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Research Paper

EXPERIMENTAL INVESTIGATION OF CHROMIUM COATED BRASS TUBULAR ELECTRODES IN MICRO EDM DRILLING OF NIMONIC C-263 ALLOY

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Abstract

Micro Electrical Discharge Machining (Micro-EDM) is a precision micromachining technique that removes material through controlled electrical spark discharges without mechanical contact, making it suitable for machining high-strength and difficult-to-machine alloys including nickel-based superalloys. This paper presents an experimental investigation of chromium-coated brass tubular electrodes—configured as single channel (CCBTEs) and multi channel (CCBTEm)—for micro-EDM drilling of Nimonic C-263, a precipitation-hardened nickel superalloy extensively used in gas turbine and aerospace components. Experiments were designed using the Taguchi L9 orthogonal array with four process parameters—Pulse On Time (TON), Pulse Off Time (TOFF), Discharge Current (DC), and Rotation Speed (RPS)—each at three levels. The performance measures evaluated are Material Removal Rate (MRR, mm^3/min) and Machining Time (min). Results indicate that the chromium coating significantly reduces electrode wear and overcut due to chromium's high hardness (~900 HV) and high melting point (1907°C). The effects of each process parameter on MRR and Machining Time are discussed in detail for both single-channel and multi-channel chromium-coated brass tubular electrode configurations.

Keywords: Micro-EDM, Nimonic C-263, Chromium-Coated Brass Tubular Electrode, Single Channel (CCBTEs), Multi Channel (CCBTEm), MRR, Machining Time, Taguchi L9.

1. Introduction

Electrical Discharge Machining (EDM) is a thermoelectric, non-traditional machining method where material is eroded from a conductive workpiece through a series of controlled electrical spark discharges occurring between the electrode tool and the workpiece while both are immersed in a dielectric medium. When the inter-electrode gap becomes sufficiently small, an electrical spark is triggered which produces extremely high localized temperatures (typically 8000–12000°C). The concentrated thermal energy melts and vaporizes microscopic volumes of material, leaving small crater-like impressions on the machined surface. Because the process does not rely on cutting forces, EDM is particularly effective for machining hard and electrically conductive materials that are difficult to process using conventional cutting techniques.

Coated electrodes have emerged as a significant advancement in EDM and Micro-EDM, playing a pivotal role in improving machining performance. By applying coatings such as silver, zinc, or chromium on the electrode substrate, wear resistance is increased, energy transfer is stabilized, and the quality of machined features is enhanced. Reducing electrode wear through such coatings extends the operational lifespan of the tool and ensures consistent spark discharge behaviour throughout the process [1].

The fundamental concepts of Electrical Discharge Machining were first established in the 1940s. B.R. and N.I. Lazarenko, two Soviet scientists, are credited with inventing EDM in 1943, demonstrating that controlled electrical sparks could erode material in a regulated manner when an electrical voltage was applied between an electrode and a workpiece submerged in a dielectric fluid [2]. As production requirements for smaller and more complex components grew, researchers and engineers began to miniaturize EDM techniques. In the 1970s and 1980s, Micro-EDM technology advanced significantly through miniaturization of electrodes and advances in control systems, enabling more accurate drilling of tiny features [3].

The Material Removal Rate (MRR) is defined as the quantity of material removed from a workpiece per unit time. The Electrode Wear Ratio (EWR) is calculated as the ratio of tool wear rate to MRR. Surface roughness (Ra) pertains to the average machined surface quality following machining and is typically measured in micrometres. These performance criteria are dependent on process parameters, which are divided into electrical parameters (discharge energy, open voltage, gap voltage, peak current, pulse on time, pulse off time, duty ratio) and non-electrical parameters (dielectric type and pressure, electrode geometry and coating) [4].

Micro-EDM is the miniaturized variant of EDM and is capable of producing micro-features such as micro-holes, micro-slots and complex three-dimensional micro-cavities with dimensional accuracy in the range of a few micrometres. It has gained significant importance in the fabrication of components for aerospace, biomedical, automotive and micro-electromechanical systems (MEMS) industries. Nimonic C-263 is a precipitation-hardenable nickel-chromium-cobalt-molybdenum superalloy primarily designed for service at temperatures up to 920°C, containing approximately 20% Cr, 20% Co, 5.9% Mo, 2.1% Ti, 0.5% Al and balance Ni. Its machinability by conventional methods is severely limited, making Micro-EDM an ideal alternative.

The geometry of the tool electrode in Micro-EDM significantly influences the machining performance. Single-channel (SC) electrodes feature a single central through-hole, while multi-channel (MC) electrodes contain multiple smaller through-holes distributed across the electrode cross-section. The present study investigates chromium-coated brass tubular electrodes in both single-channel (CCBTEs) and multi-channel (CCBTEm) configurations for micro-EDM drilling of Nimonic C-263 using the Taguchi L9 design of experiment methodology.

2. Literature Review

Several researchers have investigated the influence of electrode material, geometry, and process parameters on the performance of Micro-EDM in hard and difficult-to-machine materials. Masuzawa [5] presented a comprehensive state-of-the-art review of micromachining processes, highlighting the significance of electrode design and dielectric flushing on machining accuracy and MRR. Takahata and Gianchandani [6] investigated batch-mode Micro-EDM using arrayed copper electrodes and demonstrated that electrode geometry and inter-electrode gap significantly affect the uniformity of material removal. Pradhan et al. [7] studied Micro-EDM of titanium alloy Ti-6Al-4V using the Taguchi method and identified pulse-on time and discharge current as the most influential parameters for MRR and surface roughness.

Jahan et al. [8] investigated tungsten carbide micro-electrodes in Micro-EDM of nickel-based superalloys and confirmed that WC electrodes exhibit significantly lower tool wear compared to copper and brass electrodes at higher discharge energies. Klocke et al. [9] studied the effects of silver, copper, and chromium coatings on EDM performance in Inconel 718 and reported that silver-coated electrodes achieved higher MRR due to superior electrical conductivity, while chromium-coated electrodes demonstrated the least tool wear owing to chromium's high hardness and melting point. Nirala and Saha [10] performed Micro-EDM drilling on Nimonic 90 superalloy and reported that multi-channel electrodes provided a 15–22% improvement in MRR over single-channel electrodes due to enhanced dielectric flushing and reduced debris bridging.

Shrivastava and Dubey [11] investigated Micro-EDM of Nimonic C-263 using uncoated brass electrodes and established baseline MRR and overcut values, noting that flushing efficiency is critical for stable machining. Ali and Saha [12] applied Taguchi-Grey Relational Analysis to optimize Micro-EDM of nickel superalloys and confirmed that intermediate TON values combined with lower TOFF yield the best trade-off between MRR and dimensional accuracy. Yilmaz and Okka [13] reported that single-passage tubular electrodes give higher MRR and lower electrode wear rate than multi-channel electrodes, while multi-channel electrodes yield a better surface finish. Fu et al. [14] confirmed that deionized water as dielectric shows substantially less tool wear than machining oil irrespective of electrode type.

Krishnan et al. [15] showed that tin-coated brass electrodes in Micro-EDM led to a significant reduction in machining time and improvement in surface quality compared to uncoated brass electrodes. Karunakaran [16] demonstrated that silver-coated Cu electrodes improve machining productivity and reduce electrode wear in EDM of Inconel 800. Panchal et al. [17] reported that TiN-coated WC electrodes improved depth of cut, tool wear rate, and overcut by 16.32%, 26.9%, and 18.9% respectively compared to uncoated electrodes. Phan et al. [18] found that zinc-coated Cu electrodes exhibit greater machining efficiency than uncoated Cu electrodes for Inconel IN718. Vundrajavarapu et al. [19] investigated silver-coated brass tubular electrodes with SiC nanoparticles for Micro-EDM of Ti-6Al-4V and demonstrated significant improvements in MRR and TEWR using a combined Taguchi and fuzzy logic optimization approach.

Praveen and Madhusudhan [20] provided a comprehensive review of electrode coating effects on Micro-EDM Drilling performance, identifying brass tubes with single and multiple passages as the most commonly used tubular electrodes. Firat and Bozdana [21] investigated the effect of electrode geometry and material on Electrical Discharge Drilling (EDD) performance and hole accuracy when machining tungsten carbide. Their results showed that multi-channel electrodes provided higher MRR and EWR compared to single-channel electrodes due to more uniform spark distribution. Collectively, these studies underscore the importance of electrode coating material, channel configuration, and thermal properties in determining micro-EDM drilling outcomes.

2.1 Methods of Electrode Coating in Micro-EDM

Electrode coatings can be applied using a variety of processes, including Physical Vapor Deposition (PVD), Chemical Vapor Deposition (CVD), electroplating, and thermal spraying [22]. Physical Vapor Deposition (PVD) places electrodes in a vacuum chamber where material is evaporated and deposits on electrode surfaces, generating a thin film coating [23]. PVD offers precise control over coating thickness and composition but is somewhat expensive due to equipment and operating costs [24]. Chemical Vapor Deposition (CVD) exposes electrodes to a gas phase containing precursor molecules that undergo chemical reactions on the electrode surfaces [25]. CVD can coat complicated geometries but may necessitate high temperatures and specialized equipment [26]. Electroplating involves immersing the electrode in an electrolyte solution containing metal ions such as copper, nickel, zinc, silver, or chromium [27]. In the present work, chromium coatings on brass tubular electrodes are applied by electroplating, providing uniform coatings of controlled thickness on tubular geometries.

3. Materials and Method

3.1 Nimonic C-263

The workpiece material used in this investigation is Nimonic C-263, a precipitation-hardenable nickel-chromium superalloy manufactured to AMS 5872 specifications. The alloy is supplied in the form of rectangular blocks with dimensions of 50 mm × 30 mm × 5 mm. Prior to machining experiments, each workpiece block is cleaned with acetone to remove surface contaminants.

Chemical Composition (wt**.%):** Ni (balance), Cr 20%, Co 20%, Mo 5.9%, Ti 2.1%, Al 0.5%, Mn 0.6%, Fe 0.7%, C 0.06%, Cu 0.2% max.

Mechanical Properties: Ultimate Tensile Strength – 970 MPa; Yield Strength (0.2% proof) – 636 MPa; Elongation – 35%; Hardness – 300 HV; Density – 8.36 g/cm^3; Melting Range – 1300–1355°C; Thermal Conductivity – 11.7 W/(m·K).

The low thermal conductivity and high hot hardness of Nimonic C-263 make it exceptionally difficult to machine by conventional processes, thereby making it an ideal candidate for Micro-EDM evaluation. The Nimonic C-263 workpiece material used in this study is shown in Figure 1.

Figure 1: Nimonic C-263 workpiece material (50 mm × 30 mm × 5 mm rectangular block)

3.2 Electrode Materials

Chromium-coated brass tubular electrodes are investigated in this study, fabricated in both single-channel (CCBTEs) and multi-channel (CCBTEm) configurations. All electrodes are made from a brass tubular substrate (Cu 60%, Zn 40%) with an outer diameter of 2 mm. The CCBTEs electrode has a single central through-hole of 0.8 mm diameter, while CCBTEm electrodes have four symmetrically arranged through-holes of 0.4 mm diameter each, providing the same cumulative cross-sectional flushing area. A hard chromium coating of 5 µm thickness is applied by electrolytic chromium plating. Chromium has a hardness of approximately 900 HV and a high melting point (1907°C), which significantly reduces electrode wear during the EDM process. The chromium-coated single-channel (CCBTEs) and multi-channel (CCBTEm) electrode configurations are shown in Figure 2.

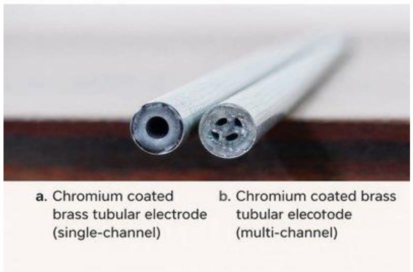

Figure 2: Electrode configurations – (a) Chromium-coated brass tubular electrode, single channel (CCBTEs); (b) Chromium-coated brass tubular electrode, multi-channel (CCBTEm)

3.3 Micro-EDM Setup

The machining trials were performed on a CNC based Micro-EDM system operating with an RC (resistance–capacitance) type pulse generator. The equipment supports micro-scale drilling with electrode diameters as small as 0.1 mm and provides positioning accuracy on the order of ±0.5 µm. Deionised water with a resistivity of 10–12 MΩ·cm was used as the dielectric fluid and circulated at a constant pressure of 0.3 MPa through the hollow tubular electrodes (internal flushing). The electrode was rotated using a motorized spindle. Each experiment was conducted for a fixed machining time of 5 minutes to ensure consistent removal volume measurements. The workpiece was mounted on a precision X-Y stage and the electrode was held vertically in the spindle chuck. Electrode feed was controlled by a servo mechanism maintaining a constant gap voltage of 80 V. The complete experimental setup is shown in Figure 3.

Figure 3: Micro-EDM experimental setup

3.4 Experimental Design – Taguchi L9 Orthogonal Array

The Taguchi method is a robust design of experiment technique that minimises the number of experiments required while maximising the information obtained about the process. An L9 orthogonal array was selected to investigate four process parameters, each at three levels. This design provides nine experimental runs capturing the main effects of all four parameters with minimum experimentation. The process parameters and their levels are presented in Table 1.

Table 1: Process Parameters and Levels

Process Parameter	Level 1	Level 2	Level 3	Unit
Pulse On Time (TON)	20	50	80	µs
Pulse Off Time (TOFF)	10	30	50	µs
Discharge Current (DC)	2	4	6	A
Rotation Speed (RPS)	100	300	500	rpm

The L9 experimental matrix derived from the Taguchi orthogonal array is presented in Table 2. The experiments were performed in random order to minimize any systematic error due to time-dependent drift in the machine and measurement instruments.

Table 2: Taguchi L9 Orthogonal Array

S.No	TON (µs)	TOFF (µs)	DC (A)	RPS (rpm)
1	20	10	2	100
2	20	30	4	300
3	20	50	6	500
4	50	10	4	500
5	50	30	6	100
6	50	50	2	300
7	80	10	6	300
8	80	30	2	500
9	80	50	4	100

3.5 Performance Measures and Measurement Methods

Material Removal Rate (MRR): MRR is calculated from the volume difference of the workpiece before and after machining, divided by the machining time: MRR = (W_before – W_after) / (ρ × t), where ρ is the density of Nimonic C-263 (8.36 g/cm³) and t is machining time. Units: mm³/min.

Machining Time: The total time (in seconds) required to machine through the Nimonic C-263 workpiece under each set of process parameters. Lower machining time indicates higher productivity. Machining time is recorded directly from the CNC Micro-EDM machine controller.

4. Results and Discussion

The experimental results obtained from the L9 Taguchi orthogonal array for chromium-coated brass tubular electrodes in single-channel (CCBTEs) and multi-channel (CCBTEm) configurations are presented in Table 3 for Machining Time and MRR. The values are derived from the experimental data recorded during Micro-EDM drilling of Nimonic C-263.

4.1 Material Removal Rate (MRR) and Machining Time

Table 3 presents the Machining Time (seconds) and MRR (mm³/min) results for chromium-coated brass tubular electrodes (CCBTEs and CCBTEm) across all nine Taguchi L9 experimental runs.

Table 3: Machining Time (s) and MRR (mm³/min) – CCBTEs and CCBTEm

S.No	TON (µs)	TOFF (µs)	DC (A)	RPS (rpm)	CCBTEs Time (s)	CCBTEs MRR (mm³/min)	CCBTEm Time (s)	CCBTEm MRR (mm³/min)
1	20	10	2	100	165.256	0.4614	117.248	0.5705
2	20	30	4	300	38.959	0.6495	45.283	0.1749
3	20	50	6	500	26.699	1.0652	32.600	1.8665
4	50	10	4	500	26.217	1.0022	33.042	0.4717
5	50	30	6	100	21.091	2.0937	25.638	0.2888
6	50	50	2	300	198.278	0.7720	156.758	0.4533
7	80	10	6	300	24.889	2.0141	22.850	1.4514
8	80	30	2	500	132.851	1.6536	97.882	0.8581
9	80	50	4	100	30.536	0.7305	41.831	0.3579

From Table 3, it is evident that MRR increases with increasing pulse on time (TON) and discharge current (DC). The highest MRR values are recorded at Run 5 (TON=50 µs, TOFF=30 µs, DC=6 A) for CCBTEs (2.0937 mm³/min) and at Run 3 (TON=20 µs, TOFF=50 µs, DC=6 A) for CCBTEm (1.8665 mm³/min). Machining time is minimum for Run 5 in CCBTEs (21.091 s) and Run 7 in CCBTEm (22.850 s), corresponding to conditions of higher discharge energy.

Effect of Process Parameters on MRR

Effect of Pulse On Time (TON) on MRR: MRR generally increases with TON for both CCBTEs and CCBTEm configurations. Higher TON delivers more energy per spark discharge, melting and vaporizing a larger volume of workpiece material per pulse. This trend is consistent with established theory that higher pulse energy leads to deeper and wider craters on the workpiece surface.

Effect of Pulse Off Time (TOFF) on MRR: MRR decreases with increasing TOFF since a longer off-time reduces the effective duty cycle, resulting in fewer sparks per unit time. However, adequate TOFF is necessary to allow the debris to be flushed away and the dielectric to re-ionise for the next productive discharge. Machining time correspondingly increases with higher TOFF values.

Effect of Discharge Current (DC) on MRR: DC is the most significant parameter influencing MRR. Higher DC increases the peak current of each spark, resulting in higher plasma pressure and temperature, which removes more material per discharge. The chromium coating, with its high hardness (~900 HV) and melting point (1907°C), maintains electrode integrity even at high discharge currents, ensuring stable spark discharge and consistent material removal.

Effect of Rotation Speed (RPS) on MRR: At low rotation speed (100 rpm), debris accumulation in the discharge gap causes increased short-circuit frequency, reducing effective spark discharge and consequently lowering MRR. At Run 1 (RPS = 100 rpm, DC = 2 A), CCBTEs recorded the highest machining time of 165.256 s with a low MRR of 0.4614 mm³/min. At intermediate rotation speed (300 rpm), Run 7 yielded a high MRR of 2.0141 mm³/min for CCBTEs and 1.4514 mm³/min for CCBTEm with minimum machining times of 24.889 s and 22.850 s respectively. At high rotation speed (500 rpm), the centrifugal action improves dielectric circulation through the internal channels; Run 3 achieved MRR of 1.0652 mm³/min (CCBTEs) and 1.8665 mm³/min (CCBTEm).

5. Conclusions

An experimental investigation of chromium-coated brass tubular electrodes in single-channel (CCBTEs) and multi-channel (CCBTEm) configurations was carried out for Micro-EDM drilling of Nimonic C-263 using a Taguchi L9 orthogonal array design. The following conclusions are drawn from this study:

The chromium-coated brass tubular electrode in single-channel configuration (CCBTEs) achieved a maximum MRR of 2.0937 mm³/min at Run 5 (TON=50 µs, TOFF=30 µs, DC=6 A) with a minimum machining time of 21.091 s. The multi-channel configuration (CCBTEm) achieved a maximum MRR of 1.8665 mm³/min at Run 3 (TON=20 µs, TOFF=50 µs, DC=6 A) with a minimum machining time of 22.850 s at Run 7. These results confirm that discharge current and pulse on time are the dominant parameters influencing MRR for chromium-coated electrodes.

The chromium coating (hardness ~900 HV, melting point 1907°C) significantly stabilises spark discharge and reduces electrode wear, leading to consistent machining performance across all L9 runs. Discharge current (DC) is identified as the most significant process parameter affecting both MRR and Machining Time for chromium-coated brass tubular electrodes, followed by pulse on time (TON). Rotation speed (RPS) exerts a moderate but important influence on machining stability.

Among the two configurations studied, CCBTEs exhibited higher MRR at moderate-to-high discharge energies with low-to-intermediate rotation speeds (100–300 rpm), while CCBTEm showed advantages in machining stability due to enhanced internal flushing at higher rotation speeds (300–500 rpm). The combination of chromium-coated multi-channel (CCBTEm) electrodes at moderate discharge parameters (TON=50 µs, DC=6 A, TOFF=30 µs) with a rotation speed of 300 rpm is recommended as the optimal configuration for balanced MRR and machining time performance when drilling Nimonic C-263.

Future investigations may include surface roughness evaluation, SEM analysis of drilled surfaces, overcut measurements, tool wear rate analysis, and multi-objective optimization using Grey Relational Analysis and TOPSIS for the chromium-coated brass tubular electrodes.

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