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Analysing Energy Consumption and Productivity in Die Sinking Electrical Discharge Machining of PCD materials

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Abstract

This study examines the application of Electrical Discharge Machining (EDM) in the processing of polycrystalline diamond (PCD) tools. It focuses on machining parameters, material removal mechanisms, and energy consumption, while also addressing the challenges posed by PCD's low electrical conductivity and unique structure. The experimental findings indicate that, although PCD can be processed using EDM, energy losses and residue formation significantly impact productivity. The research underlines the importance of optimizing parameters to enhance the efficiency of machining PCD-based materials.

Keywords

electrical discharge machining, polycrystalline diamond, removal mechanism

1. Introduction

The use of tools with a high hardness has expanded due to the need to process materials with higher hardness and hard to machine such as titanium alloys [1] and composite materials [2]. These considerations have led to the expansion of the use of polycrystalline diamond (PCD) based materials in the construction of tools for used in traditional machining. Although PCD has notable technological performance, it is difficult to machine this type of material using conventional processes, especially in the case of small tools. This is one of the reasons why it is difficult to identify such tools in manufacturers' offers.

This article presents a possible use of electrical discharge machining (EDM) to generate the necessary profile for a PCD-based cutting tool. The electrical erosion machining process is based on the removal of material based on electrical discharges, with controlled parameters, between the tool and workpiece. In other words, material removal occurs due to thermal energy of the spark in case of homogeneous materials. For this reason, it is necessary that both to be electrically conductive. If for the tool electrode the problem is solved by using materials with high electrical conductivity (e.g. Copper) [3], materials based on diamond polycrystals present a problem in this context. PCD is a material made by sintering diamond (natural or synthetic) particles into a matrix by using a binding material, usually Cobalt in commercial products.

Taking into account this way of obtaining of the final, this generates a reduced electrical conductivity of the PCD layer, due exclusively to the electrical conductivity of metallic bonding material, being known that diamond is an electrical insulator [4, 5]. Theoretically, PCD materials have an electrical conductivity, but in practice this is reduced. However, the minimum conditions are met so that PCD materials can be processed by EDM. In [6] it is stated the materials with a minimum 0.01 S/cm of electrical conductivity can be machined by EDM. Although the research refers to the processing of ceramic materials, due to the similar way of making PCD, this value can also be extended to the case of PCD.

The need to use a non-traditional process for machining PCD is primarily due to the fact that these products typically result in the form of a disc, as presented in Figure 1. Physically, this PCD layer (diamond plus binding material) is deposited on top of a carbide substrate. Due to this particularity, the first attempts to use EDM were by using wire EDM for slicing [7]. Although this method is used, and is also a starting point in choosing technological parameters in this article, it is based on the following constructive aspect. Wire EDM of PCD is based on the fact that the carbide base layer has sufficient electrical conductivity to make electrical erosion machining possible. The result is PCD pieces that can then be brazed onto various tool holders that can be used, for example, in turning operations (Figure 2).

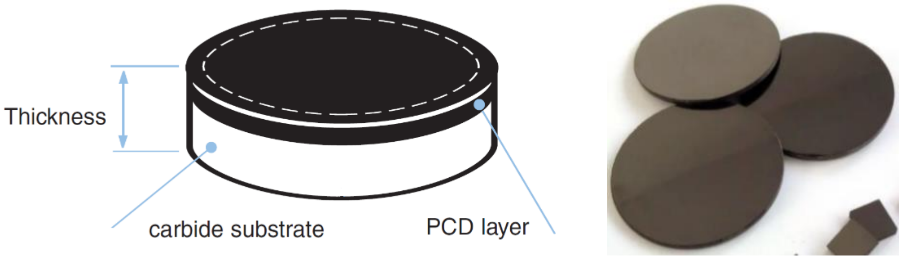


Fig. 1. PCD Structure and physical shape

Fig. 2. PCD sliced in pieces by using wire EDM

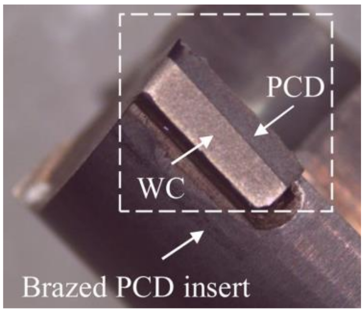


Fig. 3. PCD blanks brazed on a turning holder [8]

Regardless of whether slicing is done longitudinally or transversely, the problem of creating specific surfaces for a cutting tool remains. For wire EDM parts, grinding is the most used profiling method, or even a combined process like grinding plus electrical discharge machining [9]. These aspects were taken into account in this article to initiate experimental research on die-sink EDM of PCD.

2. Experimental research

The first issue in starting an experimental program regarding PCD machining by using die-sink EDM was to choose concrete technological parameters for machining, these being chosen by similarity to those used in wire-EDM machining of PCD.

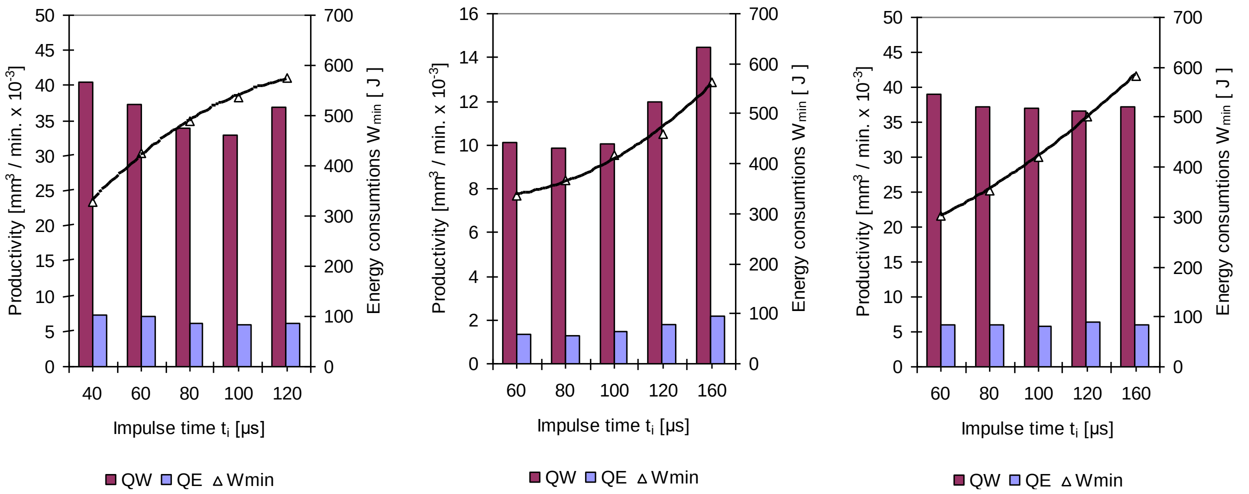
When processing homogeneous materials in terms of electrical conductivity and structure (for example, metallic materials), the erosion mechanism is known, being based on the use of heat released by the plasma channel associated with the discharges to melt the material. In the case of PCD, the material structure is not homogeneous, being the result of the random mixing between diamond and the binding material. In addition to metallic materials, diamond is a very good thermal conductor. This causes the rapid diffusion of the thermal energy generated by the discharges, which is an unfavourable aspect in relation to the location of the discharges. The consequence of this particularity implies that additional energy is required to determine dimensional processing with adequate efficiency.

The experiments described in the article were carried out using an Agie Mondostar 20 wire EDM machine. This machine is equipped with a generator capable of delivering a maximum of 64 A working current. The tool electrodes, made from copper sheet rectangles, were positioned transversely relative to the PCD blanks and had thicknesses of 0.5, 1.0, and 2 mm. The workpiece used was a PCD 020, characterized by a grain size of 20 µm and a PCD layer thickness of 0.7 mm on an 8 mm carbide substrate. The machining parameters included a synthetic dielectric made of polymers, with discharge currents set at 1.5 and 3 A. The pulse on times were 40, 60, 120, and 160 µs, while the break times were 160 and 200 µs. For all samples, the machining duration was consistently 4 minutes.

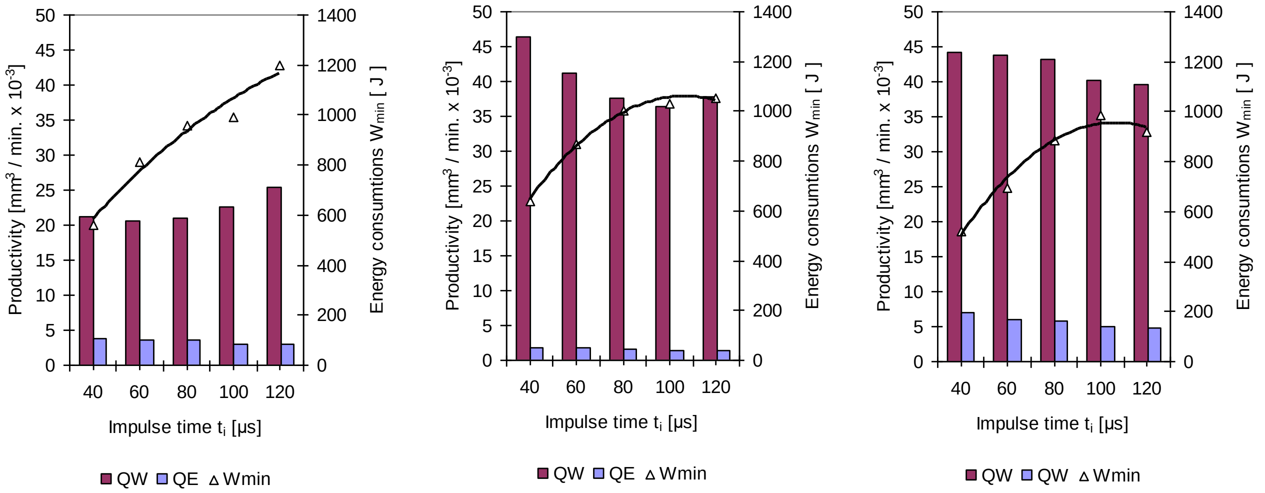
The most important parameter that characterizes the machining of Polycrystalline Diamond (PCD) is productivity. This is calculated using the following standard formula: $Q = V / t$ [mm^3/min], where Q represents productivity, V is the volume of material removed from the workpiece [mm^3], and t represents the discharge time [min].

Energetic consumption represents the amount of energy consumed to remove a quantity of material from the workpiece. Consequently, $Wmin$ is a ratio between the energy used for removal over one minute.

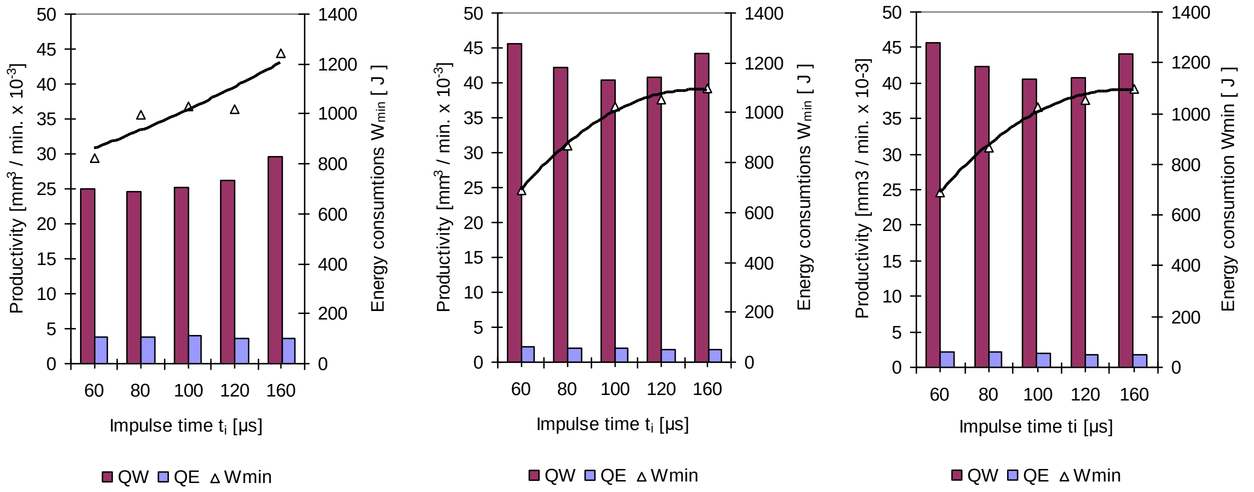
This energy includes all energetic components such as the energy for material removal from the workpiece and tool electrode, short-circuit pulses, and the energy necessary for transporting particles, etc. The experimental results are presented in Figure 4. A sample of processed PCD blank is presented in Figure 5.



a) th= 1mm, tp = 160µs, I = 1.5A b) th= 0.5mm, tp= 200µs, I= 1.5A c) th= 1mm, tp = 200µs, I = 1.5A



d) th= 0.5mm, tp = 160µs, I = 3A e) th= 1mm, tp = 160µs, I = 3A f) th= 2mm, tp = 160µs, I = 3A



g) th= 0.5mm, tp= 200µs, I = 3A h) th= 1mm, tp= 200µs, I= 3 A i) th= 2mm, tp= 200 µs, I= 3A

Fig. 4. Experimental data at EDM of PCD

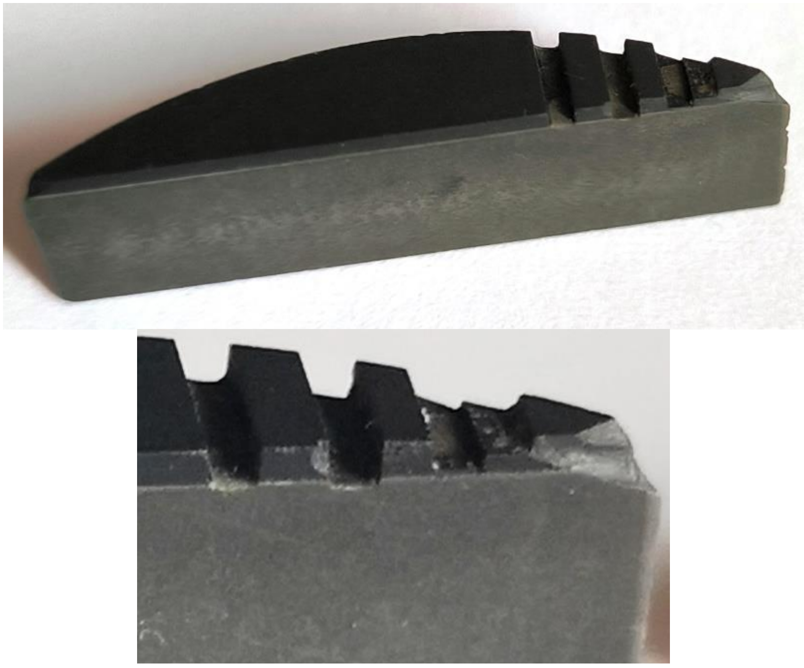


Fig. 5. PCD blanks processed by die sink EDM

3. Results and Discussions

The speed of machining Polycrystalline Diamond (PCD) is influenced by two primary factors: the amount of cobalt sintered with the diamond crystals and the particle size of the PCD. Higher cobalt content tends to enhance toughness and thermal conductivity, potentially increasing productivity. Conversely, larger PCD particles, while offering superior wear resistance in future tools, require significantly higher voltage for machining via Electrical Discharge Machining (EDM) due to their greater size and density.

For electrodes of 0.5 and 1 mm, the machining curves exhibit similar descending trends as the pulse ratio increases. This phenomenon is attributed to the limited ability to expel erosion residues. The most significant factor in the energetic balance is the increasing energy consumption for processes unrelated to electrical discharge.

These observations are more pronounced in case of the 2 mm electrode. Due to its larger surface area, the path of the eroded particles is extended, resulting in the lowest recorded productivity. In all cases, a minimum point in the central zone of the graphs can be observed, with varying explanations based on the break time duration. At lower values, the increase may be due to improved discharge conditions. At higher values, the increase is attributed to the fact that more energy is supplied to the discharge channel, leading to the removal of more material.

The distinct characteristics of electrical discharge machining polycrystalline diamond stem from the material's structural and compositional properties. Specifically, these include the laminar structure of the PCD as a composite material, the configuration of the PCD layer, and the relatively low electrical conductivity of this layer. The latter factor adversely impacts both the productivity and stability of the EDM process.

4. Conclusions

The main conclusion resulting from the experimental research is that PCD blanks can be processed by die sink EDM.

In the case of polycrystalline diamond, it is assumed that the higher plasma concentration would lead to a greater quantity of material removed with the same energy input compared to other materials. However, this is not the actual situation. For homogeneous materials, a significant amount of energy is lost in secondary processes, such as melting and the adhesion of metallic residues to the crater edges. In the case of PCD, this energy loss cannot be ignored.

Electrical discharge machining of PCD generates two types of residues, a phenomenon not observed in homogeneous materials. The relatively larger residues are diamond crystals, while the smaller ones are binder residues (cobalt, in this study). These binder residues form a thick film on the surface of the PCD, enhancing conditions for subsequent discharges.

A notable observation is that diamond particles tend to graphitize at temperatures above 800°C, which are commonly reached during EDM. This high temperature, along with the thick layer of electro-conductive material on the PCD surface, leads to an increase in short-circuit pulses. These pulses do not contribute to material removal but instead increase energy losses, which may explain the high energy consumption observed.

The most significant factor in the energy balance is the increased energy consumed for phenomena other than those related to electro discharge.

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