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Surface modification of tungsten carbide cobalt tool electrodes by heat treatment under nitrogen atmosphere for electro-discharge drilling

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Abstract
The requirements for high-precision components for tool and mould-making, automotive and aerospace industries are constantly increasing. Due to the strong mechanical properties of the used materials, such as tool steels and nickel-based alloys, conventional cutting processes are not always suitable. Instead, electrical discharge machining is used for cutting electrically conductive materials. One challenge even today is debris formation, causing arcs and short-circuits in the lateral working gap. This applies particularly to electro-discharge drilling with high aspect ratios and increased difficulties of debris removal. This leads to increased process instability, tool wear and conicity as well as decreased material removal rates.
To reduce the effects of arcing and short-circuits in the lateral working gap, tungsten carbide-cobalt tool electrodes with an outer diameter of d_O = 1.5 mm were heat-treated to increase the electrical resistivity of the electrode's surface. For this purpose, two different ambient atmospheres were selected, a nitrogen atmosphere and vacuum in comparison. Subsequently, the modified tool electrodes were used to produce boreholes in tool steel of the type Elmax Superclean with a depth of e_t = 6.75 mm by electro-discharge drilling. The surface modification in the nitrogen atmosphere led to a slightly higher material removal rate and a decrease in the linear tool wear of the tool electrode by up to 6.67 % compared to an untreated reference electrode.

Electrical discharge machining, Heat treatment, Surface

1. Introduction

Nowadays, the necessity for high-precision components is steadily increasing. These components consist of materials, such as tool steels, carbides and superalloys, which are difficult to machine by conventional methods. Electrically conductive materials with high hardness H and strength f can be machined by electrical discharge machining (EDM) instead. In addition to tool and mould making, this technology is also used for various applications in automotive and aerospace industries, e.g. fuel injection nozzles and cooling holes in turbine blades [1].

Another challenge in EDM is the formation of debris that lead to an increase in lateral discharges and short-circuits in the working gap. These types of discharges favor process instabilities, reduced material removal rates $\dot{V}_W$, increased linear tool wear Δl_e and conicity α. Particularly in electro-discharge drilling, higher aspect ratios increase this problem.

There are various approaches to improve the machining results, e. g. flushing through the inner channel of the tool electrode. This can be further improved by special methods such as inverted pressure flushing [2] or exterior flushing channels [2, 3]. Instead of actively removing the debris, coating, such as chemical vapour deposition [4] or thermal oxidation [2, 5] can also be used to insulate the lateral surface of the tool electrode, reducing the probability of short-circuits and arcing on the lateral surface A_l.

In this work, tungsten carbide cobalt tool electrodes, usually used for machining holes with smaller diameters d_o < 1 mm, were treated in a nitrogen atmosphere and compared to a treatment in vacuum. The resulting layers and their effects on the electro-discharge drilling process were analysed.

2. Methodology

2.1. Heat treatment

The multi-channel tool electrodes with an outer diameter of d_o = 1.5 mm and an inner diameter of d_i = 0.85 mm manufactured by Balzer Technik SA, Domdidier, Switzerland, were first cleaned with ethanol. Afterwards, these tool electrodes were heat treated in a nitrogen atmosphere in a furnace of type RHTC 80-450/15 from Nabertherm GmbH, Lilienthal, Germany, with the parameters given in Table 1.

Table 1 Parameters for heat treatment

Heat treatment	I	II	III	IV	V
Temperature ϑ [°C]	1,100	1,000	1,100	1,000	1,100
Duration t [h]	4				
Nitrogen pressure p [mbar]	200	200	-	-	100

Nitrogen was chosen because it can potentially diffuse into the tool electrodes and react at the surface to form insulating layers. For comparability purposes, two heat treatments were performed in a vacuum. After all heat treatments, the electrical resistivity ρ was determined by the four-point probe method using the high-precision multimeters DMM 5001 by Prema Semiconductor GmbH, Mainz, Germany and Model 175 Autoranging by Keithley Instruments, Solon, USA. In addition, images of the cross-sections of the tool electrodes were taken by scanning electron microscopy (SEM) of type DSM 982 Gemini by Carl Zeiss, Oberkochen, Germany.

2.2. Electro-discharge drilling

Drilling experiments with the heat treated tool electrodes were conducted on the machine tool AGIE compact 1 by GF Machining Solutions, Losone, Switzerland. Through holes with a depth of d = 6.75 mm were produced in tool steel of type

Elmax Superclean, from the company VOESTALPINE, Linz, Austria. In addition to the generator parameters in Table 2, pressure flushing with a flushing pressure of $p_f = 10$ bar and a rotation with a rotational speed of $n = 1{,}000$ 1/min were used. The material removal rate $\dot{V}_W$ as well as the linear tool wear Δl_e were determined.

Table 2 Generator parameters for electro-discharge drilling

Charge current i_C	Open circuit voltage $\hat{u}_i$	Ontime t_{on}	Offtime t_{off}	Discharge capacity C_e
5.6 A	160 V	32 µs	18 µs	1 µF

3. Results

3.1. Electrical resistivity

The electrical resistivities ρ measured by the four-point probe method of the heat treated tool electrodes and the untreated reference electrode are shown in Table 3.

Table 3 Electrical resistivity ρ (n.s. = not specified)

Heat treatment	Ref	I	II	III	IV	V
Electrical resistivity ρ [Ωmm²/m]	0.2064	n.s.	0.2188	0.2335	0.2190	0.2240
Standard deviation σ	0.0018	n.s.	0.0004	0.0014	0.0013	0.0001

A dependence of the electrical resistivity ρ on the heat treatment temperature ϑ can be highlighted. Tool electrodes treated at a temperature of $\vartheta = 1{,}100$ °C showed a greater electrical resistivity with up to $\rho_{III} = 0.2335$ Ωmm²/m compared to tool electrodes treated at $\vartheta = 1{,}000$ °C with up to $\rho_{IV} = 0.2190$ Ωmm²/m, respectively. Both showed an increased electrical resistivity compared to the reference tool electrode with $\rho_{Ref} = 0.2064$ Ωmm²/m. Note, that an electrical resistivity ρ for tool electrode I could not be measured, indicating complete insulation of the formed layer. No clear trend was observed for the nitrogen pressure p. To understand possible relationships, SEM images were taken to measure and characterize the layers, see Figure 1.

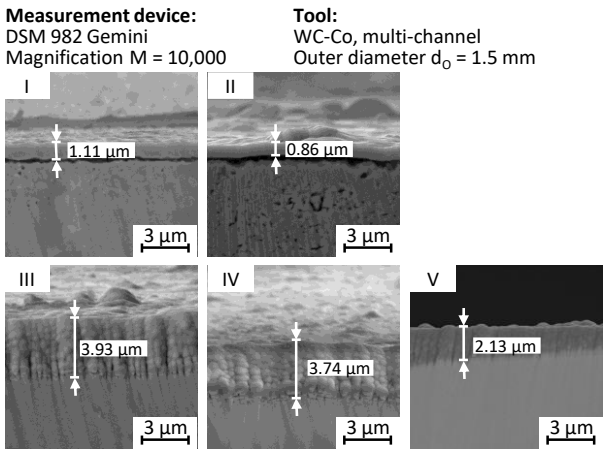

Figure 1. Cross sections of layers and average layer thickness d_l

Tool electrodes treated at a nitrogen pressure of p = 200 mbar resulted in a thin black outer layer consisting of possible compounds of tungsten and nitrogen or cobalt and nitrogen with a layer thickness of up to $d_{l,I} = 1.11$ µm in average. In contrast, lower nitrogen pressures p ≤ 100 mbar led to a type of columnar grown layers with an averaged layer thickness of up to $d_{l,III} = 3.93$ µm. The resulting different layer types as well as layer thicknesses d_l could explain why no clear trend of the electrical resistivity ρ as a function of the nitrogen pressure p could be observed. However, both types of layers were also found to have an increased layer thickness d_l at higher temperatures ϑ, which also resulted in a higher electrical resistivity ρ.

3.2. Electro-discharge drilling

The material removal rate $\dot{V}_W$ and the linear tool wear Δl_e of the drilling EDM experiments are shown in Figure 2.

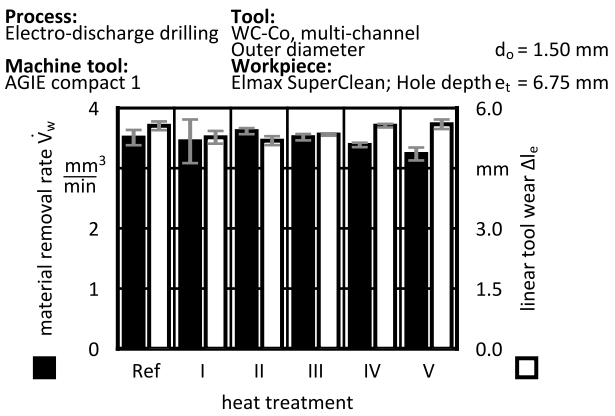

Figure 2. Electro-discharge drilling results

In the following, results of tool electrodes III – V are described first, since they have a different layer structure than tool electrode I and II. The increasing layer thickness d_l leads to a higher material removal rate from $\dot{V}_{W,V} = 3.23$ mm³/min to $\dot{V}_{W,III} = 3.51$ mm³/min as well as lower linear tool wear from $\Delta l_{e,V} = 5.62$ mm to $\Delta l_{e,III} = 5.37$ mm. However, no significant improvement could be achieved compared to the reference tool electrode with $\dot{V}_{W,Ref} = 3.50$ mm³/min. A possible reason for this could be that heat treatment with little or no nitrogen in the atmosphere did not allow a significant insulating layer to form.

In addition, the thinner layers could lead to easier delamination during the process, resulting in higher linear tool wear comparable to the reference with $\Delta l_{e,Ref} = 5.58$ mm. These delaminated parts could lead to additional debris that reduces process stability and material removal rate $\dot{V}_W$. Despite similar electrical resistivities ρ to tool electrode IV, tool electrode II resulted in a higher material removal rate $\dot{V}_{W,II} = 3.62$ mm³/min and a lower linear tool wear $\Delta l_{e,II} = 5.21$ mm compared to the reference. Therefore, the electrical resistivity ρ of the base material was possibly measured. Tool electrode I also results in a lower tool wear $\Delta l_{e,I} = 5.30$ mm, but a lower material removal rate $\dot{V}_{W,I} = 3.40$ mm³/min. The large margin of error could be attributed to the insulating layer, which caused contacting problems and high deviating results. To enable the process at all, the layer had to be removed manually to allow tool clamping and electrical contacting. Compared to the reference, besides a reduced linear tool wear Δl_e, an increased material removal rate $\dot{V}_W$ could be shown for experiment II and individual tests of experiment I, indicating insulating properties of the black layer.

4. Conclusion and outlook

While heat treatment at higher temperatures ϑ resulted in a thicker layer and a higher electrical resistivity ρ, higher nitrogen pressures p led to a different layer structure, which has to be analysed separately. Heat treatments at lower nitrogen pressures of p ≤ 100 mbar resulted in a columnar layer, causing the linear tool wear Δl_e to decrease with increasing layer thickness d_l. The formation of the thinner black layer in experiment II with a nitrogen pressure of p = 200 mbar led to promising results with a higher material removal rate $\dot{V}_W$ and lower linear tool wear Δl_e, which could be a guide for future and more in-depth investigations. Here, the influence of a possible diffusion and reaction of nitrogen on the surface will be examined.

References

[1] Kliuev M et al. 2016 *Proc. CIRP* **42** 322-27
[2] Uhlmann E, Polte M and Yabroudi S 2022 *Proc. CIRP* **113** 611-35
[3] Uhlmann E et al. 2020 *Proc. 20th euspen conference* 415-17
[4] Ferraris E et al. 2013 *CIRP Annals* **62** 191-94
[5] Uhlmann E, Streckenbach J, Börnstein J, Wolf C-S 2019 Patent WO002019137968