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PERFORMANCE OF WATER AND HYDROCARBON DIELECTRICS IN WEDM OF CEMENTED CARBIDE

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Abstract

In alignment with the United Nations Sustainable Development Goals (SDGs) 9 and 12, the global manufacturing industry continuously seeks productive, responsible, and sustainable solutions. In this context, the electrical discharge machine has shown strong potential for *processing materials with low machinability, such as superalloys and conductive ceramic-based materials, due to its ability to remove material without tribological contact. Among these, cemented carbide stands out for its high wear resistance, consisting of tungsten particles in a non-oxide ceramic phase (WC) bonded by a metallic phase (Co), resulting in elevated hardness and mechanical strength at high temperatures. However, literature presents limited studies on the WEDM of such materials using a reciprocating molybdenum wire, and even fewer when considering the influence of different dielectrics. This study aims to evaluate the behavior of deionized water and hydrocarbon-based dielectrics in the WEDM of WC-Co, focusing on their effects on process performance and surface integrity. Five levels of lateral infeed (Δy) were tested under constant discharge energy and fixed machining parameters. The results demonstrated that increasing the lateral infeed led to a reduction in material removal rate. The hydrocarbon dielectric achieved the highest wire feed rate at Δy = 100%, resulting in an 88.5% increase. Conversely, when Δy was reduced, deionized water yielded superior productivity, with a 53.5% improvement. Additionally, surface texture analysis showed a reduction in average roughness (Sa), indicating greater process stability and reduced morphological distortion with deionized water at Δy = 10%, representing a 10.3% improvement over the hydrocarbon-based dielectric. Future work will explore the effects of the recast layer on distinct grade discharge energies to optimize performance across broader machining conditions.*

Keywords:

Deionized Water Dielectric, Hydrocarbon-Based Dielectric, WEDM, Cemented Carbide, Lateral Infeed

1. Introduction

Cemented carbides are classified as composite materials comprising hard refractory carbide particles dispersed within a metallic binder matrix. Typically, the primary phase consists of tungsten carbide (WC), while cobalt (Co) serves as the ductile binder metal, resulting in a non-oxide ceramic-metal composite. According to Amorim, Weingaertner, and Bassani (2010), powder metallurgy is the predominant fabrication route for WC–Co components due to its capacity for precise control over microstructural attributes. The functional performance of these materials is primarily determined by their hardness, transverse rupture strength, and fracture toughness. Critical variables influencing these properties include the binder metal content and the grain size of the WC particles, which can range from submicron (<0.2 μm) to several micrometers (Carlini et al., 2020).

The high hardness and strength of WC–Co composites, while advantageous in in-service applications, pose substantial challenges to conventional machining processes utilizing geometrically defined cutting tools. These materials exhibit poor machinability, necessitating the use of non-traditional techniques such as Electrical Discharge Machining (EDM) and its wire-based variant, Wire Electrical Discharge Machining (WEDM). These thermal erosion processes rely on a series of discrete electrical discharges to remove material, thus avoiding direct mechanical contact and the associated tribological wear (Poroś, 2021).

WEDM is advantageous in machining hard materials, as it eliminates the mechanical stresses, tool wear, and surface integrity degradation associated with contact-based methods. The primary electrical parameters controlling discharge behavior include discharge current ($\bar{i}_e$, A), mean discharge voltage ($\bar{u}_e$, V), and pulse duration (t_e, μs). The energy released per discharge (W_e) is expressed by the time-integrated product of current and voltage, as formulated by Klocke and König (2007):

$$W_e = \int_0^{t_e} u_e(t).\, i_e(t).\, dt \quad (1)$$

A fundamental component across all EDM technologies is the dielectric fluid, conventionally applied in liquid form. As described by Klocke and König (2007), the dielectric serves multiple essential functions: enabling dielectric breakdown and ionization, facilitating plasma channel formation through energy density concentration, evacuating debris from the interelectrode gap, promoting thermal management, and maintaining electrical insulation between the wire electrode and the workpiece.

Deionized water is most frequently employed as a dielectric in WEDM, hydrocarbon-based fluids applied either in pure form or as emulsions (Carlini et al., 2020). Deionized water is obtained either through distillation or via ion exchange processes involving submicron filtration and mixed-bed resin treatment to eliminate ionic contaminants. Comparative investigations by Niamat et al. (2017) revealed that while pure hydrocarbons lead to elevated tool wear and higher material removal rates, the use of deionized water is associated with increased surface roughness. Kunieda and Kitamura (2018) further demonstrated that material removal efficiency varies significantly with discharge frequency and dielectric type. Short pulse intervals in hydrocarbon-based systems promote higher energy concentration, while the low viscosity of deionized water enhances debris flushing and thermal dissipation within the spark gap.

The present study investigates the influence of dielectric fluid type on the performance of the reciprocating WEDM Mo-wire process. The experimental matrix includes five incremental values of lateral offset applied during the machining of WC–Co composites. Process efficiency is assessed through wire feed rate (mm/min), and surface integrity is evaluated via quantitative surface texture analysis using the arithmetic mean height (Sa, μm) parameter.

2. Experimental Procedure

2.1 Materials procedure

The experimental trials were conducted using a precision wire electrical discharge machining (WEDM) system manufactured by GF Machining Solutions (GFMS), model FW1U. This equipment is equipped with a five-axis (CNC) platform and is specifically engineered with a reciprocating spool mechanism. Material removal was achieved using a molybdenum wire electrode with a nominal diameter (dw) of 0.18 mm, subjected to a tensile preload of 1200 N/mm^2, applied via a counterweight-based tensioning system to ensure consistent wire stability and straightness throughout the process.

The pulse generator was configured to operate under isoenergetic conditions, characterized by the discharge duration (te) of 25 µs, the interval time (to) of 75 µs, and Open-circuit voltage (ûi) of -70 V using rectangular pulses with identical periods. The discharge energy in both tests was We = 131,2 mJ. The input parameters that were maintained constant across all experimental trials are summarized in Table 2.1.

Table 2.1: *Independent input variables used in the WEDM machine*

Variable	Symbol	Quantity	Unit
Lateral infeed	Δ_y	10; 25; 50; 75 and 100	%
Dielectric pressure	P_{in}	0.25	MPa
Wire diameter	d_w	0.18	mm
Wire runoff speed	W_s	8.0	m/s

The dielectric fluid for the experimental program consisted of deionized water produced through a reverse osmosis system. To maintain chemical purity during operation, the fluid underwent continuous recirculation through ion exchange resin columns installed in the machine's tank. Under these conditions, the electrical conductivity of the deionized water was maintained at approximately 15.0 µS/cm. On the other hand, a hydrocarbon-based dielectric was prepared by mixing 8% volume of hydrocarbon fluid with deionized water, resulting in an electrical conductivity of 3.1 µS/cm. To ensure stability in dielectric properties and to prevent the accumulation of debris within the interelectrode gap, continuous filtration was applied to both fluids. A 5.0 µm pleated cartridge filter with a nominal particle retention threshold was used. Table 2.2 shows the physical properties of the hydrocarbon-based and deionized water dielectrics.

Table 2.2: *Physical properties of hydrocarbon-based and deionized water dielectrics*

Property	Deionized water	Hydrocarbon 8%	Unit
Viscosity at 40 °C	1.0×10^{-3}	2.4×10^{-3}	Pa.s
Density at 20 °C	1.00	1.15	g/cm^3
Electrical conductivity	15.0	3.1	µS/cm
Specific heat capacity	4.2	1.9	J/g.K
Heat of evaporation	2260.0	210.0	J/g

Regarding the test specimens used, the workpiece material consisted of a solid tungsten carbide bar with a submicron grain size ranging from 0.5 to 0.8 µm, classified as K30 grade and supplied by Ceratizit©. The test specimens were manufactured with a final geometry of 8 × 2.5 mm in rectangular cross-section and 22.5 mm in length. The cross-section faces were pre-ground before testing, resulting in a total machining perimeter of 50 mm.

2.2 Experimental methods

The machining time and the corresponding wire feed rate (Vf, mm/min) for each trial were precisely regulated through the integrated control software of the WEDM system. The experimental design incorporated five distinct lateral offset increments (Δy), expressed as a percentage of the nominal wire diameter (dw = 0.18). These values—100%, 75%, 50%, 25%, and 10%—were implemented by adjusting the frontal working gap, resulting in actual spacings of 180 μm, 135 μm, 90 μm, 45 μm, and 18 μm, respectively. Each machining condition was repeated three times (n=3) to ensure statistical reliability, and the results are presented as mean values with error bars representing the standard deviation. The schematic representation in Figure 1 illustrates the geometric arrangement of this offset/lateral infeed.

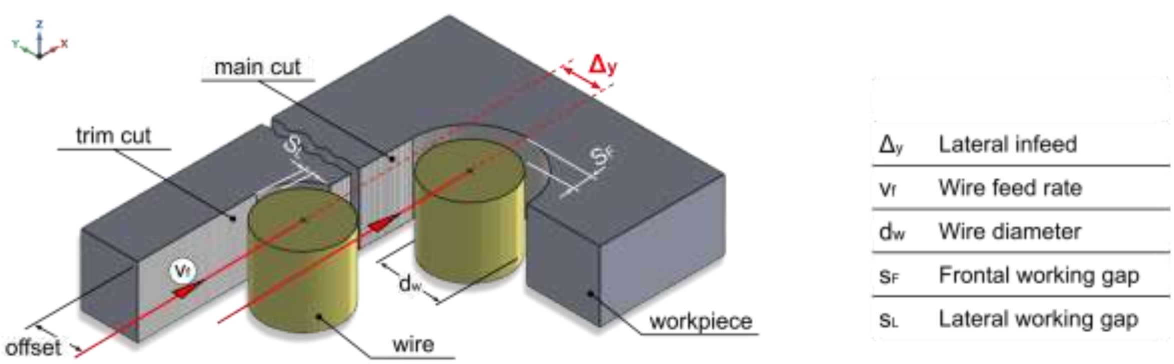

Figure 1: *Lateral infeed definition (Δ_y) and other WEDM definitions.*

After material removal, the machined surfaces were brushed manually with a polyester bristle to remove coarse debris. This was followed by washing in ultrasonic cleaning at a frequency of 40 kHz for 3 minutes in anhydrous isopropyl alcohol (C_3H_8O). This combined mechanical–chemical approach ensured both macro and micro-scale cleanliness, preventing contamination that could distort surface topography and roughness measurement.

Three-dimensional surface texture assessment was conducted using focus variation microscopy (Bruker Alicona® G5) fitted with a 20× optical lens, scanning an area of 5.0 mm × 5.0 mm. Data acquisition was performed in compliance with ISO 16610-71 (Gaussian filter, first order), applying a vertical resolution of 50 nm and a lateral resolution of 1.5 μm. Measurement settings adhered to ISO 25178-2 specifications, with a cut-off sampling length (λc) of 250 μm and a total profile length of 1.25 mm. Post-processing of the datasets was carried out in Alicona MeasureSuite 5.3.1®.

3. Results

This study establishes experimental guidelines for understanding WEDM of K30-grade tungsten carbide using molybdenum wire, with a comparative focus on deionized water and hydrocarbon dielectrics. The investigation was conducted in two stages. The first assessed process efficiency by relating the material removal rate to five levels of lateral infeed, enabling a quantitative evaluation of productivity. The second stage analyzed the three-dimensional surface texture of machined samples to determine the influence of discharge energy variations under each dielectric condition, correlating these parameters with surface integrity and finish quality.

3.1 Three-Dimensional Surface Texture Evaluation

The dielectric medium and process parameters directly influence surface texture in WEDM. Larger volumes of molten material ejected per discharge create deeper craters, increasing roughness. Longer discharge durations amplify protrusions and peaks, significantly altering surface morphology. Figure 2 illustrates both qualitative differences and metric comparisons in surface texture for each dielectric and lateral infeed setting.

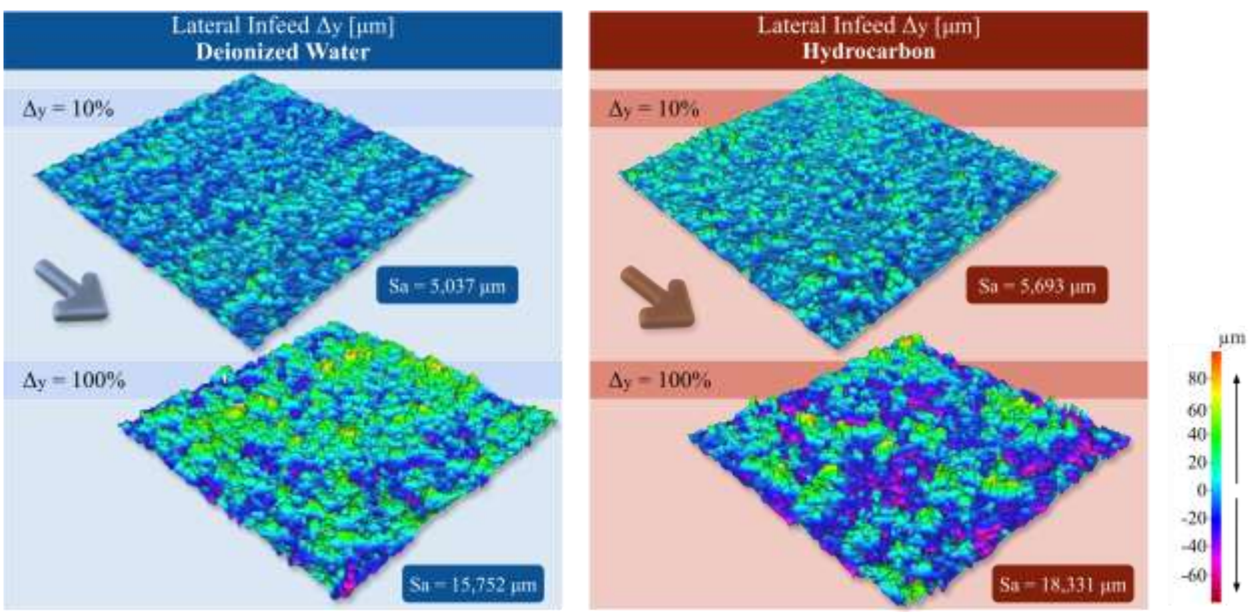

Figure 2: *Textures for different dielectrics and lateral infeed (Δ_y).*

According to Kunieda & Kitamura (2018), plasma channel initiation points during discharge are not randomly distributed. When pulse intervals are short yet sufficient to allow complete plasma formation and extinction, the resulting craters have reduced intensity. Even under stable cutting conditions, discharges concentrate near the periphery of implosion bubbles from prior discharges, leading to a non-uniform spatial distribution along the machining path. Stable discharge behavior is associated with lower roughness, even if absolute values remain high. Higher discharge frequencies can enhance both process efficiency and surface quality. However, excessive debris in the working gap may act as conductive bridges, disturbing plasma formation and reducing stability, thereby increasing roughness amplitude (Kitamura, Kunieda, & Abe, 2015).

High lateral infeed increments (Δ_y) yielded the most significant roughness values, as greater material removal was achieved. While beneficial to productivity, this also promoted debris accumulation within the narrow gap, increasing the likelihood of short circuits and abnormal discharges (Carlini et al., 2021). The combined effects of dielectric type and discharge energy strongly influenced process stability, repeatability, and wear predictability, emphasizing the need for optimized parameter selection to limit tool degradation and dimensional variability.

3.2 Technological Performance

Material removal rate depends on both the volume removed per discharge and process stability. Each pulse requires several microseconds for the plasma channel to extinguish (Kunieda et al., 2005). If the interval between discharges is too short, subsequent pulses may strike residual heat zones, while also reducing the time available for dielectric flushing.

Contamination from eroded particles and dielectric breakdown by-products can alter machining behavior, influencing removal rate, electrode wear, and surface finish. The discharge energy, expressed as $We \approx ue \cdot ie \cdot te$ (mJ), is the primary determinant of removal performance (Reolon et al., 2019). In this study, material removal rates were measured in mm/min, with Figure 3 showing the comparative performance of deionized water and hydrocarbon-based dielectrics across varying lateral infeed settings.

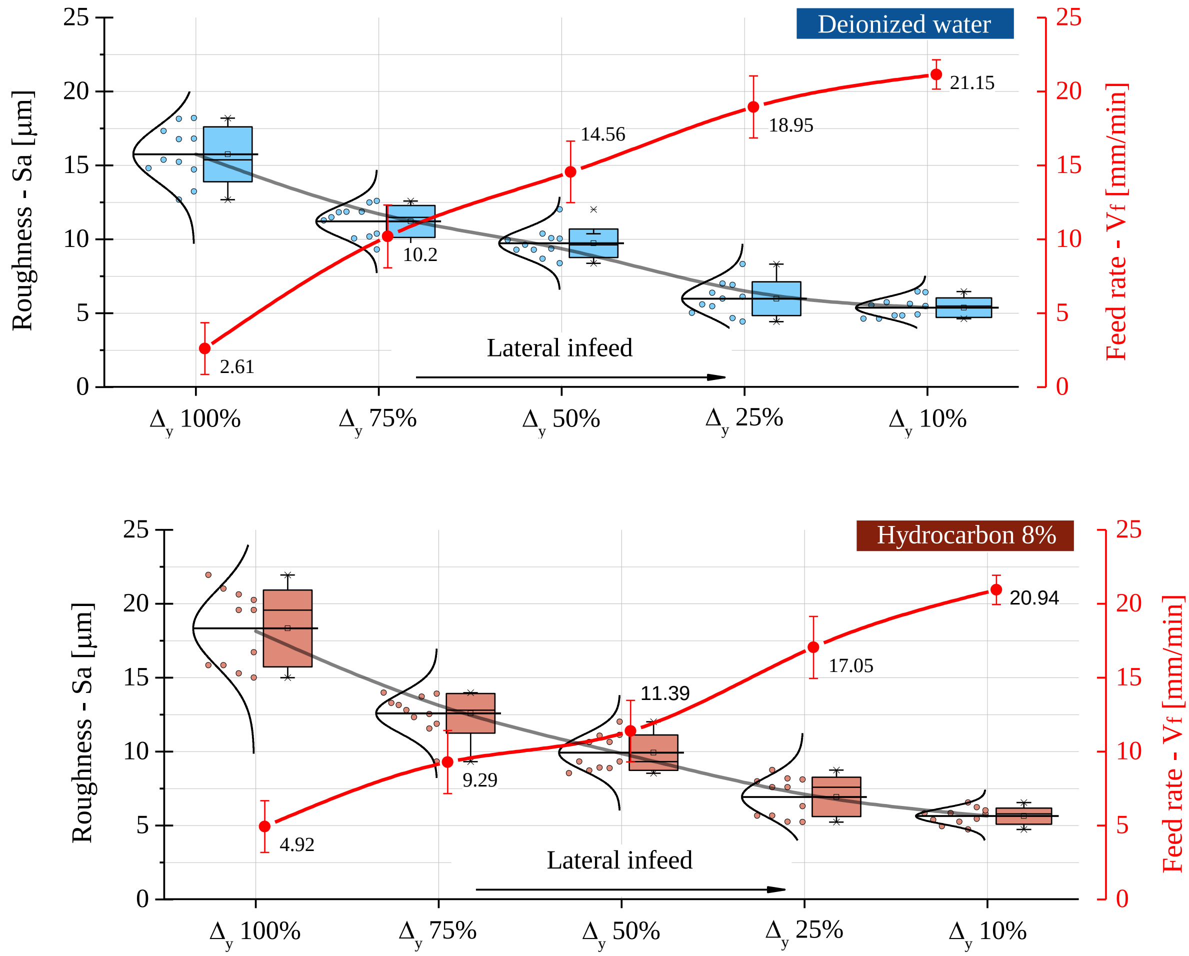

Figure 3: *Technological performance behavior for dielectric fluid and Δy variation.*

Under equivalent discharge energy and pulse duration, hydrocarbons yielded lower average surface roughness. As noted in Kunieda & Kitamura (2018), reducing discharge duration decreases energy density. It improves finish quality, whereas higher energy densities intensify the Joule effect, producing deeper craters and sharper peaks from resolidified material.

The dielectric also plays a critical role in sustaining the plasma channel. Hydrocarbon offered superior stability, with discharges still favoring the periphery of previous implosion bubbles (Kitamura, Kunieda, & Abe, 2015). When pulse intervals were optimized to allow plasma extinction without overlapping, hydrocarbon conditions promoted better technological performance.

4. Conclusions

This study investigated the influence of two dielectric fluids on both the technological performance and surface texture during the wire electrical discharge machining (WEDM) of submicron-grain tungsten carbide (WC–Co) using molybdenum wire. Five levels of lateral infeed were tested, with deionized water employed as the dielectric medium in one set of trials. Given the limited literature on WEDM with molybdenum wire, the present findings contribute to expanding the understanding of its machining behavior. The main conclusions are as follows: (i) Effect of discharge energy: Increasing discharge energy enhanced wire feed rate (Vf) and overall productivity. However, at the maximum lateral infeed ($\Delta y = 100\%$), productivity decreased markedly due to inadequate removal of debris from the working gap. (ii) The hydrocarbon-based dielectric provided superior machining performance at higher lateral infeed levels ($\Delta y \geq 50\%$), while deionized water outperformed at low infeed ($\Delta y = 10\%$). (iii) Surface integrity: Deionized water yielded lower surface roughness values. This effect is attributed to its low viscosity, which facilitates debris removal and reduces the occurrence of abnormal discharges. (iv) Influence of intermediate lateral infeed: For Δy between 25% and 75%, a nonlinear trend was observed—lower lateral infeed increased Vf while reducing surface roughness.

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