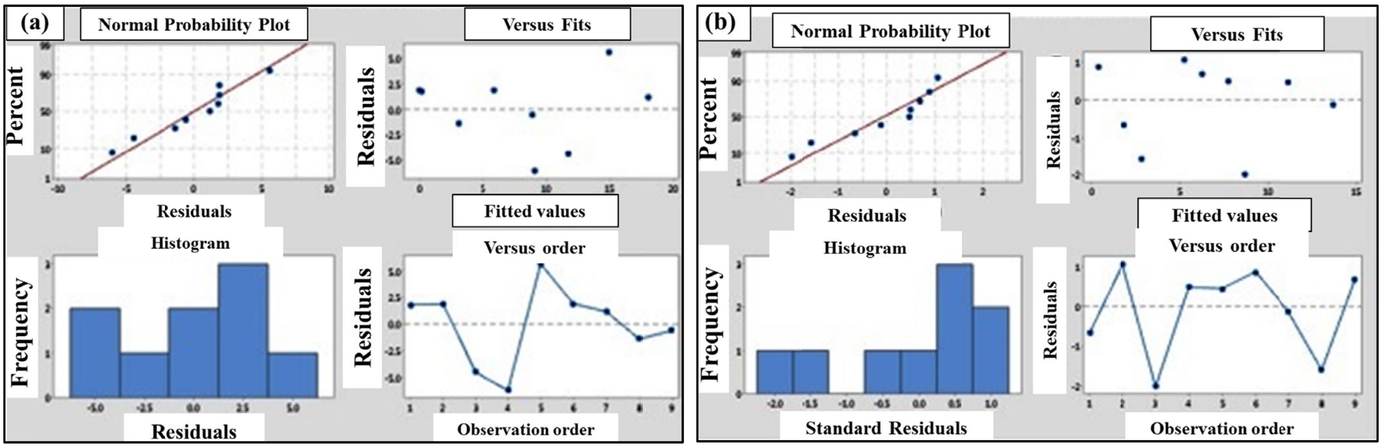

Fig. 4. Normal probability graphs for MRR: (a) for PMEDM; and (b) EDM

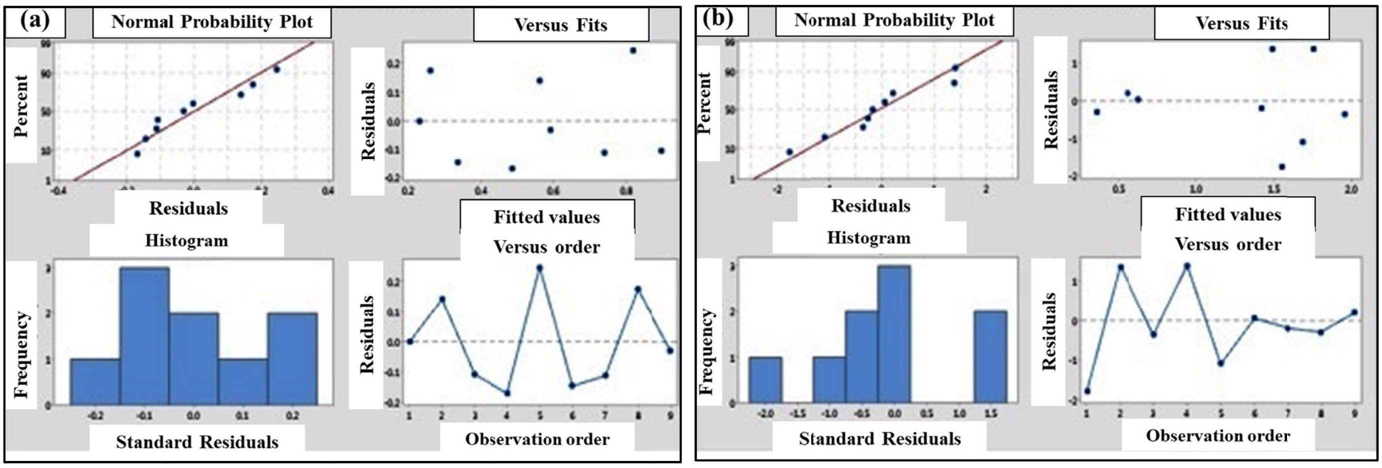

Fig. 5. Normal probability graphs for TWR: (a) for PMEDM; and (b) EDM

Figs. 6 and 7 show the comparison of material removal rate (Fig. 6) and tool wear rate (Fig. 7) variations across experimental runs for EDM and powder-mixed EDM (PMEDM).

3.2. Microstructure and EDX Examinations

A scanning electron microscope 'SEM' (JEOL, JSM-6610LV, JAPAN) was used for microstructure and EDX analysis of the machined specimen, Fig. 1(d). SEM analysis was done at 500× magnification. Figs. 8 and 9 depict the microstructures of the Inconel 800 specimens machined at different parametric combinations: (i) T_{on}: 60 µs, T_{off}: 30 µs, I_P: 4 A; (ii) T_{on}: 90 µs, T_{off}: 30 µs, I_P: 8 A; (iii) T_{on}: 120 µs, T_{off}: 30 µs, I_P: 12 A; and (iv) T_{on}: 120 µs, T_{off}: 60 µs, I_P: 8 A. Fig. 8 shows the SEM micrograph of the Inconel 800 specimen machined by powder-mixed EDM i.e. PMEDM. Whereas, Fig. 9 shows the SEM micrograph of the Inconel 800 specimen machined by conventional EDM.

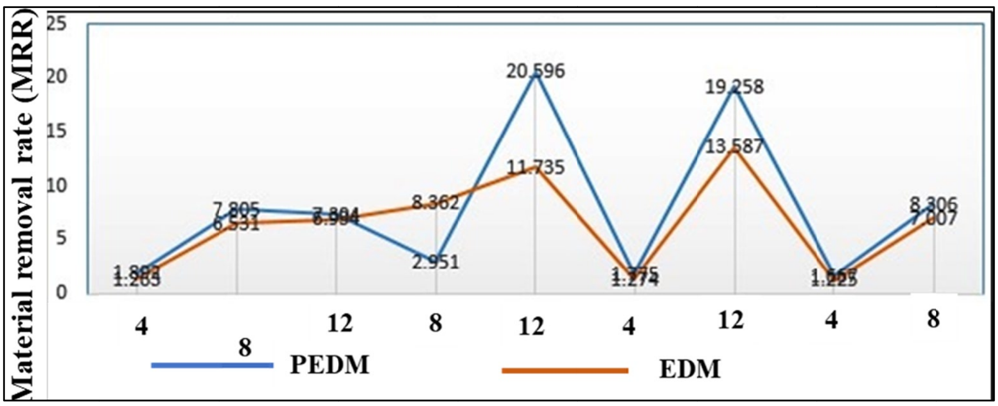

Fig. 6. Comparison of MRR variation across experimental runs for EDM and PMEDM

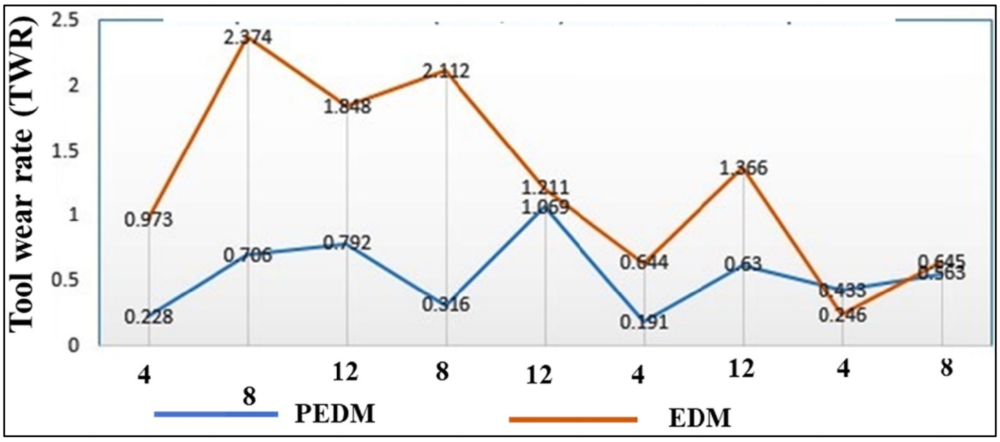

Fig. 7. Comparison of TWR variation across experimental runs for EDM and PMEDM

Graphite electrode was used for machining all specimens. Fig. 8 illustrates the formation of fragments, craters, and debris on the machined specimen by PMEDM. Whereas, Fig. 8 shows the formation of longer cracks, deep and irregular craters, and the formation of removed particles on the machined specimen by EDM. From Figs. 8 and 9, it can be concluded that: (i) EDM machining produces deeper and more irregular craters than PMEDM; (ii) surfaces machined by EDM exhibit a higher accumulation of removed particles compared to those machined by PMEDM; and (iii) longer cracks form on surfaces treated with EDM rather than those processed with PMEDM.

EDX is used to determine the elemental composition of the material. Despite the continuous flow of dielectric fluid carried, some removed particles deposited on the surface of the specimen. EDX analysis reveals the quantity and percentage of these residual foreign particles. Figs. 10(a) and (b) display the EDX analysis results for specimens machined using the same parameters (i.e., T_{on}: 120 µs, T_{off}: 60 µs, I_P: 12 A) with EDM and PMEDM, respectively. The elemental compositions (by weight percentage) of the specimens are as follows: (i) EDM: C: 11.06%, O: 3.51%, Cr: 13.61%, Fe: 8.92%, Ni: 62.36%; and (ii) PMEDM: C: 11.06%-13.67%, O: 3.51%-2.8%, Cr: 13.61%-14.11%, Fe: 8.92%-8.24%, Ni: 62.36%-59.79%, Cu: 0.6%, WC: 0.8%. Copper and tungsten carbide were detected in the specimen machined using PMEDM. This presence could be attributed to the melting and subsequent solidification of the tool material, as well as the dispersion of powder particles within the EDM oil.

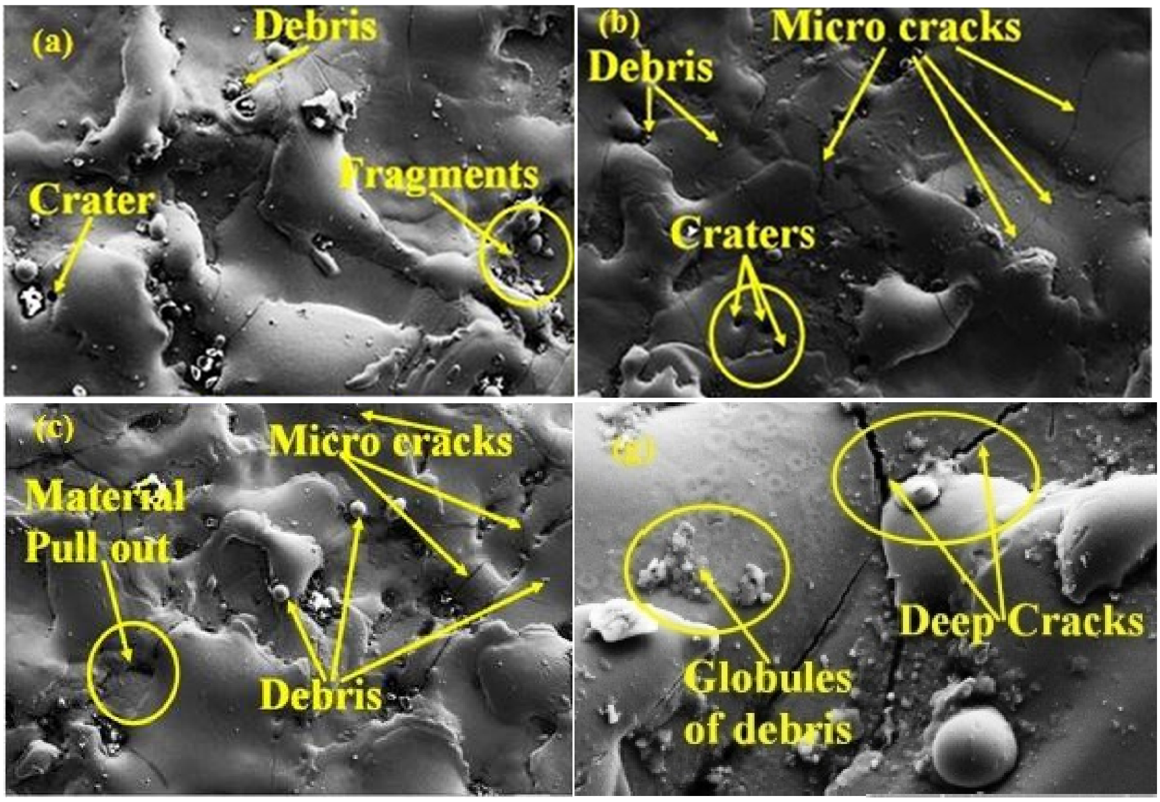

Fig. 8. SEM graphs of Inconel 800 specimen machined by PMEDM

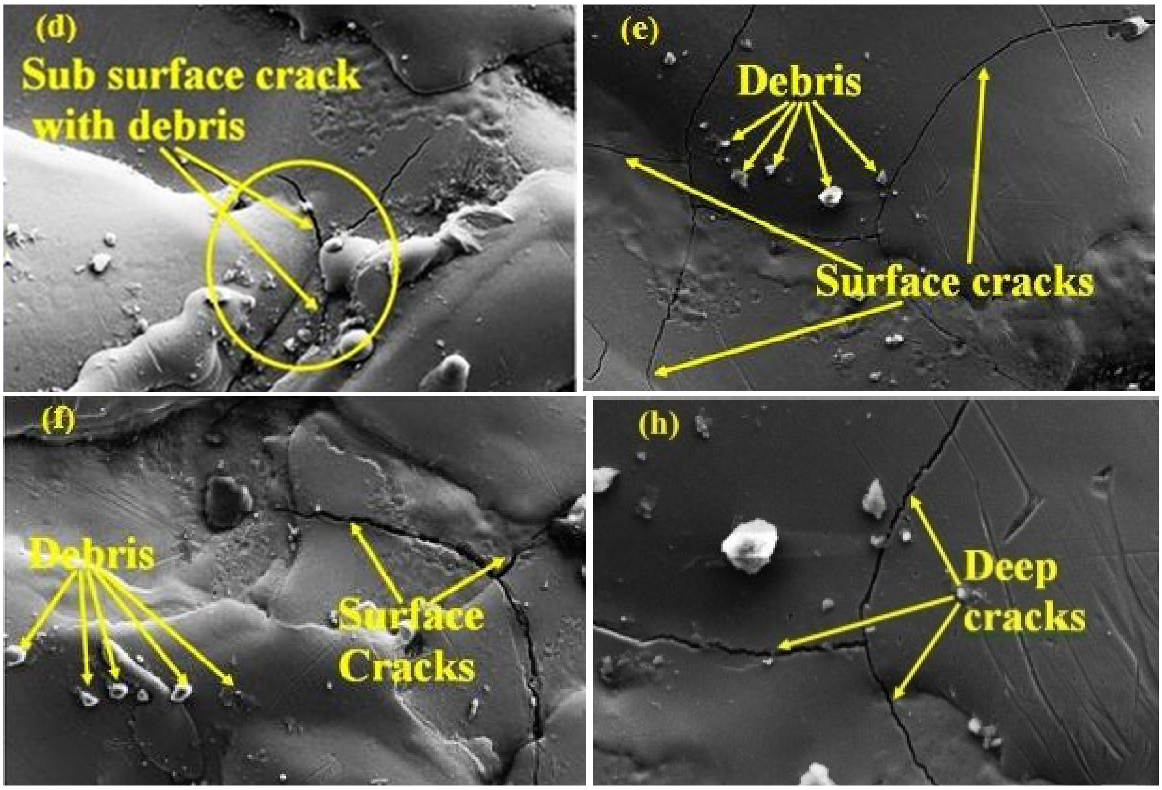

Fig. 9. SEM graphs of Inconel 800 specimen machined by EDM

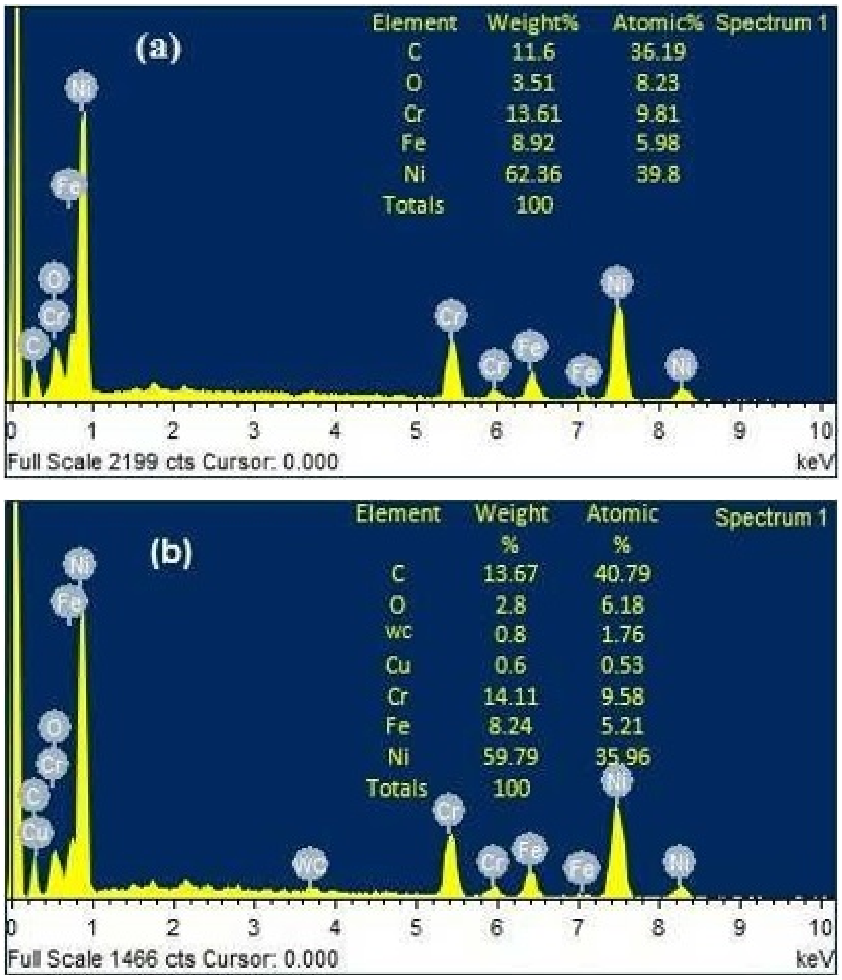

Fig. 10. EDX analysis of specimen machined by EDM and PMEDM using identical paraments: (a) EDM: and (b) PMEDM

4. Conclusion

The primary goal of this research is to enhance the machinability of Inconel-800 and perform a comparative evaluation between EDM and PMEDM. The results of this study indicate that the peak current and powder concentration are the two main factors influencing MRR. An increase in peak current and the addition of conducting powder in EDM oil leads to a higher MRR. It was observed that a powder concentration of 6 g/l in the EDM oil improved the MRR from 6.44 mm^3/min to 7.95 mm^3/min, representing an approximate increase of 19.05% compared to EDM oil. This demonstrates that adding powder to the dielectric fluid enhances machining efficiency. For tool wear rate (TWR), it was observed that electrode erosion increased during machining by conventional EDM. However, in powder-mixed EDM (PMEDM) using EDM oil with a conducting powder concentration of 6 g/l, TWR decreased from 1.269 to 0.548 mm^3/min, resulting in a 56.81% reduction in TWR. Additionally, peak current was found to be the most significant factor affecting TWR, followed by pulse on time (T_{on}) and pulse off time (T_{off}). In conclusion, the comparative analysis revealed that powder-mixed EDM (PMEDM) is superior to conventional EDM in terms of productivity and tool durability. This indicates that PMEDM not only improves machining efficiency but also substantially decreases electrode wear, making it a more effective and long-lasting technique compared to conventional EDM.

Author Contributions

Experimentation, Methodology, S. K.; Conceptualization, S.K., H. S. and S.K.C.; Data Curation, S.K. and S.K.C.; Software and Formal Analysis, S.K.; Writing – First Draft, S.K. and S.K.C.; Writing – review and editing, S.K.C.; Validation, S.K.; Editing and Supervision, S.K.C. and S. J. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

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