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ANALYSIS OF TOOL WEAR RATE DURING ELECTRICAL DISCHARGE MACHINING OF NON-CONDUCTIVE MATERIAL

Dragan Rodić, Marin Gostimirović, Milenko Sekulić,
Borislav Savković, Anđelko Aleksić

University of Novi Sad, Faculty of Technical Sciences, Department of Production Engineering

Abstract. *In contemporary industrial and technical domains, non-conductive ceramic materials have gained significant importance owing to their outstanding properties. However, their inherent brittleness makes their processing a major challenge, rendering conventional methods ineffective. To overcome this problem, electrical discharge machining with an assisting electrode has proven to be effective. The main problem of this innovative machining is the high tool wear compared to conventional EDM. Therefore, this paper analyzes the influence of basic parameters such as discharge current and pulse duration on the tool wear rate when eroding zirconium ceramics. In order to reduce tool wear, graphite powder was added to the dielectric. The discharge current has the greatest influence on the wear rate of the tool and the pulse duration is slightly shorter. The addition of graphite powder to the dielectric has a demonstrably positive effect on the wear rate of the tool.*

Key words: *Assisting electrode, Zirconium ceramic, Discharge current, Pulse duration, Graphite powder.*

1. INTRODUCTION

Electrical discharge machining (EDM) has long been a popular process for material removal, which is particularly suitable despite the different physical and metallurgical properties of electrically conductive materials. However, the increasing demand for ceramic materials in the metalworking industry poses a challenge due to the complexity of their sintering process, limiting the ability to machine intricate shapes in the final product. Various methods such as diamond grinding, ultrasonic machining, laser cutting, water jet cutting and ion beam machining are viable solutions for machining ceramics. However, there are still limitations in productivity, quality control and cost efficiency, so there is a need for innovative approaches to ceramic machining [1].

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Corresponding author: Dragan Rodić
University of Novi Sad, Faculty of Technical Sciences, Department of Production Engineering, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia
E-mail: rodicdr@uns.ac.rs

One innovative technique, Assisting Electrode Electrical Discharge Machining (AEEDM), has emerged through the introduction of an electrically conductive layer that enables the machining of traditionally non-conductive ceramics. The principles of this method were originally developed in the early 1990s and pioneered in 1995 by Japanese scientists Fukuzawa, Tani, Iwane and Mohri [2]. In their work, they presented a method in which a self-adhesive metal plate acts as an auxiliary electrode, which is attached to the workpiece together with a soft metal tool. This technique changed the ceramic surface and facilitated the machining process by developing an electrically conductive layer, which was a major leap forward in ceramic machining technology. The assisting electrode plays a central role as it promotes the first electrical discharge in AEEDM [3]. The high temperatures in the discharge zone decompose the layer of the supporting electrode, which leads to the dissolution of the dielectric and the deposition of carbon particles that form an electrically conductive carbon layer, which is essential for process stability [4].

Research by various scientists emphasizes the use of a carbon-based dielectric oil to consistently form this conductive carbon layer to ensure process safety and stability [5]. Several studies emphasize the importance of this dielectric medium for the formation of the electrically conductive carbon layer, which is critical for successful AEEDM processing of non-conductive ceramics [6]. Studies investigating different supported electrode designs show their technological impact on the AEEDM [7]. Comparative analyses show that the use of a copper grid significantly reduces surface roughness, which promises improved machining precision. Further studies investigate the influence of tool materials and thermal conductivity on AEEDM productivity [3]. For example, the choice of copper or graphite tools has an effect on the formation of carbon layers and surface quality. In addition, the thermal conductivity of aluminum oxide correlates directly with machining efficiency. In die-sinking EDM with high discharge energy, the researchers found that tool polarity has a significant influence on crater volume, depth and relative tool wear. In addition, the formation and stability of the carbon layer during die-sinking EDM depend on the discharge energy. This is a decisive factor that determines the properties of the layer and influences the efficiency and precision of the entire process [8].

The application of AEEDM has limitations, in particular the relatively high wear rate of the tools. To overcome these limitations, the addition of an electrically conductive powder is crucial, as it reduces the insulating properties of the dielectric [9]. Consequently, this change results in a larger working gap, which enables more efficient flushing of the working space between the tool and the workpiece. Consequently, this process improvement aims to reduce tool wear during machining.

This research uses a novel hybrid auxiliary electrode that combines a self-adhesive copper metal foil with a graphite layer. The main objective is a comprehensive analysis of tool wear in the Assisting Electrode Electrical Discharge Machining (AEEDM) technique. In particular, the relationship between the discharge current and the pulse duration is to be investigated. In addition, the influence of the incorporation of graphite powder into the dielectric material as one of the basic parameters was investigated. The main focus of this work is to establish that the combination of the AEEDM process with a composite powder dielectric leads to a significant improvement in tool wear rate, particularly when machining non-conductive ceramics. By demonstrating this improvement, the research highlights the effectiveness of this combined approach in significantly improving machining processes with non-conductive ceramic materials.

2. MATERIAL AND METHODS

The experiments were conducted utilizing an Agie Charmilles SP1-U die-sinking EDM machine to process insulating zirconium oxide (ZrO_2) using isotropic graphite electrodes with a cross-section of 10×10 mm^2. The selection of graphite tools was deliberate, considering their stability in forming the essential electrically conductive layer required for machining non-conductive ceramics like zirconium oxide.

A novel technique has been devised specifically for machining insulating ceramic materials with EDM. This method involves applying a layer of graphite 33 lacquer and a copper foil adhesive layer (3M grade 1181) onto the workpiece surface. Typically, self-adhesive aluminum and copper metal foils are employed in conjunction with graphite coatings. The combination of a metal foil and a graphite coating constitutes what is termed a hybrid assisting electrode.

Table 1 outlines the processing conditions customized for zirconium oxide. Throughout these experimental setups, the discharge current remained constant at 1.5 A, while deliberate adjustments were made to the pulse duration to explore its impacts on the machining process. This systematic variation in the pulse duration enables a comprehensive study of its influence on machining outcomes and facilitates establishing a discernible correlation between the pulse duration and the tool wear rate in zirconia.

Table 1 Machining conditions

Parameters	Experiments		
	Test 1	Test 2	Test 3
Discharge current [A]	1.5	1.5	1.5
Pulse on time [µs]	42	75	100
Open circuit voltage [V]	300	300	300
High tension current[A]	0.5	0.5	0.5
Polarity	(-)	(-)	(-)
Duty factor [%]	50	50	50

After analyzing the pulse duration, a series of experiments were carried out to investigate the effects of introducing graphite powder into the dielectric medium. This subsequent phase comprised three further experiments that differed in their composition. The first experiment served as a baseline and was performed without additional powder. Subsequently, the second experiment was carried out with a graphite powder concentration of 4 g/l in the dielectric medium. Finally, the third experiment was carried out with a higher concentration of 8 g/l graphite powder added to the dielectric material. These intentional variations in graphite powder concentration were used to thoroughly evaluate the influence and effectiveness of the different concentrations on the AEEDM process. These experiments provide a detailed understanding of how the different concentrations of graphite powder affect tool wear rate and machining performance, and offer important insights for future optimization of the machining of non-conductive ceramics.

The tool wear rate (TWR) is defined as follows: Before each machining operation, the total length of the tool is measured using an Abbe microscope to measure the length. After machining, the tool is measured again to determine its length after the operation. The difference between these two lengths indicates the wear of the electrode in the longitudinal direction. If this value is divided by the erosion depth, the result is the so-called tool wear rate.

3. RESULTS AND DISCUSSION

The application of assisted electrical discharge machining (AEEDM) to ZrO_2, a notoriously difficult material, encountered a significant obstacle in the initiation of electrical discharges, particularly at an open voltage of 100 V. This obstacle was caused by insufficient discharge energy in the machining gap between the tool electrode and the ceramic workpiece, preventing the formation of an effective carbon layer, which is essential for the machining process.

This limitation led to operational inefficiencies and posed a significant problem. However, a decisive breakthrough was achieved by introducing an auxiliary current of 0.5 A in conjunction with a voltage increase to 300 V. This strategic adaptation not only overcame the previous hurdles, but also enabled the successful processing of insulating ceramics and overcame the challenges associated with ZrO_2. Remarkably, this optimized configuration was achieved and validated with the SPU-1 machining system, representing a significant advance in the application of AEEDM for intricate and insulating ceramic materials.

As stated in the study [5], the most important input parameters in AEEDM, especially for insulating ceramics, are discharge current and pulse duration, which are widely regarded as the most important factors in EDM processes. Previous studies in the field of AEEDM have reported the use of discharge currents of up to 6 A for tool cross-sections of up to 1 cm^2, Fig 1.

In order to determine the stable pulse duration under certain processing conditions, a test experiment was carried out in which a constant discharge current of 1.5 A was maintained. The pulse on-time was varied at 42 μs and 100 μs, while the duty cycle τ remained constant at 50%. The aim of this experiment was to determine the optimum pulse duration to ensure the stability of the EDM process under the prescribed machining parameters. It should be determined according to the explanations in Table 1.

The results showed that pulse durations below 42 µs could not induce the formation of a carbon layer on the ceramic surface, making the AEEDM process for ZrO_2 completely unfeasible in this range. In contrast, a negative effect on surface roughness was observed at pulse durations longer than 100 µs, leading to a significant deterioration. In addition, the process showed signs of instability, which manifested itself in unwanted interruptions and affected the continuity and precision of the process. This highlighted the critical range of pulse duration between 42 µs and 100 µs, where a delicate balance exists to ensure effective carbon layer formation and optimal surface finish while maintaining process stability in AEEDM for ZrO_2.

Incomplete discharges have a detrimental impact on both workpiece surface integrity and tool longevity, as depicted in Fig 2. The presence of heightened discharge energy within the machining zone directly correlates with the discharge current, pulse length, and discharge voltage. In the realm of Advanced Electrical Discharge Machining (AEEDM), maintaining complete control over discharge voltage and current proves challenging.

Consequently, delving into the influence of pulse duration becomes pivotal, given its role in regulating discharge energy.

Manipulating pulse duration emerges as a strategic method to govern discharge energy, presenting a promising avenue for controlling the machining process. This adjustment empowers fine-tuning of the discharge energy, offering a viable means to optimize tool wear, surface quality, and overall process stability in AEEDM. Such control over this parameter compensates for the inherent limitations in adjusting other electrical parameters, underscoring its significance in achieving optimal machining outcomes.

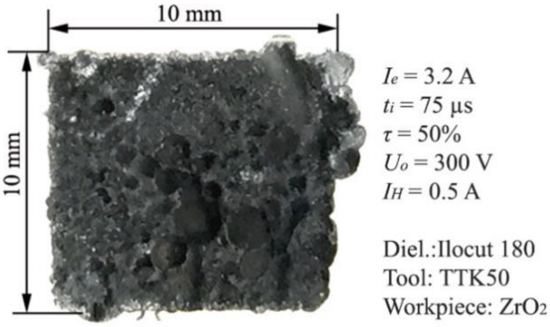

Fig. 1 The eroded surface after AEEDM with high discharge energy

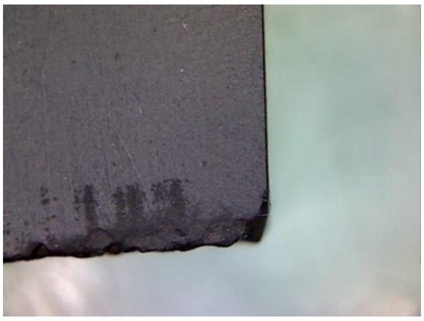

Fig. 2 Tool-electrode after AEEDM

The influence of the pulse duration on the wear rate of the tool is obvious, as can be seen in Fig 3. With increasing pulse duration in the range from 40 µs to 100 µs, a significant deterioration in the wear rate of the tool can be observed. This observation is consistent with previous preliminary tests and literature research conducted for AEEDM processes. Furthermore, it is worth mentioning that the selected range of pulse duration is based on both preliminary tests and findings from the existing literature. The recorded data show a direct correlation between longer pulse durations within the specified range and increased tool wear during AEEDM of insulating ceramics.

It is also interesting to emphasize that the duty cycle τ, which was constant at 50% in these experiments, plays a crucial role. The duty cycle in AEEDM processes for insulating ceramics is typically in the range of 20% to 50%, as described in the literature. This consistency of duty cycle is consistent with the parameters used in practice and contributes to the research on the effects of pulse duration on tool wear rate in AEEDM processes for insulating ceramics.

The start of the machining process required minimal input power, which led to the formation of a thin layer of pyrolytic carbon. However, this initial phase showed a remarkably high tool wear rate (TWR). Stable machining conditions were achieved in the pulse duration range of 40 to 100 µs, resulting in increased material removal. Significantly, a striking trend emerged that showed a direct correlation between pulse duration and tool wear rate, highlighting an increase in TWR with longer pulse duration. While these initial observations underline this correlation, further experiments are imperative to validate and consolidate these results.

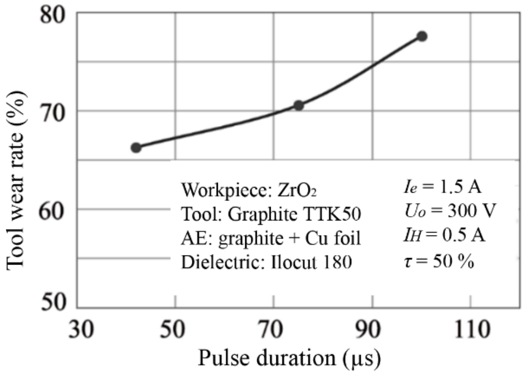

Fig. 3 Influence pulse duration on TWR

Conducting comprehensive experiments and careful analysis is essential to fully understand the exact effects of pulse duration on tool wear rate. These efforts are critical to determining the optimal pulse duration that strikes a balance between increasing material removal efficiency and controlling tool wear rate in AEEDM processes for insulating ceramics.

The current application of Assisted Electrical Discharge Machining (AEEDM) is reaching its limits, mainly due to the relatively high tool wear on electrically non-conductive materials. To overcome these challenges, a hybrid approach called Assisted Electrode Powder Mixed Electrical Discharge Machining ((AE + PM) EDM) has been introduced. In this innovative technique, an electrically conductive powder is introduced into the dielectric medium [10].

The integration of an electrically conductive powder serves to transform the conventional AEEDM process into a hybrid methodology [11]. This addition changes the dielectric properties, effectively increasing the conductivity and transforming the dielectric into a more conductive medium. Consequently, this change leads to an increase in the working gap between the tool and the workpiece. Importantly, this increased working gap allows for more efficient flushing of the machining area during the process [12].

A series of experiments were conducted to evaluate the influence of powder concentration on the effectiveness of the machining process. In these experiments, the input machining parameters remained constant, as shown in Fig. 4, while the powder concentration was systematically adjusted from 0 to 8 g/l. When applying the developed technique of AE (Assisted Electrical) + PM (Powder Mixed) EDM for the machining of zirconia ceramics, a remarkable trend was revealed: the introduction of graphite powder into the dielectric significantly improved the machining performance.

The results of the preliminary tests clearly showed that although the addition of graphite powder led to an improved tool wear rate, there was an upper limit to the optimum concentration. It was observed that tool wear escalated beyond a tipping point, namely beyond a concentration of 4 g/l graphite powder. From these experiments it can be concluded that the upper limit for the graphite powder concentration should be 8 g/l.

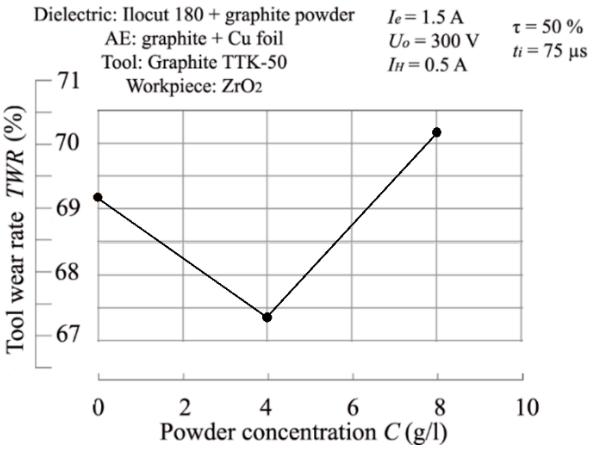

Fig. 4 Influence powder concentration on TWR

It can be clearly seen that the addition of graphite powder to the dielectric has a positive effect on the tool wear rate. Graphite powder, which is added to the liquid dielectric, reduces the insulating properties of the dielectric and causes an increase in the working gap between the tool and the workpiece. An increase in the working gap means more efficient circulation of the dielectric, i.e. washing of the working space between the tool and the workpiece. In this way, the EDM becomes stable, which leads to a reduction in tool wear. The main benefit of this change is the improved flushing of the working area between the tool electrode and the workpiece. By reducing the insulating properties of the dielectric through the use of an electrically conductive powder, the (AE + PM) EDM technique achieves greater efficiency. This strategic modification strengthens the AEEDM process, overcomes its inherent limitations and enables more effective machining of electrically non-conductive materials.

4. CONCLUSION

This study focuses on the analysis of tool wear rate (TWR) in electrical discharge machining (EDM) of non-conductive materials. A hybrid auxiliary electrode, consisting of a graphite coating and a copper strip attached to the workpiece, enables successful machining of zirconia. Research identifies the pulse duration as a critical factor that significantly influences the TWR. This effect is related to the simultaneous increase in discharge energy within the machining zone, which leads to increased tool wear, especially in the initial discharge zone. The integration of graphite powder in the dielectric together with the presence of the auxiliary electrode effectively reduces the relative tool wear by 6%. The lowest tool wear is achieved with a powder concentration of 4 g/l, a pulse duration of 75 µs and a discharge current of 1.5 A. These results show the promising potential of (AE + PM) EDM techniques in improving machining processes for challenging materials. The study highlights the relatively unexplored area of (AE + PM) EDM methods and signals a significant opportunity for continuous improvement and fine-tuning. Further research to optimize these processes promises greater efficiency, precision and suitability for machining electrically non-conductive materials.

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