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MONITORING OF PHYSICAL PARAMETERS DURING THE PROCESSING OF CEMENTED CARBIDE END MILLS USING PLASMA DISCHARGE IN ELECTROLYTE

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Abstract
This study introduces an innovative Plasma Discharges in Electrolyte (PDE) as a novel method for cutting edge preparation of cemented carbide tools. Unlike traditional abrasive methods, PDE removes material through localized discharges in a vapor–plasma envelope, enabling non-contact edge rounding. The aim of the article is to evaluate observed parameters such as voltage, current, cutting edge radius during the PDE process. Experimental results on a 4-flute end mill show that edge radius develops non-linearly, with the highest material removal at the beginning. PDE proved up to 110% faster than drag finishing for larger radii.

Keywords:
Cutting edge preparation, Cutting edge radius, Cemented carbide, Plasma discharges in electrolyte, Drag finishing

1 INTRODUCTION

The optimization of cutting tool edge geometry has become a pivotal aspect of tool performance and wear resistance in advanced manufacturing processes. The creation of perfectly sharp cutting edges is not only technically challenging but often undesirable due to their lower durability and increased susceptibility to premature wear [Bassett 2012]. Instead, edge preparation through carefully controlled microgeometry, such as introducing a defined cutting edge radius or chamfer, has been shown to substantially enhance tool life and cutting performance.

In the study [Bouzakis 2014] analyzed the influence of various edge preparation methods on coated tools used for milling difficult-to-machine materials such as Inconel 718 and Ti6Al4V. The study concluded that larger edge radii and chamfers significantly reduced tool loading and delayed the onset of wear. Interestingly, the benefits of edge preparation were found to be minimal for materials like 42CrMo4 and 304L, where unprepared tools already experienced moderate cutting loads. The authors also addressed the trade-offs between the precision of microgeometry formation and associated manufacturing costs.

Authors [Denkena 2014] provided a systematic overview of cutting edge geometries and their standardized characterization. They emphasized the need for reliable, reproducible edge shapes to ensure consistent machining outcomes. As tool geometries continue to evolve with high-performance demands, so does the need for more sophisticated and unconventional methods of edge preparation.

Among the emerging techniques, laser-based preparation methods have demonstrated great potential. For example, Breidenstein et al. [Breidenstein 2013] investigated the influence of laser machining on the surface integrity of cemented carbide tools prior to the PVD coating. They found that laser treatment could successfully modify edge geometry without compromising subsequent coating adhesion. Similarly, Lickschat et al. [Lickschat 2020] performed fundamental studies on ultrashort pulsed laser ablation in carbide tools, demonstrating consistent ablation across different pulse durations at threshold fluence, making laser systems attractive for precision edge shaping.

The application of marking lasers for edge preparation was explored by Aurich et al. [Aurich 2011], achieving cutting edge radii ranging from 9 to 47 μm. This process offered a controllable alternative to traditional brushing and blasting. Additionally, Konrad et al. [Konrad 2012] compared laser-prepared cutting tools to ground tools in CFRP machining, finding that laser-processed tools performed comparably well, while also offering benefits such as localized material removal and the potential for in-process reconditioning.

Beyond laser approaches, hybrid methods such as electrolytic abrasive edge honing have been explored for their ability to combine electrochemical and abrasive mechanisms. Li et al. [Li 2018] demonstrated that this technique could effectively generate consistent edge profiles in cemented carbide tools. Electro-erosion honing, as described by Yussefian et al. [Yussefian 2010], further expanded the repertoire of non-mechanical methods for refining sharp cutting edges, using aluminum and copper counterfaces to form radii without being limited by the hardness of the tool material.

A particularly innovative method attracting growing attention is Plasma Discharges in Electrolyte (PDE). Unlike abrasive methods, PDE achieves material removal through the generation of electrical discharges in a vapor–gas film, leading to localized melting and vaporization of the surface [Podhorský 2015]. This process has been applied in a range of surface finishing tasks, from polishing and deburring to functional surface modifications [Yerokhin 1999]. The adaptability of PDE allows for diverse metallurgical transformations, including plasma electrolytic oxidation and alloying (e.g., nitriding, carburizing), making it suitable for applications in steels, titanium, and aluminum [Danilov 2019].

In recent years, PDE has been applied directly to the modification of cutting edge geometries. Vopát et al. [Vopát 2019] demonstrated that PDE can be used to achieve uniform edge rounding on cemented carbide tools without mechanical contact. Their further study [Vopát 2024] detailed a novel approach for forming cutting edge radii with high reproducibility while preserving favorable surface topography. The statistical evaluation of the PDE process in this study revealed that parameters such as current density and pulse duration significantly affected material removal rates and final edge shape.

The potential of PDE in tool manufacturing has also been supported by research on its effects on tool life and coating adhesion. Vopát et al. [Vopát 2020] analyzed AlCrSiN-coated carbide tools treated with PDE and found enhanced coating-substrate bonding and improved tool life, underscoring the technique's industrial viability. Moreover, Parfenov et al. [Parfenov 2016] explored the electric field's role in controlling surface layer removal during electrolytic plasma polishing, highlighting its precision and adaptability.

From a functional standpoint, PDE-treated cutting tools demonstrate reduced surface roughness and improved fatigue resistance. These qualities are crucial in high-performance applications, such as the machining of superalloys and heat-resistant steels. According to Celaya et al. [Celaya 2019], the cutting edge radius significantly affects tool life during Inconel 718 milling, further justifying the integration of advanced edge preparation techniques like PDE in such contexts.

In addition to these findings, other authors have emphasized the environmental and operational benefits of PDE. Compared to abrasive methods, PDE produces less waste and requires minimal post-processing [Yerokhin 1999], [Podhorský 2015]. Its applicability across a wide range of materials and geometries makes it a versatile tool in modern manufacturing.

The aim of the experiment is to initially investigate the development of PDE process parameters such as the course of voltage, current, temperature, and the achieved edge rounding radius during the edge preparation of a cutting tool – a cemented carbide end mill. According to the literature review, this issue has not been thoroughly explored, and the mechanism of material removal during the polishing of cemented carbide is not yet known. The article is one of the first to discuss the edge preparation of geometrically complex tools using the PDE method.

2 MATERIALS AND METHODS

In the experiment, a 4-flute end mill was used as the test sample. The cutting tools were manufactured using a Reinecker WZS60 tool grinding machine. For the production of the tools, a cylindrical blank made of cemented carbide (WC + 10% Co), marked CTS20D, with a diameter of 10 mm and a length of 73 mm, supplied by Ceratizit, was used. The immersion depth of the tool in the electrolyte was 50 mm. The end mill was clamped using a clamping sleeve (Fig.1).

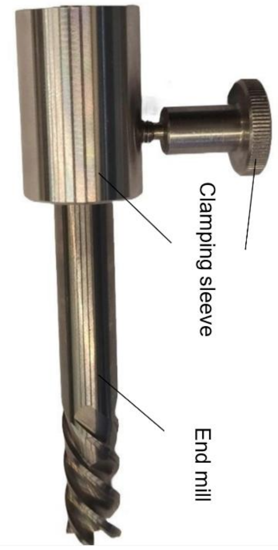

Fig. 1: Clamped end mill.

All clamping components were made of corrosion-resistant austenitic stainless steel, designated AISI 304.

The experimental setup for the PDE process (Fig.2) consisted of a 10-liter container. An electrode (cathode) connected to the negative pole of the power supply was mounted along the inner perimeter of the container. During the experiment, an electrolyte with a concentration (Ce) of 15% was used, with a set voltage of 340 V and a temperature of 69 °C.

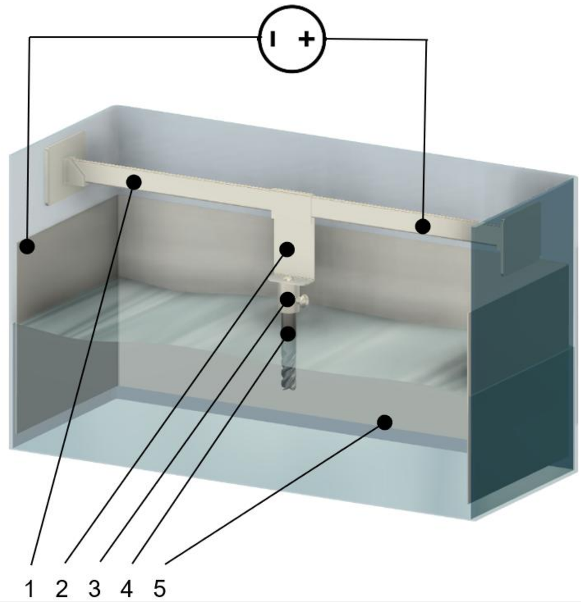

Fig. 2: Experimental setup for PDE process with used equipment: hanging rod (1), sample holder (2), clamping sleeve (3) end mill (4), electrolyte (5).

It should be noted, however, that process parameters such as voltage (U), current (I), and temperature (T_e) change during the polishing process. Therefore, the objective of the experiment was to record and clarify the variations in these monitored parameters. These parameters significantly influence the intensity of material removal as well as the resulting cutting edge rounding.

The end mill sample was tested three times to improve statistical significance. The process parameters (voltage U and current I) were recorded using a digital multimeter. The electrolyte temperature (T_e) was measured using a thermocouple placed approximately 100 mm from the sample.

3 RESULTS

Figure 3 shows a graph illustrating the dependence of voltage (U), and Figure 4 shows the dependence of electrolyte temperature (T_e) on the PDE process time Regarding temperature, the following can be observed. At the beginning of the process (0–0.5 min), the temperature is at its lowest and gradually increases linearly throughout the process. Prior to the start of the PDE process, the electrolyte is preheated to a temperature of 69 °C using heating elements.

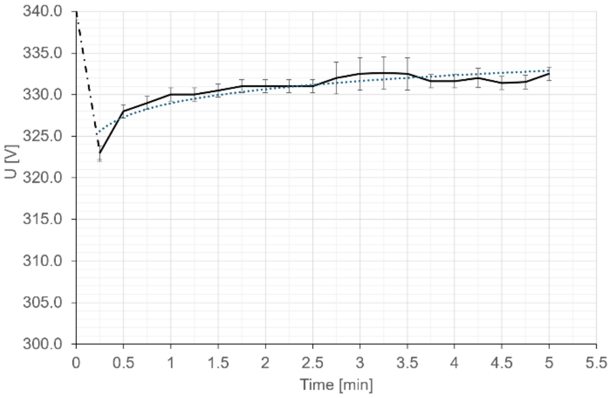

Fig. 3: Voltage dependency on time.

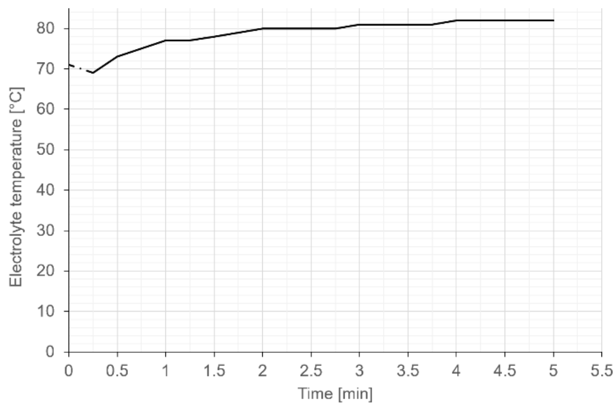

Fig. 4: Temperature dependency on time.

Immediately after the PDE process begins, a significant amount of heat is generated, which depends on the size of the treated sample. The rate of electrolyte heating is also affected by the volume of electrolyte in the container. The test apparatus is not equipped with an electrolyte cooling system. As a result, the electrolyte temperature (Te) increases linearly, reaching up to 82 °C.

Regarding voltage, a rapid decrease can be observed at the beginning of the process (0–0.5 min). This rapid decrease is caused by the initiation of the PDE process, where the initial voltage of 340 V represents the open-circuit voltage i.e., when the tool was not yet in contact with the electrolyte. Upon contact and immersion into the electrolyte, the voltage decreased to a value of 323 V.

Due to the gradual immersion of the tool into the electrolyte, which requires several seconds depending on the sample size, a vapor–plasma envelope forms progressively around the tool. The vapor–plasma envelope does not form abruptly, and the process is largely unstable during the initial phase (0–0.5 min). At the beginning of the process, there is a significant change in current density and electrical resistance between the electrodes and the sample, which contributes to the instability of the process. Once the vapor–plasma envelope is formed around the entire sample and the current density, temperature, and other factors stabilize, the process becomes predictable and stable. At the start of the process, the most rapid material removal occurs at the elevated areas of the sample (edges).

The magnitude and behavior of the voltage are significantly affected by the process temperature as well as the size and topology of the sample. After the stabilization of the process (0.5–5 minutes), the voltage does not follow a linear trend but rather a logarithmic one (the increase becomes smaller over time). During the experiment, slight fluctuations were recorded, and for this reason, a trend line was constructed to represent the theoretical development of the voltage over time with respect to the process parameters.

Figure 5 shows a graph depicting the dependence of current on the PDE process time.

From the graph, it is evident that at the beginning of the process (0–0.5 min), the current rapidly increased from 0 A to 53.4 A. This increase is caused by the gradual immersion of the tool into the electrolyte and the formation of the vapor–plasma envelope at the start of the PDE process. When the tool comes into contact with the surface of the electrolyte, the circuit closes and the current (I) begins to flow.

As mentioned earlier in relation to the voltage, due to the gradual immersion of the tool into the electrolyte—which requires several seconds depending on the sample—the vapor–plasma envelope forms progressively around the tool. The vapor–plasma envelope does not form abruptly, and the process is largely unstable in its initial phase (0–0.5 min). At the beginning of the process, there is a significant change in current density and electrical resistance between the electrodes and the sample, which contributes to the instability of the process. Once the vapor–plasma envelope is fully formed around the entire sample and the current density, temperature, and other factors stabilize, the process becomes predictable and stable.

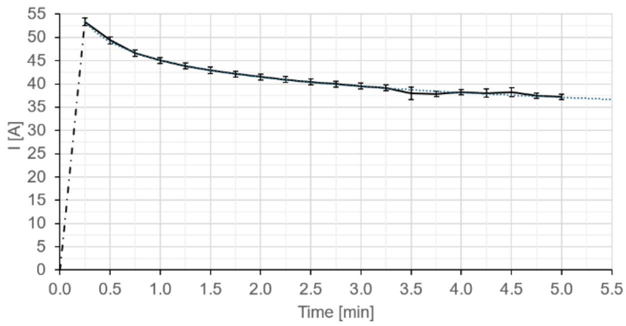

Fig. 5: Current dependency on time.

Current fluctuations (at 3.5 min and 4 min) are caused by the pulsating component of the output voltage and local changes in current density. Additionally, the observed oscillations may be partially attributed to the fact that the plotted values represent averaged data, which can smooth out short-term variations while still reflecting underlying instabilities. It is observed that the current and voltage values follow a similar pattern but in opposite directions.

Therefore, a trend line was constructed to represent the theoretical development of the current over time with respect to the process parameters.

The dashed line in the Fig. 3,4 and 5 represents a step change in voltage, current, and partially in temperature at the beginning of the process, caused by the formation of a plasma envelope around the sample.

The process parameters (temperature, voltage, and current) were monitored until a radius of r_n = 35 μm was reached (after approximately five minutes). The process then continued until a radius of r_n = 50 μm was achieved (after approximately nine minutes), but without further recording of these parameters.

Figure 6 shows a graph illustrating the dependence of the edge rounding radius (r_n) on the PDE process time. The graph clearly indicates that the progression of the achieved edge rounding r_n is not linear. The amount of material removed from the polished surface strongly depends on the electrolyte temperature (T_e) and the initial surface roughness prior to polishing.

During the polishing process, the surface roughness decreases. As a result, the material removal rate is at its maximum at the beginning of the process and gradually decreases as the surface becomes smoother.

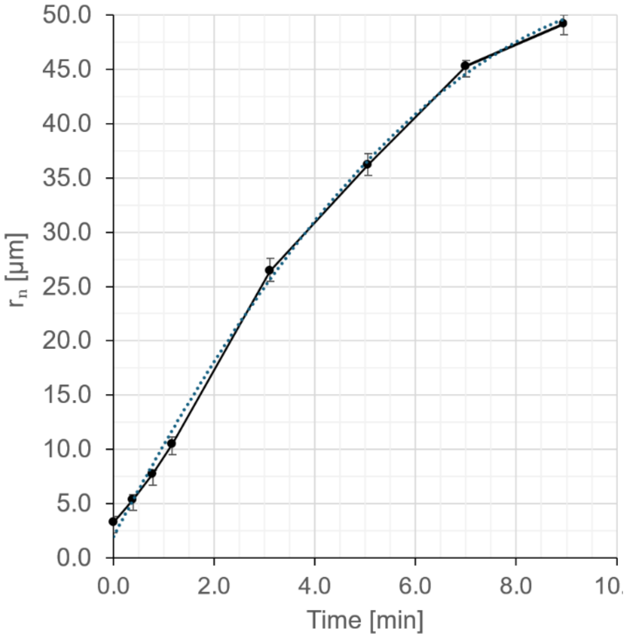

Fig. 6: Cutting edge radii dependency on time.

4 DISCUSSION

The PDE method was compared with the DFM method, for which the data were obtained from the dissertation of a co-author [Pätoprstý, 2022]. In that study, an experiment was conducted using a prototype drag finishing device. Technological parameters such as finishing time, immersion depth, and others were set on the device. Aluminum oxide (Al_2O_3) was used as the finishing medium, and the cutting tool was clamped using a universal chuck.

From Figure 7, it can be seen that the percentage difference in the speed of achieving an edge rounding radius of **r_n = 25 μm** using the PDE method is approximately **60% faster** than the radius achieved using the DFM method.

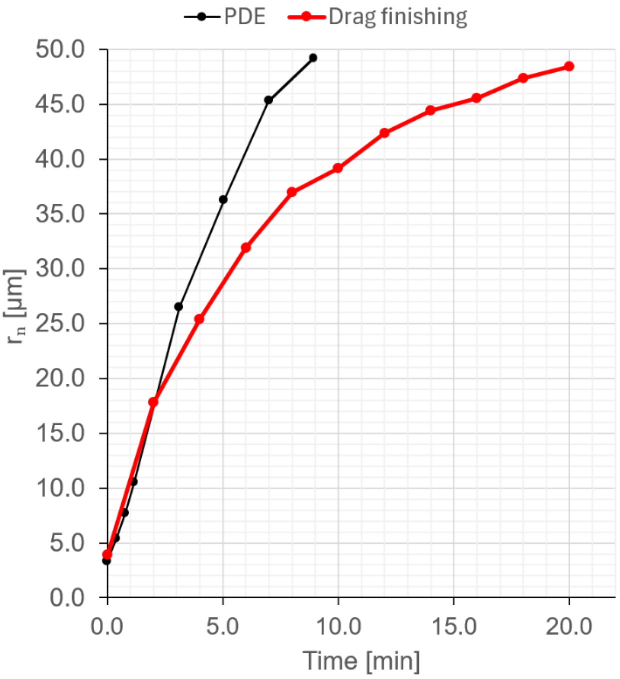

Fig. 7: Comparison cutting edge radii achieved with PDE and DFM methods.

The difference between the PDE method and the DFM method is even more pronounced in the case of larger radii (Table 1).

Tab. 1: Comparison of cutting edge radii achieved with PDE and DFM methods.

Cutting edge radius	**Rounding speed increase using PDE compared to DFM**
25 μm	60%
30 μm	71%
45 μm	110%

5 CONCLUSION

The study investigates the optimization of cutting edge microgeometry, with a focus on Plasma Discharges in Electrolyte (PDE) as a novel, non-mechanical method for edge rounding of cemented carbide cutting tools (WC + 10% Co, grade CTS20D).

The experimental part of the study used a 4-flute cemented carbide end mill with a diameter of 10 mm. A 4-flute end mill was used as the test sample, with an immersion depth of 50 mm in an electrolyte of 15% concentration. The process was carried out at a set voltage of 340 V and a starting electrolyte temperature of 69 °C.

The voltage dropped upon immersion, stabilizing as the plasma envelope formed, while the electrolyte temperature steadily increased to 82 °C due to the lack of cooling. Current and voltage were monitored to assess process behavior. The most intense material removal occurred during the initial unstable phase, tapering off as the surface roughness decreased.

Results showed that edge radius development (r_n) did not follow a linear trend. Instead, material removal rates slowed over time, correlating with smoother surface finishes. Comparison with the DFM (drag finishing) method revealed that PDE achieved a 25 µm radius approximately 33% faster and a 40 µm radius about 110% faster, highlighting its efficiency.

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