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Investigation of the Fundamentals of Tool Electrode Wear in Dry EDM

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Abstract

The fundamentals of the tool wear in dry electrical discharge machining (DEDM) were investigated by plasma optical emission spectroscopy. Interpretation of the spectral lines suggests that single DEDM discharges with point-type cathode tool (Cu) and anode workpiece (Al) present characteristics of hot anode vacuum arcs (HAVA). The anode is active and the cathode is passive in a HAVA, which is probably the main reason for the relatively large workpiece erosion and very small tool wear reported for DEDM in the literature. The plasma characteristics change substantially inverting the electrodes polarity, thereby both electrodes have an active role in the discharge.

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Keywords: Electrical discharge machining (EDM); wear; mechanism; optical emission spectroscopy; plasma in microgaps

1. Introduction

Electrical discharge machining (EDM) is a well-established manufacturing process, widely applied in production of dies and moulds. EDM commonly works with de-ionized water or oil dielectric media, depending on the application.

The research effort in dry electrical discharge machining (DEDM) has increased during the last years due to its much better environmental conditions and process strengths. Depending on the process application, DEDM is able to provide higher material removal rates, better surface roughness, lower tool electrodes wear and less heat-affected zones on the workpiece surface than EDM in liquid dielectric, as shown by Kunieda et al. (2003) [1]. Moreover, he infers that the greatest advantage of DEDM is the very low wear of the tool electrode, which is independent of electrical discharge pulse duration. This result has been reported with the tool as cathode and the workpiece as anode, which leads to higher material removal rates and lower tool wear ratio.

Further development of the DEDM technology depends on the elucidation of the physical phenomena involved in this process. According to Li et al. (2004) [2], stronger energy is absorbed by the anode electrode than by the cathode electrode in DEDM. However, the mechanisms of the discharge energy distribution over the electrodes are not properly explained yet.

The open voltages (U_{open}) applied in DEDM are normally lower than the gaseous dielectric strength. Roth et al. (2012) [3] proposed that the discharges under this condition are triggered by a mechanism similar to a vacuum breakdown in gaps smaller than 5 µm. Ion-enhanced field emissions take place in such small gaps, as reported by Klas et al. (2011) [4]. It occurs due to the high electric fields combined with lowering of the potential barrier seen by the electrons in the cathode as ions approach. Thus, the electron emission process depends primarily on the electric field (E) rather than on its relation with the density of neutral particles in the gap (E/N).

According to Timko et al. (2010) [5], vacuum discharge plasmas develop first by building-up a density of neutral particles in the gap. Whereas neutrals slowly fill the gap, charged particles leave the system quickly, accelerated by the high electric field. The avalanche of ionization starts when the neutral density reaches a critical value. The increased ion flux results in further sputtering or evaporation, creating even more neutrals. The coupled phenomena of evaporation, sputtering, ion flux and erosion are the sustaining mechanism for the discharge. The electrode erosion mainly occurs due to the bombardment of its surface by charged particles passing through micro electrical discharge plasmas. Thus, the understanding of the fundamental properties of microplasmas is necessary to explain the erosion mechanisms in DEDM.

The aim of the present work is the investigation of the tool electrode wear fundamentals in DEDM under different

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electrode polarities. Electrical discharge plasmas are characterized by optical emission spectroscopy and electrical parameter analysis. The results are associated to the tool electrode wear reported in the literature.

Nomenclature

U_{open}	Open voltage [V]
I	Current [A]
t	Pulse duration [µs]
E	Electric field [$V.m^{-1}$]
N	Density of neutral particles [cm^{-3}]
T	Plasma temperature [K]
N_e	Density of electrons [cm^{-3}]
λ	Wavelength (nm)

2. Materials and methods

The experimental setup for discharge generation consists out of a Form 1000 EDM Agie machine, adapted to perform single electrical discharges. Electrical data from the sparks were acquired and measured by a LeCroy Wave Runner 44MXi-A oscilloscope.

Light optical emission spectroscopy was performed using an Acton Research Spectrograph 0.275 m connected to a Vision Research Phantom V12.1 high-speed camera (1 million frames/s and 300 ns exposure time). An optical fibre is positioned near the erosion gap and guides the light emitted by the sparks into the spectrograph.

The electrical discharge experiments were performed with a point-to-plane electrode configuration. The tool is a cylindrical copper electrode of 1 mm diameter with conical extremity, while the workpiece is a larger aluminium electrode with flat surface, as presented in the Figure 1.

High purity materials were adopted in the experiments for optical emission spectroscopy, since impurities can hamper the spectra interpretation. Moreover, aluminium was used as workpiece material due to its relatively low excitation and ionization energies, which provide clear atomic and ionic emission lines. The dielectric used in the experiments was air at atmospheric pressure.

Single electrical discharge experiments were done applying U_{open} = 250 V and I = 20 A. Optical emission spectroscopy was performed for electrical discharges with pulse durations of 316 µs.

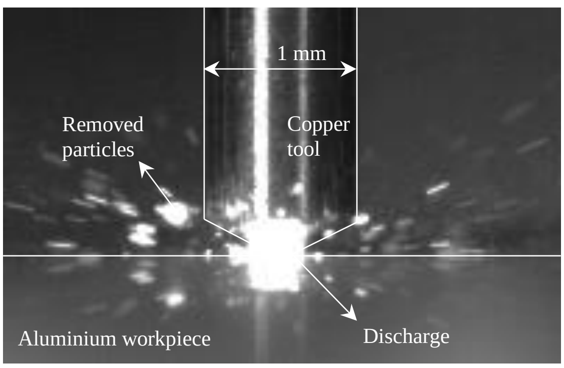

Figure 1: Copper and aluminium electrodes configuration (I = 20 A; U_{open} = 250 V; t = 316 µs)

3. Experiments and results

3.1. Time-resolved optical emission spectroscopy analysis

Time-resolved optical emission spectroscopy provides information about fundamental properties of electrical discharge plasmas and their species. It shows that the microplasmas obtained from discharges with cathode tool present very weak Cu spectral lines intensities, while the Al lines are very strong. The situation changes significantly with the tool as anode. The Cu lines have relatively high intensity already at the first microseconds of the discharge and they increase during the time in comparison with the Al lines. The Figures 2 and 3 present the emission spectra of both cases.

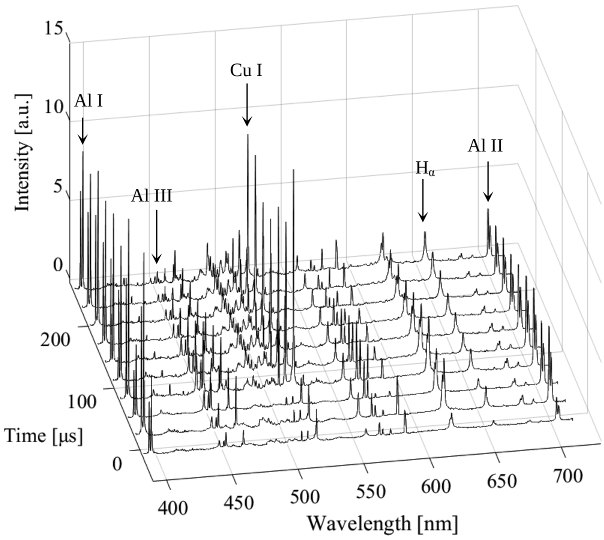

Figure 2: Emission spectra of a single electrical discharge with anode tool

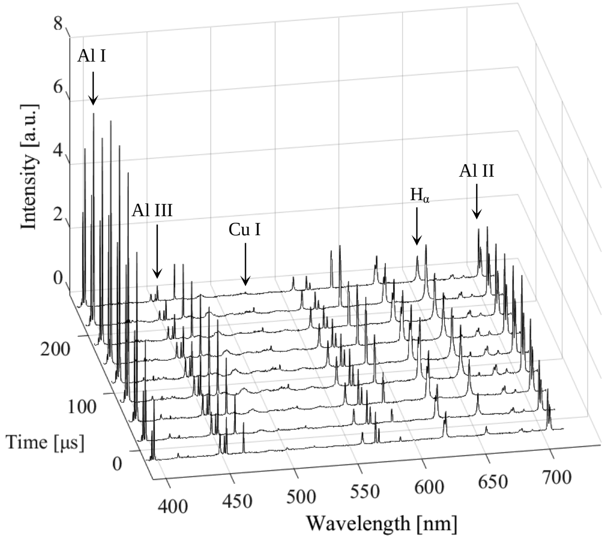

Figure 3: Emission spectra of a single electrical discharge with cathode tool

The intensities of the emission lines are linked to the populations of different excited species in the plasma. Thus, in order to obtain indications of the proportion of species coming from anode and cathode materials, ratios between the different lines were calculated. The strongest intensity lines of the metallic species, Cu I (521.82 nm), Al I (396.15 nm), Al II (704.21 nm) and Al III (452.9 nm), were selected and used as reference for the ratio analysis. The Figure 4 presents the intensity ratios of discharges with anode tool.

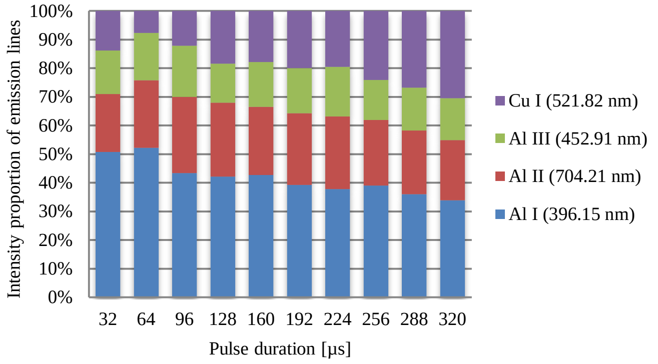

Figure 4: Ratios of intensity lines of electrical discharges with anode tool

Although the intensities of the Al lines stay strong, the intensity ratios of the Cu line change from around 10% to 30%, showing an increase tendency of the Cu (tool material) content of the plasma during the time. The variation of the emission line ratios is very different for electrical discharges with cathode tool, as presented in the Figure 5.

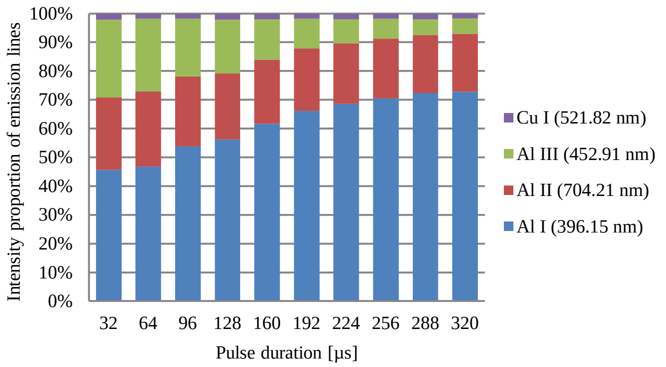

Figure 5: Ratios of intensity lines of electrical discharges with cathode tool

On the one hand, the line intensity ratios indicate that the Cu content of the plasma is very small and nearly constant, independently of the discharge pulse duration. On the other hand, the Al I intensity ratios vary from around 45% to 70%, suggesting an increase in the Al I neutral content of the plasma during the time. The ratios of the ionic Al II line stay relatively constant, whereas the Al III ratios are progressively reduced from about 30% to 5%.

3.2. Plasma temperature and density of electrons

The plasma temperature (T) is a statistical value of the average kinetic energy of its particles. The temperatures were determined by the two-line Boltzmann method, assuming local thermal equilibrium in EDM plasmas, as proposed by Descoeudres (2006) [6]. The two-line Boltzmann method is described in detail by Griem (1997) [7]. It is based on measurements of the intensity ratio of two strong and properly isolated spectral lines emitted by atoms or ions of the same element. Two Al II emission lines, 559.33 nm and 704.06 nm, were chosen due to the relatively high difference between their upper energy levels. The time-resolved temperatures are presented in the Figure 6 for single discharges under different polarities. The plasma temperatures are slightly higher applying the anode tool. The temperature starts to decrease with the cathode tool after 160 μs, whereas it is relatively stable with the anode tool after 128 μs, around 17’000 K.

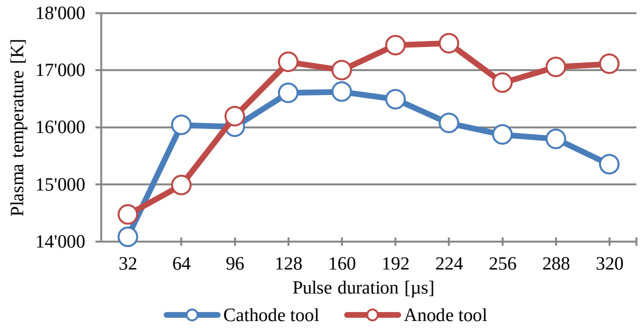

Figure 6: Time-resolved plasma temperature

The present results provide average approximations of the plasma temperature during the time. Further plasma characterization by emission spectra simulation could estimate the plasma temperature profiles and their influence on the spatial distribution of different ionic species.

The density of electrons (N_e) is also an important physical parameter to characterize plasmas and how they interact with the electrode material. The densities were calculated from the H_α line (656.28 nm) broadening, dominated by the Stark effect. The theories of Gigosos et al. (1996) [8] were used for the density of electrons determination based on H_α full width at half maximum measurements. The electron density of the plasma rises under the both polarities, becoming relatively stable afterwards. The electron density becomes ~1.35×10^{17} cm^{-3} with the cathode tool electrode and ~1.55×10^{17} cm^{-3} with the anode tool electrode (Figure 7).

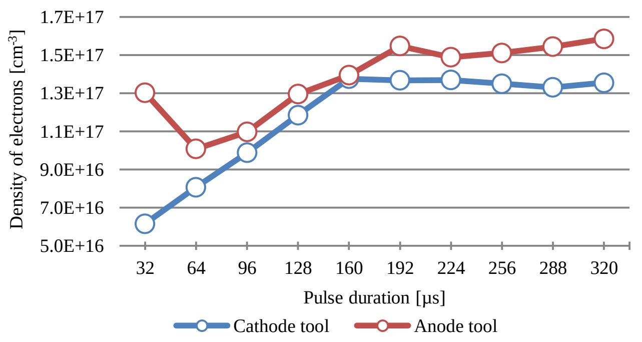

Figure 7: Time-resolved density of electrons

4. Discussion

The analysis of the line intensity ratios provided by the discharges with anode tool suggests that material from tool and workpiece contribute to the plasma composition under a time dependent rate. It means that part of the anode tool material increasingly evaporates for long pulse durations. It leads to relatively large electrode wear, as reported by Kunieda et al. (1997) [9]. The line intensity ratios change during the entire discharge, with relatively high temperature and density of electrons after 128 μs and 192 μs respectively.

Differently, the line intensity ratios obtained from cathode tool material in electrical discharges are small and relatively constant. It indicates that the cathode is almost inert and no substantial increase in its vapour occurs during the time. The electron density starts to be stable and the plasma temperature decreases after 160 µs. Higher Al I and lower Al III intensity ratios, plasma temperature reduction and relatively constant electron density of long pulses probably take place due to the growing evaporation of the anode material. It could also indicate transition of a transient to steady state discharge; however, further analysis of time-resolved burning voltage behaviour is necessary to identify it properly.

The electrical discharges in DEDM with point-type cathode tool fit to the characteristics of hot anode vacuum arcs (HAVA). According to Boxman et al. (1995) [10], the cathode serves as source of electrons in a HAVA; nonetheless, the anode and the inter-electrode plasma provide most of the energy to the discharge. Little cathode activity takes place and it can be viewed as a relatively passive electrode. The energy of the ions and neutrals coming from the anode are relatively low and negligible cathode material sputtering takes place. Furthermore, the cathode is commonly a receiver of material from the anode and the net cathode erosion can be negative, phenomenon also reported in DEDM by ZhanBo et al. (2004) [11]. The Figure 8 presents the conditions of the electrodes after 30 discharges under different polarities. The pictures are from the top of the conical extremity of the electrodes. The anode tool clearly present craters, whereas the cathode tool does not have visible craters and is covered by aluminium from the workpiece.

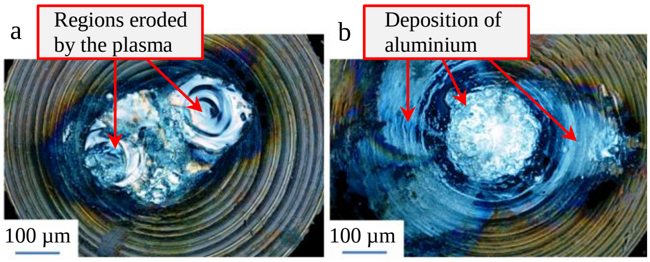

Figure 8: (a) Anode tool electrode; (b) Cathode tool electrode

In spite of the different plasma contents, the burning voltage of the discharges under different polarities presents similar values. The root mean square value of the voltages calculated for the discharges with cathode tool is around 16.5 V, whereas the value obtained for anode tool is just slightly higher, about 17 V. The burning voltage of low current vacuum discharges between Cu-Cu electrodes is ~20.5 V, while the value for discharges between Al-Al electrodes is ~16.5 V, as reported by Anders (2001) [12].

The obtained burning voltages are also an indication of the similarity between DEDM discharges and anode dominated vacuum arcs. According to Boxman et al. (1995) [10], HAVA are supported by moderate power if the anode is thermally isolated from its surroundings. Since the electrical discharges take place in microsecond scale, the anode hot spot can be considered in a first approximation as thermally isolated.

A fundamental reason for the occurrence of electrical discharges with HAVA characteristics in DEDM with cathode tool is the electrodes geometry. The point-type cathode concentrates the current to the anode spot until its material temperature reaches sufficiently high values to become an intensive source of metal vapour, as described by Boxman et al. (1995) [10]. A plane cathode is not able to restrict the current to a small anode spot region. Thus, the discharges take place distributing the energy over the both electrodes, point anode and plane cathode, causing relatively large tool wear.

5. Conclusions

An investigation of the tool wear fundamentals in DEDM was developed for different electrode polarities. The results suggest that the point-type cathode tool concentrates the current to a hot anode spot, leading to the formation of discharges similar to anode dominated vacuum arcs. Thus, the active anode and passive cathode electrodes are probably the main reasons for relatively large workpiece erosion and very small tool wear reported in the literature.

The inverted polarity, applying the tool as anode, provides time dependent erosion of anode and cathode electrodes. It occurs due the plane cathode geometry, which is not able to concentrate the discharge to a limited anode spot. Therefore, anode and cathode are active, leading to the distribution of the discharge energy over both electrodes. It explains the smaller workpiece material removal and larger tool electrode wear for point anode tool and plane cathode workpiece in DEDM.

Acknowledgements

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