http://doi.org/10.24867/JPE-2023-01-024

Journal of Production Engineering

Vol. 26 No. 1

JPE (2023) Vol.26 (1) Original Scientific Paper

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# ANALSYS OF DEFECT LAYER IN ELECTRICAL DISCHARGE MACHINING OF NON-CONDUCTIVE CERAMIC

*Received: 19 June 2023 / Accepted: 11 July 2023*

***Abstract:** The aim of the research is to describe a new approach for processing non-conductive ceramics. A method of electrical discharge machining with an assisting electrode is presented, which allows the machining of zirconium ceramics. An analysis of the defective layer, i.e., the recast layer and the heat-affected zone, was performed. Two parameters, discharge current and pulse duration, were chosen to study the effects on the thickness of the defect layer. The test results show that increasing the discharge current and pulse duration increases the thickness of the defect layer. This is due to the increase of discharge energy, which causes more heat in the machining zone. Future research can be directed to the analysis of a larger number of test points to see a better dependence between the machining parameters and the thickness of the defect layer.*

***Key words:** Assisting electrode, zirconia ceramics, recast layer, heat affected zone.*

***Analiza defektnog sloj pri elektroerozivnoj obradi elektroneprovodljive keramike.** Cilj istraživanja je da se opiše novi pristup obrade elektroneprovodljive keramike. Prikazan je metod elektroerozivne obrade sa pomoćnom elektrodom koji omogućava obradu cirkonijum keramike. Pri tome je izvršena analiza defektog sloja, odnosno rastopljenog sloja i zone uticaja toplote. Odabrana su dva parametra, struja pražnjenja i dužina impulsa, da bi se ispitao uticaj na debljinu defektnog sloja. Rezultati ispitivanja pokazuju da se povećanjem struje pražnjenja i dužine impulsa povećava debljina defektnog sloja. Razlog tome je povećanje energije pražnjenja koja prouzrokuje veću toplotu u zoni obrade. Buduća istraživanja mogu biti usmerena na analizu većeg broja eksperimentalnih tačaka kako bi se videla bolja zavisnost između parametara obrade i debljine defektnog sloja.*

***Ključne reči:** Pomoćna elektroda, cirkonijum keramika, rasopljeni sloj, zona uticaja toplote.*

## 1. INTRODUCTION

EDM is a widely used unconventional technique that finds extensive practical applications. It enables the machining of electrically conductive materials, irrespective of their physical or metallurgical characteristics. Its utility lies in processing challenging materials and intricate components with complex geometries, which are otherwise impractical or impossible to machine using traditional methods. The fundamental requirement for EDM is that the workpiece possesses a minimum level of electrical conductivity [1].

Despite the numerous advantages ceramic materials possess over metallic materials, their acceptance in the metalworking industry has been a gradual process [2]. This can be attributed, in part, to the limitations imposed by the sintering process, which restricts the production of complex geometries and poses challenges for machining the final ceramic product [3]. However, the machining of ceramic materials has gained importance in various industries due to their exceptional properties, such as high strength, heat resistance, corrosion resistance, and wear resistance. Several machining methods, including diamond grinding, ultrasonic machining, laser machining, abrasive water jet cutting, and ion beam processing, have been employed to machine ceramic materials. Nevertheless, these methods have certain limitations in terms of productivity, machining quality, and economic viability, which do not fully meet the requirements of modern production. Therefore, it is necessary to explore alternative methods for processing ceramic materials [5].

Assisting Electrode Electrical Discharge Machining (AEEDM) allows for the processing of electrically non-conductive ceramic materials by utilizing an assisting electrode, an electrically conductive layer placed on the workpiece's top surface [4]. The concept of incorporating the assisting electrode into EDM technology was initially documented in 1995 by Fukuzawa et al, Japanese scientists [5]. Their research presented a novel approach to electrical discharge machining, enabling the machining of non-conductive ceramic materials. By employing an adhesive metal plate as the assisting electrode, an initial electrical discharge occurs between the tool and the workpiece. As the assisting electrode layer is gradually removed due to the high temperatures in the discharge zone, dielectric dissolution takes place, leading to the deposition of carbon particles on the surface. This deposition forms an electrically conductive layer, known as the carbon layer, which ensures process stability during AEEDM. The formation process of the electrically conducting layer is also outlined by Tany et al [6] emphasizing the requirement of carbon-based dielectric oil for stable erosion of non-conductive ceramics. Similar phenomena and observations have been reported by Mohri et al [7]. and Hanaoka et al [8].

In the field of electrical discharge machining (EDM) for non-conductive ceramic materials, the typical approach involves the use of adhesive aluminum and copper metal foils, along with graphite coatings, as assisting electrodes [9]. When aluminum or copper metal foils are combined with graphite coatings, they form what is referred to as a hybrid assisting electrode, as depicted in Figure 1.

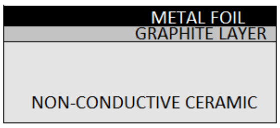

Fig. 1. Hybrid assisting electrode

Limited research has been conducted on this topic, but existing findings suggest that the material removal rate during EDM of non-conductive ceramic materials is significantly lower compared to that of metallic materials. Once the assisting electrode (AE) layer is removed, the high temperatures prevailing within the discharge zone lead to the decomposition of the dielectric. As a result, carbon particles are deposited onto the surface of the workpiece, effectively forming an electrically conductive layer.

To sustain the erosion process, the presence of a conductive layer is vital, and this layer needs to be continuously regenerated. Typically, this conductive layer is formed on the workpiece's surface through the decomposition of carbon material sourced from the hydrocarbon-based dielectric fluid environment. In the literature, this layer is also referred to as the pyrolytic layer or carbon layer [10].

The AEEDM process is visually depicted in Figure 2. Initially, the surface of the workpiece is coated with an electrically conductive material, enabling the occurrence of the first electrical discharge between the tool and the assisting electrodes. Subsequently, the discharge becomes continuous, traversing through the conductive layer and reaching the workpiece material, resulting in the production of the carbon layer, also known as the pyrolytic layer. Throughout the electrical discharge process, a conductive carbon layer is continuously formed on the workpiece, playing a crucial role in maintaining the stability of the entire machining process.

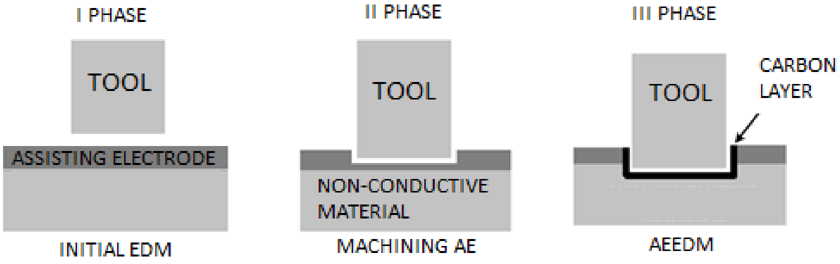

Fig. 2. EDM of non-conductive material using assisting electrode

Following the AEEDM process, significant changes can be observed in the surface morphology of non-conductive ceramics. The machining results in the deposition of various layers and induces microstructural alterations on the surface of the workpiece. Figure 3 provides a visual representation of the layers that were observed on the workpiece's surface after undergoing the AEEDM process.

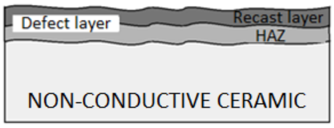

Fig. 3. Layers on top workpiece after AEEDM

The EDM process is characterized by random erosion, occurring at the smallest distance between the tool and workpiece surfaces. Higher discharge energy leads to a poor surface finish with larger craters, while lower discharge energy is recommended for achieving a less damaged surface with smaller craters. The formation and stability of the carbon layer, in addition to the materials used for the workpiece and tools, the type of dielectric, and the polarity of the tool, are influenced by the discharge energy, which is determined by the voltage, discharge current, and pulse duration [11]. Chen et al. conducted a study on the significant input parameters that affect machining performance and found that discharge current and pulse duration have a significant impact on surface quality [12].

It can be concluded that the current application of AEEDM is limited due to its relatively low surface quality. Additionally, due to the challenges in conducting experiments, there are only a limited number of scientific papers available on this type of machining. Therefore, the main contribution of this research is to analyze the defect layer during the EDM of non-conductive material. One specific non-conductive ceramic material studied in this research is zirconia ($ZrO_2$). A hybrid assisting electrode was utilized, consisting of self-adhesive copper metal foil and a graphite layer. The objective of this work is to demonstrate the feasibility of processing ceramics by examining the formation of carbon layers on the workpiece surface.

## 2. MATERIAL AND METHODS

A series of experiments was carried out on a die-sinking EDM machine Agie Charmilles of the SP1-U type. The isotropic graphite with a cross-section of 10×10 $mm^2$ was used as an electrode for machining insulating zirconium oxide $ZrO_2$. The reason for using graphite tools is that the formation of the electrically conductive layer is more stable than other types of tools, such as copper.

Based on the research [13], the main input parameters are discharge current and pulse duration where they are also commonly considered the most important parameter in EDM of insulating ceramics. According to the previous studies in the field of AEEDM, discharge currents up to 6 A have been used for tool cross sections up to 1 $cm^2$. Accordingly, tests were performed at 1 and 2 A. The pulse on time was 42 µs and 75 µs, and the duty cycle τ was constant 50%, Table 1.

| Parameters | Test 1 | Test 2 |
|---|---|---|
| Discharge current [A] | 1 | 2 |
| Pulse on time [µs] | 42 | 75 |
| Open circuit voltage [V] | 300 | 300 |
| High tension current [A] | 0.5 | 0.5 |
| Polarity | negative | negative |
| Duty factor [%] | 50 | 50 |

Table 1. Machining conditions

After AEEDM, the following experimental techniques were employed for assessing the defect layer of the non-conductive ceramic. In order to measure the thickness of the defect layer, a light microscope with a maximum magnification of up to 500x was used.

## 3. RESULT AND DISCUSSION

The values of defect layer for two machining tests is shown in Table 2. The electrical discharge energy depends on the machining parameters such as discharge current, voltage and pulse duration, because these parameters affect the defect layer.

| Parameters | Defect layer DL [µm] |
|---|---|
| Test 1 | 10.11 |
| Test 2 | 18.51 |

Table 2. The values of defect layer for machining tests

The determination of the thickness of the defective layer of the workpiece material was made by taking three measurements at the points where the thickness is greatest. The defective layer consists of a recast layer and a heat-affected zone. An example of the determination of the thickness of the defective layer in the AEEDM of zirconium is shown in Figure 4.

Since extremely high temperatures occur in the workspace during AEEDM, thermal defects are expected to occur in the surface layer of the workpiece material. Since these are changes in the condition of the surface layer that can significantly affect the function of the workpiece, special attention must be paid to them. The cross-section of surfaces machined with AEEDM at different discharge currents and pulse durations is shown in Figure 5.

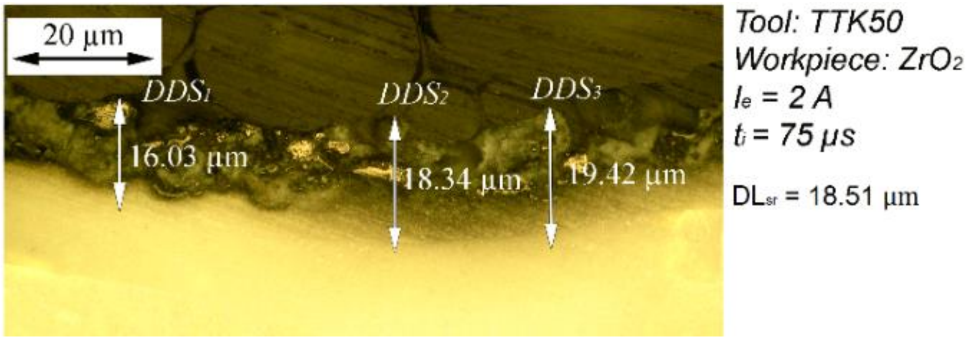

Fig. 4. Example of defining the thickness of the defective layer after AEEDM

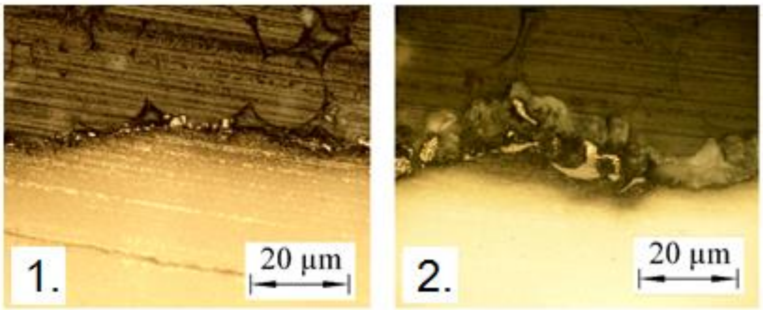

Fig. 5. Example of cross-sections of AEEDM at (1) 1A and 45 µs; and (2) 2A and 75 µs (optical pictures).

At a higher discharge current of 2 A and a pulse duration of 75 µs, the results of the second test showed a remarkable discrepancy in the defect layer compared to the first test. At the high discharge energy (test 2), the defect layer was found to extend to a depth of about 18 µm, which is almost twice as deep as in test 1. This observation suggests that higher discharge energies lead to a greater thickness of the defect layer. As can be seen, Figure 5 shows a comparative plot of the layer thickness for the different tests, providing a visual representation of the differences in processing quality. In this figure, it is clear that the differences in processing quality are more pronounced when stronger processing parameters are used. A closer look at the eroded surfaces after they have been exposed to the hydrocarbon oil reveals a significant presence of carbon. The carbon particles are primarily from the hydrocarbon oil and tool materials, in this particular case graphite. The erosion process facilitates the deposition of these carbon particles on the eroded surfaces, contributing to the observed carbon content.

## 4. CONCLUSION

The paper discusses the outcomes of an experimental study conducted to analyze the defect layer in non-conductive ceramic materials. By applying a graphite coating and utilizing an adhesive copper foil on the workpiece's surface, a hybrid assisting electrode was created, enabling successful electrical discharge machining of zirconia. The experiments demonstrated that lower discharge energy leads to improved machining quality. Specifically, superior results were obtained with a discharge current of 1 A and a pulse duration of 42 µs. These conditions resulted in a reduced defect layer. Overall, the research findings enhance our understanding of the AEEDM process, ultimately contributing to its increased competitiveness in the industry. As AEEDM is a relatively new machining technique that has yet to be fully explored, there remains significant potential for continuous improvement and refinement in the future.

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## ACKNOWLEDGMENT

This paper has been supported by the Provincial Secretariat for Higher Education and Scientific Research through the project no. 142-451-3175/2023-01/01: “Research of the innovative electricial discharge machining process of non-conductive materials”.

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