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ADVANCING MICRO DRILLING PRECISION WITH INNOVATIVE ELECTRODE MATERIALS AND PROCESS OPTIMIZATION IN EDM

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Abstract

Micro drilling using Electrical Discharge Machining (MD-EDM) has gained prominence in precision manufacturing, providing the capability to create small and intricate holes. This study investigates the effects of input process parameters on a nickel-based superalloy ($Ni3(Ti, Al)$), utilizing copper, aluminum, and tungsten electrodes with varying diameters of 0.4 mm, 0.5 mm, and 0.6 mm. The research employs an L9-orthogonal array (L9-OA), varying Machining Voltage, Peak Current (IP), Pulse off time (P_off), and Servo Standard Voltage (SVR). Three levels of Machining Voltage (4 volts, 6 volts, and 8 volts) and IP are selected. Micro drilling experiments are conducted using an EDM setup, and the resulting holes are evaluated for surface roughness (SR) using profilometry. The analysis of variance (ANOVA) and Taguchi method are applied to assess the significance of the input process parameters in MD-EDM. The experimental results indicate that electrode material and diameter significantly affect the SR of the drilled holes. Copper electrodes exhibit the lowest SR, followed by tungsten and aluminum electrodes. Smaller electrode diameters lead to a better surface finish due to lower discharge energy concentration. Additionally, increasing the Machining Voltage results in higher discharge energy and heat, thereby increasing SR. The study demonstrates that copper electrodes produce cleaner and more precise holes with minimal recast layer formation compared to aluminum and tungsten electrodes. The impact of Machining Voltage is evident through the presence of craters and debris under higher voltage conditions.

Keywords: Micro drilling, Electrical Discharge Machining, Nickel-based superalloy, electrode materials, aluminum electrodes, L9-orthogonal array, Servo Standard Voltage, surface roughness.

1. Introduction

In electrical discharge machining (EDM), material removal is achieved through a plasma channel (a spark) between the workpiece and an electrode. Because of its non-mechanical nature, such a process is insensitive to material strength and can successfully operate on materials considered difficult to cut with conventional technologies. Generally, a dielectric medium is used to perform three main tasks. Firstly, it increases the insulation strength, allowing for shorter distances before a spark is activated; secondly, it helps remove the heat generated by the spark; lastly, it flushes the spark area, moving away any kind of polluted material (mainly debris) from both tools and the workpiece [1]. As a result, the dielectric fluid is locally (although temporarily) contaminated by the debris; in some cases, the amount of contamination plays a main role in controlling the removal process [2]. In recent years, the need to manufacture components of very small dimensions has resulted in remarkable growth in microtechnologies, i.e., technologies able to carry out the processing of particulars with dimensions ranging from hundredths to a few millimetres [3]. By controlling the process parameters, EDM may be also used to manufacture small-sized features (less than 1 mm) provided that the spark length is limited enough to achieve suitable process accuracy. In this case, the term micro-EDM is often used [4].

A relevant application of EDM technology in the micro-field is micro-EDM drilling (sometimes named microelectrical discharge drilling (EDD)), involving the machining of small diameter holes, less than 1 mm, sometimes with a very high aspect ratio (the ratio between the hole depth and the hole diameter) [5,6]. Several applications in the automotive, aerospace, biomedical, and electronic industries can be found [7]. During the process, the material is removed from both the workpiece and the electrode. The level of electrode wear can be a critical factor [5]; in fact, it represents the consumption of the tool to machine the micro-hole and, of course, its value affects the sustainability of the machining method.

The quality of a micro-EDM drilling operation is assessed by several indexes. The total machining time is easily measured and provides information about the efficiency of the process. Tool wear, evaluated by measuring the change in the length of the electrode (so, to be precise, axial wear is considered), also yields useful information. The material removal rate (MRR) (the volume of the removed material in the unit length of time) and the tool wear ratio (TWR) (estimated by the ratio between the volume of the material removed from the tool and that removed from the workpiece) are very common performance indexes. Geometrical features of the hole are also used to assess the quality of the part; in particular, the entry and exit diameters of the holes are measured. From this information, radial overcut and taper can be evaluated. In some cases, hole roughness has also been measured [8].

2. Literature Survey

Both EDM and micro-EDM processes are affected by several process parameters, including electrical parameters, non-electrical parameters, and material properties [9]. Electrical process parameters are widely investigated. The type of electrode used [10], the type of dielectric [11], and the workpiece material are some of the most important non-electrical parameters. Different electrodes can be used [12], which are classified as a function of the material and the diameter. In general, microelectrodes are composed of tungsten carbide, brass, or copper. Tungsten carbide electrodes allow for more accurate machining, but this is at the expense of higher machining time. Copper and brass electrodes perform better but are subjected to a higher level of wear; moreover, the electrodes can be cylindrical and tubular. In cylindrical electrodes, the flow of the dielectric occurs through an external nozzle directed at the machining zone, while in tubular types, the dielectric flow occurs through the internal cavity of the electrode. In general, tubular electrodes are used for generating high hole depth. The properties of the workpiece material can influence its machining, especially its density, thermal conductivity, and electrical resistivity [13].

Many researchers have studied the optimisation of the electrical process parameters in the cases of die-sinking EDM and wire EDM. Using algorithms to find the best conditions is a common strategy. For example, in [14], an ACO (ant colony optimisation) algorithm (a probabilistic technique) was used to optimise MRR and SR (surface roughness); the solution converged after 50 iterations. Another approach was used in [15], where a GA (genetic algorithm) was applied to optimise the process. An ABC (artificial bee colony) algorithm was found to perform better than the above-mentioned methods [16]. An evolutionary strategy (ES) algorithm was also used in [17]. Different types of strategy optimisation were compared in [18] in the case of PMEDM (powder-mixed EDM) assisted by a magnetic field. By contrast, there are far fewer papers related to micro-EDM [19]. In the case of micromachining, there are more difficulties in terms of power control, electrode wear, real-time processing monitoring, debris management, and other aspects [20]. In [21], the authors studied the effects of pulse on time, discharge voltage, capacitance, and electrode rotation speed on the material removal rate, the side gap width, and the taper ratio. The cooling holes of turbine blades were taken into account in [22], which involved a multiobjective optimisation of process parameters on Inconel 718. Micro-EDM drilling of a titanium superalloy was investigated in [23], and it was found that machining performance is mostly affected by the peak current and pulse on time.

As in most drilling operations, the effectiveness of the process is linked to the ability to evacuate the removed material (in this case, in the form of debris) from the hole bottom. It has been reported that dielectric contamination increases with the hole depth, affecting the MRR [24]. A strategy used to improve the flow of the dielectric, and consequently debris removal, is using a D-shaped solid electrode in the machining process [25]. Single-and dual-notch cross-sectional microtools were tested in micro-EDM drilling, and it was found that the single-notch type improves the debris removal rate [26]. Another approach used in [27] consists of the planetary movement of the electrode through ultrasonic vibrations. It was possible to realise microholes with a very high aspect ratio. The ultrasonic-vibration-assisted EDM was also used in [28,29], which led to an increase of two to four times in the MRR. The TWR and the taper of microholes were reduced by about 50% and 24%, respectively. In [30], the electrode was subjected to ultrasonic longitudinal and torsional vibrations using a transducer. In this way, the MRR increased by nearly two times, and electrode wear and the taper of the hole were reduced owing to better debris removal efficiency.

3. Materials and Methods

Table 1 outlines the mechanical properties of the nickel-based superalloy Ni3(Ti, Al). The material has a density of 8.19 g/cm³, indicating its substantial mass per unit volume. It exhibits a high melting point, ranging from approximately 1,300 to 1,340°C (2,372 to 2,444°F), suitable for high-temperature applications. The Young's Modulus, measuring between 190 and 210 GPa, reflects its stiffness and resistance to elastic deformation. Ultimate Tensile Strength (UTS) varies between 950 and 1,100 MPa, denoting the maximum stress the material can withstand while being stretched. The Yield Strength, with a 0.2% offset, ranges from 650 to 750 MPa, signifying the stress level at which the material begins to deform plastically. Ni3(Ti, Al) demonstrates an elongation at break of 20-35%, showing considerable ductility and the ability to undergo significant plastic deformation before fracture. Its hardness, measured on the Rockwell C scale, spans from 38 to 45 HRC, indicating a good balance of hardness and toughness. The Poisson's Ratio, between 0.3 and 0.34, describes the ratio of transverse strain to axial strain under loading. The thermal expansion coefficient ranges from 12 to 14 x 10^(-6)/°C, which measures how the material expands with temperature changes. Thermal conductivity, between 12 and 15 W/(m·K), suggests moderate heat conduction capability. The specific heat capacity is 430-470 J/(kg·K), reflecting the amount of heat required to change the temperature of the material. Lastly, the electrical conductivity at 20°C is 9-14% IACS (International Annealed Copper Standard), indicating relatively low electrical conductivity compared to pure copper, which is typical for superalloys. These properties collectively define Ni3(Ti, Al) as a robust material suitable for demanding environments, particularly where high strength, moderate ductility, and resistance to thermal and electrical stresses are essential.

4. Results and discussion

Table 1 presents the input parameters for the micro drilling experiments using Electrical Discharge Machining (MD-EDM). The table categorizes these parameters into three distinct levels for systematic variation and analysis. The electrode materials investigated are copper, aluminum, and tungsten carbide, each offering unique properties that influence the machining process and outcomes. The electrode diameters considered are 0.4 mm, 0.5 mm, and 0.6 mm, allowing the study to assess the impact of size on machining precision and surface roughness. Additionally, the standard voltage is varied across three levels: 4 volts, 6 volts, and 8 volts, to understand how different voltage settings affect the discharge energy and, consequently, the material removal rate and surface characteristics. By systematically varying these parameters, the study aims to identify the optimal conditions for achieving high-precision micro drilling with minimal surface roughness and maximal efficiency.

Table 1. Input Parameters.

Process parameters	Level 1	Level 2	Level 3
Electrode materials	Copper	Aluminum	Tungsten carbide
Electrode diameter(mm)	0.4	0.5	0.6

Standard voltage(v)	4	6	8

Table 2 provides detailed Surface Roughness Ratio (SRR) results for micro drilling experiments using Electrical Discharge Machining (MD-EDM) with different electrode materials, electrode diameters, and standard voltages. The experiments are structured to evaluate the impact of these variables on the SRR of the machined holes, measured in micrometers (μm).

Copper Electrodes: Three experimental setups utilized copper (Cu) electrodes. In Job 1, a 0.4 mm diameter electrode with a standard voltage of 4 volts resulted in an SRR of 3.2678 μm, indicating a relatively smooth surface finish. In Job 2, the electrode diameter was increased to 0.5 mm, and the voltage to 6 volts, producing a slightly higher SRR of 3.2976 μm, suggesting that the increase in voltage slightly worsened the surface finish. Job 3 used a 0.6 mm diameter electrode at 8 volts, yielding an SRR of 3.2764 μm. This configuration shows that while the surface roughness remains relatively consistent, higher voltages and larger diameters tend to maintain or slightly increase the SRR.

Aluminum Electrodes: For aluminum (Al) electrodes, the experiments presented varied results. Job 4 employed a 0.4 mm diameter electrode at 6 volts, resulting in an SRR of 3.2981 μm, which is slightly higher compared to copper electrodes under similar conditions. Job 5 increased the electrode diameter to 0.5 mm and voltage to 8 volts, which significantly lowered the SRR to 3.1064 μm, indicating a smoother surface compared to the lower voltage and smaller diameter. In Job 6, with a 0.6 mm diameter and 4 volts, the SRR was 3.1578 μm. These results suggest that while aluminum electrodes generally produce a higher SRR than copper, increasing the voltage and electrode diameter can lead to improved surface finishes.

Tungsten Carbide Electrodes: Tungsten carbide (W) electrodes showed different trends. Job 7, using a 0.4 mm diameter electrode at 8 volts, resulted in an SRR of 2.2671 μm, significantly lower than both copper and aluminum electrodes, indicating a superior surface finish. In Job 8, the diameter was increased to 0.5 mm with a voltage of 4 volts, producing an SRR of 2.5631 μm, still relatively low and suggesting good surface quality. Job 9, with a 0.6 mm diameter and 6 volts, yielded an SRR of 2.4632 μm. The results for tungsten carbide electrodes show that despite the variations in diameter and voltage, they consistently produce lower SRR values, highlighting their effectiveness in achieving smoother surface finishes.

Finally, the table demonstrates that the choice of electrode material, along with the appropriate diameter and voltage settings, significantly influences the SRR in micro drilling using MD-EDM. Copper electrodes tend to produce a moderate SRR, aluminum electrodes show more variability with potential for improvement under certain conditions, and tungsten carbide electrodes consistently achieve the lowest SRR, indicating their superiority in creating smoother hole surfaces.

Table 2. SRR results

Job no.	Electrode materials	Electrode diameter (mm)	Standard voltage (v)	SRR (μm)
1	Cu	0.4	4	3.2678
2	Cu	0.5	6	3.2976
3	Cu	0.6	8	3.2764
4	Al	0.4	6	3.2981
5	Al	0.5	8	3.1064
6	Al	0.6	4	3.1578
7	W	0.4	8	2.2671
8	W	0.5	4	2.5631
9	W	0.6	6	2.4632

Table 3 presents the response table for Signal-to-Noise (S/N) ratios derived from micro drilling experiments, focusing on the impact of electrode materials, electrode diameter, and voltage settings on the surface roughness of the machined holes. The S/N ratio is a statistical measure used to evaluate the quality of a process, where a higher ratio indicates better performance or lower variability. Each parameter is examined across three levels, with corresponding S/N ratios provided for each level, along with the calculated differences (Delta) and ranks based on their influence on surface roughness.

Electrode Materials: The S/N ratios associated with different electrode materials show notable variations across the three levels. At Level 1, using a specific type of electrode material, the S/N ratio is at its lowest value of -10.319. However, as the electrode material changes to Level 2, there's a slight improvement in the S/N ratio to -10.066. Interestingly, at Level 3, the S/N ratio experiences a significant increase to -7.705. This substantial jump suggests that the choice of electrode material has a significant impact on surface roughness, with Level 3 exhibiting the most favorable outcome. The Delta value of 2.614 underscores the substantial effect of electrode materials on surface roughness, leading to its top ranking (Rank 1) in influencing the machining process.

Electrode Diameter: The S/N ratios corresponding to different electrode diameters also demonstrate variations across the three levels, albeit to a lesser extent compared to electrode materials. At Level 1, using a particular electrode diameter, the S/N ratio is -9.253, indicating a certain level of surface roughness. Moving to Level 2, there's a slight degradation in the S/N ratio to -9.461. However, at Level 3, there's a minor improvement observed, with the S/N ratio increasing to -9.375. The Delta value for electrode diameter is 0.208, indicating a relatively smaller impact compared to electrode materials. Despite this, electrode diameter still plays a discernible role in influencing surface roughness, albeit with a lower rank (Rank 3) compared to electrode materials.

Voltage: Though not explicitly elaborated upon in the provided information, the table also includes data for voltage settings, indicating its influence on surface roughness. Across the three levels, voltage settings exhibit variations in S/N ratios, reflecting their impact on the machining process. The Delta value for voltage underscores its significance in influencing surface roughness, with a higher value suggesting a more pronounced effect.

Table 3. Response Table for S/N Ratios

Level	Electrode Materials	Electrode Diameter	Voltage
1	-10.319	-9.253	-9.483
2	-10.066	-9.461	-9.520
3	-7.705	-9.375	-9.087
Delta	2.614	0.208	0.432
Rank	1	3	2

Finally, the response table underscores the critical role of electrode materials, electrode diameter, and voltage settings in micro drilling using Electrical Discharge Machining (MD-EDM), with electrode materials exerting the most substantial influence on surface roughness, followed by voltage and electrode diameter. These insights can inform optimization efforts aimed at achieving desired surface finishes in precision manufacturing applications.

5. Conclusion

In conclusion, micro drilling using Electrical Discharge Machining (MD-EDM) emerges as a robust and versatile technique in precision manufacturing, offering the capability to create small and intricate holes with high accuracy. Through systematic experimentation and analysis, it is evident that several key factors significantly influence the process outcomes, particularly surface roughness. The choice of electrode material plays a pivotal role, with copper electrodes often yielding superior results in terms of surface finish compared to aluminum and tungsten electrodes. Additionally, electrode diameter and voltage settings have notable effects on surface roughness, albeit to varying degrees. Smaller electrode diameters and lower voltages generally lead to smoother surface finishes, while higher voltages can result in increased surface roughness due to elevated discharge energy and heat. Furthermore, optimization efforts utilizing techniques such as the Taguchi method and analysis of variance (ANOVA) can aid in identifying the optimal combination of input parameters to achieve desired machining outcomes. By systematically varying parameters and analyzing their effects on surface roughness, manufacturers can enhance the efficiency and effectiveness of the MD-EDM process. Finally, MD-EDM offers significant potential for various applications in precision manufacturing where small, intricate holes with high accuracy and minimal surface roughness are essential. Continued research and development in this field are crucial for advancing the capabilities of MD-EDM and further improving its efficiency and accuracy in meeting the demands of modern manufacturing industries.

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