OPTIMIZATION OF ELECTRO DISCHARGE DRILLING PARAMETERS FOR MICRO HOLE MACHINING IN SUPERNI 276 USING COPPER AND BRASS TOOLS

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ABSTRACT

SuperNi 276 is commonly used in turbine applications, but its hardness makes creating micro holes for internal cooling difficult with traditional machining methods. In this study, Electro Discharge Drilling (EDD) was used to drill micro holes with diameters of 0.5mm, 0.6mm, 0.7mm, and 0.8mm, employing copper and brass tubular tools. Input parameters included peak current, pulse on time, pulse off time, and tool diameter, while voltage was kept constant. An L16 orthogonal array was applied to design experiments and determine the optimal input settings. The objectives were to maximize the material removal rate (MRR), minimize the tool wear rate (TWR), and ensure that the microhardness in the recast layer zone and heat-affected zone (HAZ) remains close to that of the base material. The experiments showed that copper tools achieved the highest MRR (0.115938 mm^3/sec), while brass tools had the lowest TWR (0.0026 mm/sec) and provided microhardness in the recast layer and HAZ are closer to base material. The results indicate that the choice of tool material and input parameters significantly affects tool life and thermal damage to the material, making these factors crucial for achieving optimal machining performance.

Keywords:
Electro Discharge Drilling (EDD), Heat-Affected Zone (HAZ), Material Removal Rate (MRR), Recast Layer, SuperNi 276, Tool Wear Rate (TWR)

I. Introduction

SuperNi 276 is a modern alloy with excellent mechanical properties, making it ideal for turbine blade applications. Micro holes are essential on turbine blades for internal cooling, which protects them from thermal damage caused by high steam temperatures. Creating these micro holes in SuperNi 276 is challenging with conventional machining methods. EDD is an effective technique for precisely machining micro holes in hard materials like SuperNi 276. Copper and brass tubular tools are commonly used for this purpose. During the drilling process, input parameters such as peak current, pulse on time, pulse off time, voltage, dielectric medium, tool speed, feed rate, and tool diameter are considered. Experimental studies have shown that parameters like peak current, pulse on time, pulse off time, and tool diameter have a more significant effect on hole quality compared to voltage, dielectric medium, tool speed, and feed rate.

Microhole drilling is a critical manufacturing process, with extensive research focused on improving precision, efficiency, and surface integrity. Chenxiang Zhang et al. [1] demonstrated the effectiveness of electrochemical discharge drilling (ECDD) in nickel-based superalloys, highlighting the influence of working fluid conductivity on residual stress and surface quality. Similarly, Neeraj Sharma et al. [2] optimized EDD parameters using advanced methodologies, achieving minimal errors in drilling rate and tool wear. Innovations in electrode designs have further advanced the field; Ravinder Kumar et al. [3] showed that a single-notch tungsten carbide electrode enhanced material removal rates and surface quality, while Siqian Gong et al. [4] demonstrated the benefits of helical microelectrodes in nickel-based alloys. Hybrid approaches, such as the electromagnetic field-assisted micro-EDM by Mukhopadhyay et al. [5], improved circularity and reduced tool wear, underscoring the potential of combined techniques. Post-machining enhancements like abrasive water flow polishing (AWFP) by Zhuang Liu et al. [6] effectively removed recast layers and reduced surface roughness, showcasing solutions for achieving superior hole quality.

Material-specific adaptations and optimization techniques further highlight the versatility of microhole drilling processes. Rahul Davis et al. [7] compared standard EDD with powder-mixed EDD (PM-EDD) in machining Inconel 718, finding that abrasive powders significantly improved material removal rates and surface finish. For composite materials, Abhishek Sharma et al. [8] used optimization algorithms to minimize defects during EDD of Al/SiC composites. Optimization of key parameters has also led to significant improvements in dimensional accuracy, as demonstrated by Ranjan Kumar et al. [9] and Ravinder Kumar et al. [10] for Ti6Al4V. Lastly, P. Kuppan et al. [11] highlighted the trade-offs in electrode performance for deep hole drilling of Inconel 718, identifying copper-tungsten and graphite electrodes as optimal for wear resistance and surface finish. These studies collectively demonstrate advancements in process design, parameter optimization, and post-treatment methods, addressing challenges in microhole fabrication across diverse materials and applications.

Recent advancements in EDD have focused on optimizing process parameters to enhance precision and machining efficiency for a wide range of materials. M. Machno et al. [12] developed a mathematical model to predict the influence of discharge voltage, current amplitude, and pulse duration on machining outcomes, including tool wear and material removal rates. Alemu Workie Kebede et al. [13] optimized μ-EDD for titanium alloys using a multi-objective genetic algorithm, revealing the impact of capacitance and voltage on surface quality and burr formation. Additionally, Varish Ansari et al. [14] employed Taguchi methods to improve drilling speed and taper angle in magnesium-based nanocomposites. Kamal Kumar et al. [15] applied Taguchi's design along with Grey relational analysis to optimize drilling rate and electrode wear in die steel. Meanwhile, Ravinder Kumar et al. [16] analyzed the effects of voltage, feed rate, and tool speed in copper, revealing optimal conditions for material removal and wear minimization. Studies such as those by Trung-Thanh Nguyen et al. [17] and M. Risto et al. [18] further explored process optimizations, demonstrating improvements in specific drilling energy, hole taper, and geometrical accuracy. Innovative approaches have also been explored to improve hole quality and machining performance. For instance, M. Risto et al. [18] identified the trade-offs between productivity and accuracy by adjusting discharge energy for borehole diameter control. Murat Sarıkaya et al. [19] optimized discharge current and dielectric pressure for deep hole drilling in AISI 304 stainless steel, showing the effectiveness of response surface methodology and artificial neural networks in predicting machining outcomes. Selva Babu Balasanmuganathan et al. [20] investigated electrochemical micromachining (ECMM) for superalloys, achieving significant improvements in material removal rate and surface quality. Vibration-assisted EDD, as explored by Gaurav Kumar Pandey et al. [108] and Krupa Serah Jacob et al. [21], demonstrated enhanced drilling efficiency and reduced recast layer formation for titanium and aluminum composites. Environmental sustainability was also addressed by Tasnim Arif et al. [22], who optimized EDD parameters using deionized water for Inconel-718, resulting in improved material removal rates and reduced hole taper. These studies highlight the continuing evolution of micro-drilling technologies, emphasizing the importance of parameter optimization and hybrid methods to address complex challenges in advanced material processing.

The effectiveness of EDD depends significantly on the selection of process parameters, which directly influence the MRR, TWR, recast layer thickness, HAZ, and microhardness. However, choosing the right combination of parameters remains a challenge. This study applies the Taguchi method to systematically explore the impact of key EDD parameters—tool diameter, peak current, pulse on time, and pulse off time—using copper and brass tube tools. The goal is to identify the optimal conditions for achieving high-quality micro-holes with minimal tool wear and acceptable surface characteristics, thereby advancing the use of EDD in machining high-performance alloys like Super Ni 276.

II. Methodology

2.1. Material selection

2.1.1. SuperNi 276

SuperNi 276, supplied by MIDHANI Ltd., Hyderabad, is employed for steam turbine blade manufacturing in power generation. The primary elements and their weight percentages are listed in Table 1.

Table 1 Composition of SuperNi 276.

Major constituent element	Weight (%)
Nickel (Ni)	58.2
Chromium (Cr)	16.2
Molybdenum (Mo)	16.1
Tungsten (W)	3.1
Iron (Fe)	4.2

2.1.2. EDD machine and tool material

The EDD machining experiments are conducted at Sri Sai Vinayaka CNC Technologies (DK703C, Jiangsu, China), Balanagar, Hyderabad, using distilled water as the dielectric medium. Copper and brass tubular tools with diameters of 0.5mm, 0.6mm, 0.7mm, and 0.8mm are used for machining Super Ni 276. The machining process is performed as per ASTM B643 standards.

2.2. Control parameters

The control parameters for EDD experimentation include peak current (I), pulse on time (Ton), pulse off time (Toff), and tool diameter (D), while voltage is kept constant at 2V. These factors are pivotal in determining drilling performance and output quality. The selected parameter ranges are as follows: tool diameter (0.5 mm to 0.8 mm), pulse on time (10 µs to 40 µs), pulse off time (2 µs to 5 µs), and peak current (2 A to 5 A).

While machining the output parameters such as MRR and TWR are estimated. After machining recast layer thickness, HAZ (Olympus BX53M - Evident Corporation, Japan), and microhardness (Vickers micro hardness test - Mitutoyo HM-200, Japan) in recast layer zone and HAZ are analysed to understand the impact of the machining process on the material's mechanical integrity and long-term performance. Analysis of these parameters also allows for the optimization of EDD parameters to minimize negative effects, ensuring that the drilled holes maintain the required precision and functionality without compromising the material's structural properties.

III. Experimental investigation

3.1. Estimation of MRR and TWR

To study the impact of control parameters on output parameters, 256 experiments would be required. To optimize this number, the four-factorial Taguchi method is applied. Consequently, an L16 orthogonal array is used in this work. The levels and values for Taguchi's L16 orthogonal array are presented in Table 2. MRR and TWR are estimated based on design of experiments for both copper and brass tools.

Table 2 Taguchi's L16 orthogonal array with values of levels

Experiment No.	Tool diameter (mm)	Pulse on time (µs)	Pulse off time (µs)	Current (A)
1	0.5	10	2	2
2	0.5	20	3	3
3	0.5	30	4	4

4	0.5	40	5	5
5	0.6	10	3	4
6	0.6	20	2	5
7	0.6	30	5	2
8	0.6	40	4	3
9	0.7	10	4	5
10	0.7	20	5	4
11	0.7	30	2	3
12	0.7	40	3	2
13	0.8	10	5	3
14	0.8	20	4	2
15	0.8	30	3	5
16	0.8	40	2	4

3.2 Recast layer and Heat affected zone

HAZ includes the recast layer, which is a thin, brittle layer of resolidified material, and the underlying area that has undergone thermal cycling, leading to microstructural changes such as grain growth or phase transformations. The use of copper electrodes, and brass electrodes can significantly impact the characteristics of the HAZ. Microscopic analysis is a common method used to measure the recast layer thickness and HAZ. Understanding the extent of the HAZ, surface integrity, and potential residual stresses is essential for ensuring the quality and performance of the machined workpiece, optimizing process parameters, and selecting the appropriate tool material for desired outcomes.

3.3. Evaluation of microhardness

Microhardness refers to the measurement of a material's hardness on a small scale, typically using minimal loads to create an indentation on the material's surface. After EDD, microhardness tests are conducted on the base material, recast layer zone, and HAZ to evaluate changes in hardness resulting from micro-drilling.

Understanding the extent of the recast layer thickness, HAZ, and microhardness is essential for ensuring the quality and performance of the machined workpiece, optimizing process parameters, and selecting the appropriate tool material for desired outcomes.

IV. Results and discussions

4.1. MRR and TWR

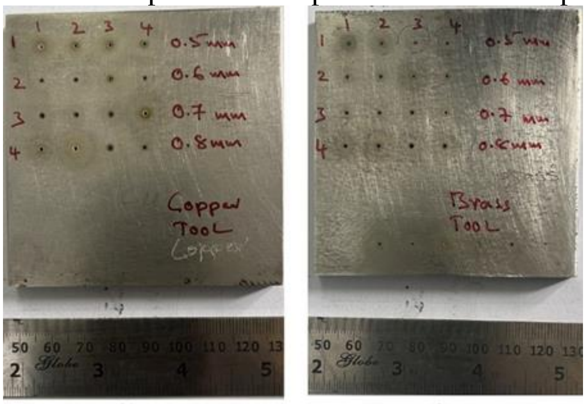
Figure 1 shows the specimens after EDD with copper and brass tools. Analyzing the experimental data from Table 3, which details the process parameters for micro-hole machining using copper and brass tools on EDD, the focus is on maximizing MRR while minimizing TWR. The MRR and TWR are estimated using equations (1) and (2):

$$\text{TWR}=\frac{\text{Initial length of the tool-Final length of the tool}}{\text{Time taken for machining}} \qquad (1)$$

$$\text{MRR}=\frac{\text{Volume of the material removed}}{\text{Time taken for machining}} \qquad (2)$$

For the copper tool, the lowest recorded TWR is 0.0171 mm/sec in Experiment No. 1, while the maximum MRR is 0.115938 mm^3/sec in Experiment No. 16. On the other hand, the brass tool shows an even lower minimum TWR of 0.0026 mm/sec in Experiment No. 14, demonstrating its advantage in minimizing tool wear. The highest MRR for the brass tool is 0.065940 mm^3/sec, found in Experiment No. 11, which, while not as high as the maximum MRR for copper, is still considerable.

Considering these factors, the brass tool emerges as the better option for applications prioritizing tool longevity due to its significantly lower TWR. Although the copper tool achieves a higher maximum MRR, the brass tool maintains a good balance with a moderate MRR and minimal tool wear. Therefore, for applications that require both durability and efficient material removal, the brass tool is recommended due to its superior TWR performance while providing a sufficient MRR.



(a) (b)

Fig. 1. Specimen after EDD with (a) copper tool and (b) brass tool.

Table 3 MRR and TWR of SuperNi 276 for copper and brass tools

Experiment No.	Copper tool		Brass tool	
	TWR (mm/sec)	MRR (mm3/sec)	TWR (mm/sec)	MRR (mm3/sec)
1	0.0171	0.002872	0.0478	0.005120
2	0.0562	0.006615	0.1386	0.011658
3	0.1132	0.007406	0.1548	0.014018
4	0.1333	0.008722	0.1940	0.017575
5	0.3438	0.052988	0.3529	0.049871
6	0.7391	0.073722	0.1111	0.015700
7	0.1585	0.020678	0.0303	0.006423
8	0.5000	0.070650	0.2692	0.032608
9	0.3333	0.054950	0.1558	0.029973
10	0.3333	0.059177	0.3415	0.056290
11	0.2750	0.057698	0.4286	0.065940
12	0.0359	0.010349	0.0680	0.015700
13	0.0750	0.025120	0.0625	0.018840
14	0.0367	0.010048	0.0026	0.007709
15	0.4516	0.097239	0.0870	0.032765
16	0.5000	0.115938	0.1078	0.029553

4.2 Analysis of Recast layer thickness and HAZ

4.2.1 Analysis of Recast layer thickness

A recast layer forms during EDD as a result of intense heat from electrical discharges, which melts and vaporizes parts of the workpiece material. This molten material may resolidify on the drilled surface, influenced by factors such as discharge energy, pulse duration, dielectric fluid type, and electrode material. The recast layer can affect surface quality, introduce residual stresses, and alter mechanical properties, often requiring post-processing to address. Accurate measurement of the recast layer thickness, typically using microscopic analysis, is essential to evaluate machining quality and ensure desired results. For this study, the Olympus BX53M microscope is employed to analyze the recast layer formed during the drilling of Super Ni 276. The experimental results for the copper tool and brass tool are summarized in Table 4.

Table 4: Maximum and minimum thickness of recast layer for copper and brass tool

Experiment No.	**Copper tool**			**Brass tool**		
	Minimum	**Maximum**	**Average**	**Minimum**	**Maximum**	**Average**
1	4.01	8.77	6.39	13.45	24.19	18.82
2	24.27	35.85	30.06	19.15	48.08	33.61
3	12.42	31.45	21.93	15.12	31.71	23.41
4	8.08	24.99	16.53	19.67	32.71	26.19
5	17.42	19.83	18.62	33.86	38.23	36.04
6	16.16	22.76	19.46	67.55	68.76	68.15
7	4.53	12.01	8.27	7.29	22.45	14.87
8	32.88	44.20	38.54	12.67	15.97	14.32
9	14.41	15.79	15.10	59.01	73.34	66.17
10	28.27	39.14	33.70	13.63	30	21.81
11	6.39	15.04	10.71	23.05	23.07	23.06
12	18.94	28.03	23.48	31.45	32.31	31.88
13	12.82	24.52	18.67	159.28	186.71	172.99
14	22.04	24.77	23.40	46.13	49.64	47.88
15	20.69	26.46	23.57	35.46	49.99	42.72
16	19.62	23.36	21.49	108.15	127.59	117.87

4.2. Analysis of HAZ

In EDD, the Heat Affected Zone (HAZ) is crucial due to high temperatures, impacting surface integrity, recast layer formation, and microstructural changes. Copper and brass tools influence HAZ characteristics, making it essential to optimize parameters and tool material for quality outcomes, as shown in table 5.

Experiment. No.	**HAZ of Copper tool (mm)**	**HAZ of Brass tool (mm)**
1	68.67	79
2	103.38	134.15
3	92.55	110.4
4	108.14	116.26
5	143.31	89.23
6	111.02	91.61
7	121.64	147.96
8	104.31	160.21
9	164.63	134.86
10	119.76	134.89
11	99.56	180.98
12	81.96	129.53
13	130.86	172.24
14	65.03	132.15
15	42.86	121.85
16	43.64	151.96

Table 5: HAZ in SuperNi 276 with Copper and Brass tools

4.3. Analysis of microhardness

Microhardness testing of the base material, HAZ, and recast layer zone was performed using a Vickers microhardness tester. Table 6 summarizes the measured microhardness values for SuperNi 276, processed with a copper tool under varying control parameters during EDD.

Table 6 Microhardness at base material, HAZ, recast layer zone of copper tool and brass tool

Experiment No.	Copper tool			Brass tool		
	Base material	Recast layer zone	HAZ	Base material	Recast layer zone	HAZ
1	343.2	347.4	319.6	347.2	334.6	320.6
2	351.9	345.9	324.6	345.9	340.1	323.5
3	348.6	354.3	317.3	350.6	341.7	311.6
4	341.8	347.6	326.4	342.6	334.3	317.7
5	345.3	368.1	325.2	342.4	350.6	338.4
6	351.1	342.6	316.4	348.2	352.6	315.9
7	344.3	341.6	326.2	346.6	345.2	329.2
8	348.6	335.3	331.6	342.8	356.6	326.6
9	341.9	328.8	316.5	348.1	344.8	317.9
10	346.1	334.3	324.1	342.6	348.1	324.1
11	341.4	327.6	319.6	349.4	356.4	336.6
12	343.2	335.1	314.4	343.8	345.1	321.3
13	344.2	327.6	307.1	346.4	355.9	314.1
14	344.8	338.3	313.8	349.1	357.6	329.8
15	345.6	326.9	314.6	342.5	338.2	317.7
16	337.6	345.1	324.2	343.8	334.7	326.9

4.3.1 Base material

The microhardness of the base material remains relatively consistent across all experiments, regardless of the tool used. For the copper tool, values range between 337.6 HV and 351.9 HV, while for the brass tool, they lie between 342.4 HV and 349.4 HV. These stable values indicate that the base material experiences minimal thermal or mechanical alterations during the EDD process. The localized nature of EDD ensures that the heat and material removal are confined to the machined area, preserving the inherent hardness of the base material.

4.3.2 Recast layer zone

The recast layer exhibits the highest hardness among the tested zones, with values ranging from 327.6 HV to 368.1 HV for the copper tool and 334.3 HV to 357.6 HV for the brass tool. This increased hardness is primarily due to the rapid solidification of molten material during the EDD process. The thermal cycling and rapid quenching of this layer lead to the formation of a hard, brittle structure, often characterized by refined microstructures and potential alloying effects from the tool material. Notably, the brass tool typically results in slightly higher hardness in the recast layer compared to the copper tool. This is attributed to the higher thermal conductivity of brass, which facilitates faster heat dissipation, promoting a finer microstructure in the solidified layer.

4.3.3 Heat-Affected Zone (HAZ)

The microhardness in the HAZ is generally lower than in the recast layer and comparable to or slightly lower than the base material. For the copper tool, HAZ hardness values range from 307.1 HV to 331.6 HV, while for the brass tool, they fall between 314.1 HV and 336.6 HV. This decrease in hardness is due to thermal softening caused by prolonged exposure to elevated temperatures without material melting. The microstructure in the HAZ may undergo recovery or slight coarsening, leading to reduced hardness. However, the brass tool shows slightly higher hardness in HAZ compared to the copper tool, likely because its better heat dissipation minimizes the extent of thermal softening.

Across all zones, the brass tool generally results in higher hardness values compared to the copper tool, particularly in the recast layer and HAZ. This can be attributed to the superior thermal conductivity of brass, which allows for more effective heat management during EDD. As a result, the extent of thermal damage in the HAZ is reduced, and the recast layer benefits from refined microstructural transformations. These findings emphasize the critical role of tool material in influencing the microhardness distribution across different zones.

V. Conclusions

This study compares the performance of brass and copper tools in EDD, focusing on TWR, MRR, recast layer thickness, HAZ, and microhardness distribution. Brass tools excel in durability with significantly lower TWR and offer balanced performance with moderate MRR and minimal wear, making them ideal for applications prioritizing tool life and efficiency. Copper tools, however, are superior in minimizing recast layer thickness, especially under specific operational settings, making them preferable for applications where thin recast layers and reduced thermal damage are critical. Brass tools produce larger HAZ and higher hardness across zones due to their superior thermal conductivity, which enhances microstructural refinement but also increases thermal influence on the workpiece. The choice between brass and copper tools depends on application requirements. Brass tools are recommended for longevity and balanced performance, while copper tools are ideal for minimizing recast layers and thermal damage. These findings emphasize the importance of selecting appropriate tool materials to optimize EDD performance.

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