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# Dependence of Crater Formation in Dry EDM on Electrical Breakdown Mechanism

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**Abstract**

The research effort in dry electrical discharge machining (DEDM) has increased during the last years. The process has advantages in comparison with EDM in oil-based dielectric media, such as low tool electrode wear, thin recast layers on the work piece surface and much more environmentally friendly conditions. However, the plasma-material surface interactions involved in dry EDM are not properly explained yet. Therefore, a characterization of the erosion phenomena in dry EDM under different breakdown mechanisms is presented. Plasmas and craters generated by single electrical discharges are studied. The plasma expansion is recorded and measured by high-speed imaging experiments, while electrical signals, current and voltage, are monitored. The plasma species are identified by emission spectroscopy. The results show that gas discharges triggered by streamers have larger plasma expansions than sparks generated from vacuum breakdown mechanism. Several small craters can be generated from a single gas discharge, spread over of the work piece surface. The plasma formed from vacuum breakdown is restricted to smaller areas, providing larger and less spread craters. This explains the higher material removal rate of the process with vacuum breakdown in very small gaps.



*Keywords:* dry EDM; single electrical discharges; spectroscopy; high-speed imaging; breakdown mechanisms; crater analysis; plasma in microgaps

## 1. Introduction

Electrical discharge machining (EDM) is a widely applied non-conventional machining process. Its applications involve mainly the production of work pieces with complex geometries and difficult-to-machine materials, thanks to the material removal principles of the process. EDM commonly works with de-ionized water or oil-based dielectric media, depending on the application. Dielectric isolates tool and work piece and also cools and flushes the erosion gap.

However, oil-based dielectric media, usually employed in die-sinking EDM, are not environmentally friendly [1]. The research effort in dry EDM has increased during the last years due to its much better environmental conditions and process strengths, such as low electrode wear and thin recast layers formed on the work piece surface [2].

Some fundamental phenomena in dry EDM are not properly explained yet, making difficult further systematic process improvements. The material removal process in dry EDM is based on plasma-material surface interactions. The characterization of these interactions is necessary to understand and explain the erosion mechanisms. Moreover, electrical discharges can be generated through different breakdown mechanisms, which depend on the applied open voltage, erosion gap, materials and shape of electrodes.

The breakdown of gas discharges under relatively small gaps and low voltages is triggered by a positive streamer. Positive streamer is a weakly-ionized channel very rapidly formed from an intensive primary electron avalanche starting from cathode. Once the primary avalanche reaches the anode, the streamer grows back from the anode towards the cathode with a positively charged "head". The spark takes place when the streamer has contact with both electrodes. The transition streamer-to-spark is still poorly understood. The phenomenon probably occurs due to a "back streamer", similarly to a "return stroke", well-known from lightning discharges [3].

The breakdown voltage of gas discharges can be estimated from Paschen's law, which is expressed as a function of the gas pressure and the gap distance between electrodes. Nevertheless, deviations from Paschen's law are observed for discharges in gaps smaller than 5 µm in case of at least one metallic electrode. Lower breakdown voltages associated to smaller electrode gaps have been reported, independently from the gas pressure [4, 5].

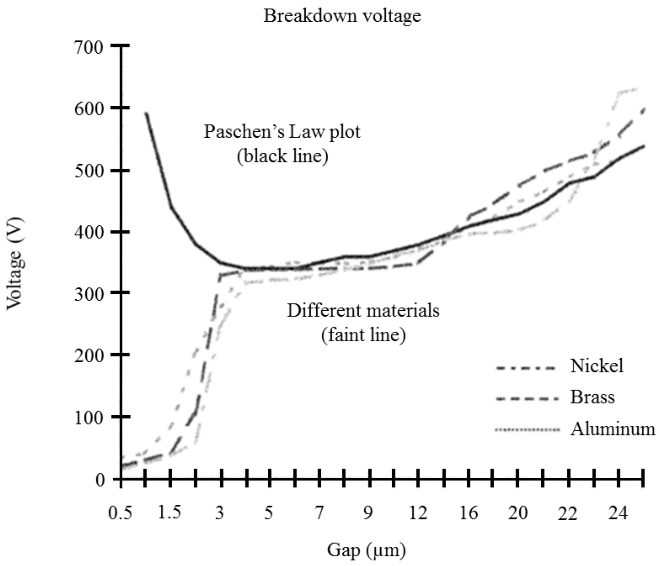


Figure 1: Breakdown voltages in air versus gap at atmospheric pressure for different electrode materials [4]

The reason for reduction of breakdown voltage in gaps smaller than 5 µm is a mechanism similar to a vacuum breakdown. Ion-enhanced field emissions take place due to high electric fields obtained in such small gaps, combined with lowering of the potential barrier seen by the electrons in the cathode as ions approach. The electron emission process depends primarily on the electric field (E) rather than on the relation between electric field and density of neutral particles in the gap (E/N), leading to deviations from the Paschen's law [6]. This phenomenon has been reported even for discharges between finely polished planar electrodes, reducing the effect of electric field increase in protrusions or sharp edges [7].

According to Timko (2010) [8], plasma from a vacuum breakdown develops first by build-up of a density of neutral particles in the electrode gap, since ionization events are rare in the beginning. Charged particles leave the system quickly, accelerated by the electric field, while neutrals move slowly, filling the gap. The avalanche of ionization starts when the neutral density reaches a critical value, which corresponds to the ionization mean free path. The increased ion flux results in further sputtering, creating even more neutrals. Such coupled phenomena of sputtering, ionization, ion flux and erosion are the sustaining mechanism for the vacuum discharge.

The present work characterizes the erosion phenomena in dry EDM under different breakdown mechanisms, since different breakdowns can lead to different plasmas and plasma-material interactions. Time resolved data obtained from single electrical discharges are associated to craters left on planar metallic surfaces. The plasma expansion is recorded and measured by high-speed imaging experiments. An oscilloscope monitors the discharge current and voltage. Moreover, species of the plasma are identified by emission spectroscopy.

**Nomenclature**

| | |
|---|---|
| U | Voltage [V] |
| I | Current [A] |
| t | Pulse duration [µs] |
| E | Electric field [$V.m^{-1}$] |
| N | Density of neutral particles [$m^{-3}$] |

## 2. Materials and Methods

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

Light emission spectroscopy is the most suitable tool to analyse plasmas in small gaps and was performed using an Acton Research Spectrograph 0.275 m connected to a Vision Research Phantom V12.1 Hi-speed camera (1 million frames/s and 300 ns exposure time). An optical fibre, positioned near the erosion gap, guides the light emitted by the sparks. The high-speed camera records the plasma expansion with an optical filter of 515 nm centre line and 25 nm FWHM (full width at half maximum). The filter is employed to acquire only the light emitted at 510.55, 515.32 and 521.82 nm wavelengths originating from Cu I emission lines.

The tool is a cylindrical electrode of 1 mm diameter with conical extremity, which allows the plasma visualization, while the work piece is a larger electrode with flat surface. The material is copper (purity: 99.9%) for both, tool and work piece. The craters produced by single sparks on the work piece surface are measured by a 3D Optical Surface Metrology System Leica DCM 3D.

Two dielectric media are used in the experiments, air and argon, which have different minimum breakdown voltages, around 327 and 137 V respectively [9]. Air from experimental setup environment is directly used as dielectric medium, whereas argon is injected in the gap between electrodes with low pressure (< 0.1 bar), aiming to reduce effects of the flow on the discharge behaviour.

Single spark experiments were done applying U = 250 V and I = 20 A for both dielectric media. Plasma expansion measurement and spectroscopy are performed for 316 µs long discharges. The craters left on the work piece surface are made by single discharges with pulse duration varying from 4.9 µs to 316 µs. This allows comparison between crater formation and discharge development. The measured currents and voltages are used to exclude experiments with occurrence of short circuit.

The minimum sparking voltage of argon is lower than the open applied voltage. Therefore, the breakdown voltage behaves according to Paschen's law and a gas discharge is formed. However, the electrical discharges in air just occur in gaps smaller than 5 µm for the applied setup. Hence, a vacuum breakdown mechanism takes place with voltage below the minimum value of the Paschen's curve.

## 3. Experiments and results

### *3.1. Crater Analysis*

Craters are formed on a planar work piece surface by single discharges in air and argon as dielectric media with identical electrical parameters. The analysis of the craters aims characterization of the erosion phenomena based on their morphology.

Single electrical discharges in air as dielectric were performed with different pulse durations. The adopted pulse durations are: 4.9, 15, 32, 75, 100, 133, 154, 178, 205, 237, 274 and 316 µs. Moreover, the experiments were done with the tool set as cathode, since the anode side has larger material removal. A crater made by a single discharge of 4.9 µs pulse duration in air is shown in Figure 2.

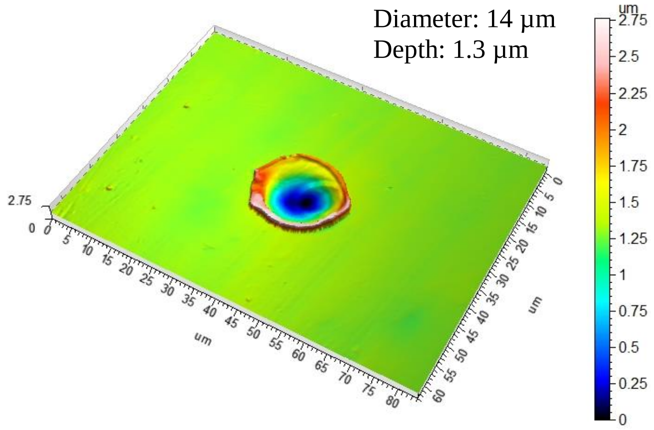


Figure 2: Single crater made in air by spark with 4.9 µs duration (U = 250 V; I = 20 A; Negative tool electrode)

The results show that craters made by longer discharges in air are deeper and larger than craters made by short pulses, with duration of 4.9, 15 and 32 µs. Furthermore, several craters can be formed from a single spark discharge. The Figure 3 presents a single crater, whereas the Figure 4 shows several craters, both provided from 75 µs long single discharges with the same setup conditions and electrical parameters.

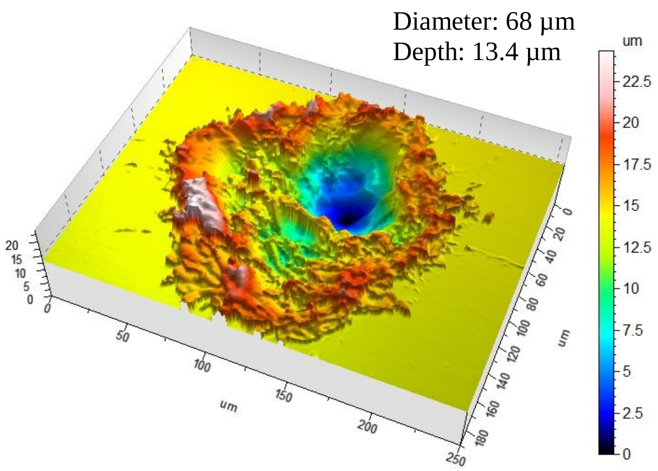


Figure 3: Single crater made in air by spark with 75 µs duration (U = 250 V; I = 20 A; Negative tool electrode)

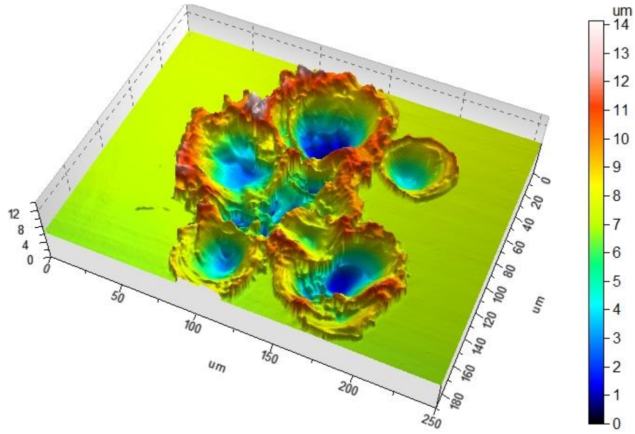


Figure 4: Several craters made in air by spark with 75 µs duration (U = 250 V; I = 20 A; Negative tool electrode)

The experiments in air show that craters made by discharges with pulse durations between 4.9 and 32 µs have relatively low crater depth, around 2 µm. For pulse durations bigger than 75 µs, the crater depth increases abruptly, reaching around 10 µm. There is a small decrease in depth for pulses longer than 100 µs. The evolution of the average craters depth in function of time is shown in the Figure 5.

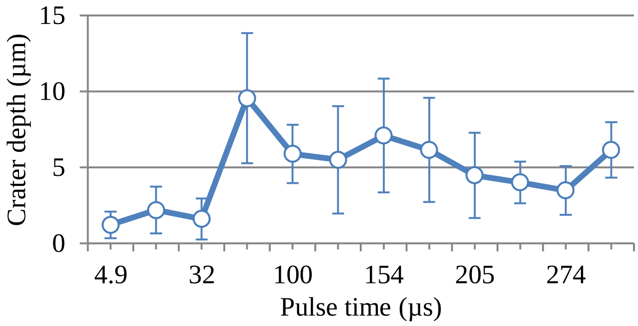


Figure 5: Evolution of the crater depth average during the time in air (U = 250 V; I = 20 A; Negative tool electrode)

The volume of material removed by the sparks is also relatively stable for 4.9, 15 and 32 µs pulse durations, with erosion values between $10^2$ and $10^3$ µm$^3$ per discharge. There is a strong increase in erosion observed for 75 µs long discharges, reaching material removal values above $10^4$ µm$^3$. The material removal does not increase further for pulses longer than 75 µs. The evolution of the averaged material removal for different pulsed discharge durations is shown in Figure 6.

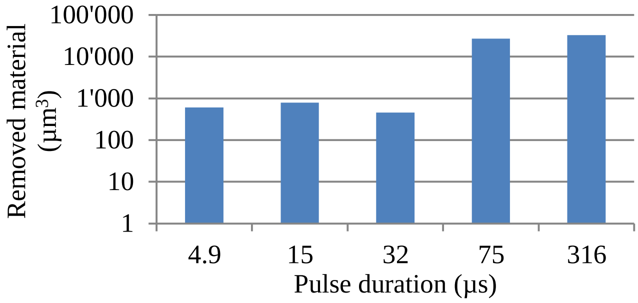


Figure 6: Evolution of the averaged material removal in function of time (U = 250V; I = 20 A; Negative tool electrode)

The material erosion is very different for discharges performed in argon compared to discharges in air. It most probably occurs due to the breakdown mechanism. Single discharges made with the tool as cathode were not able to create any craters and the surface of the work piece material was just smoothly burned. However, setting the tool as anode, the discharges are capable to generate several small craters. Figure 7 shows the distribution of craters on the work piece surface made from a 316 µs long single discharge by applying the tool as anode, whereas Figure 8 presents the amplification of the region highlighted in Figure 7. The vast majority of the black dots in the figures are very small craters.

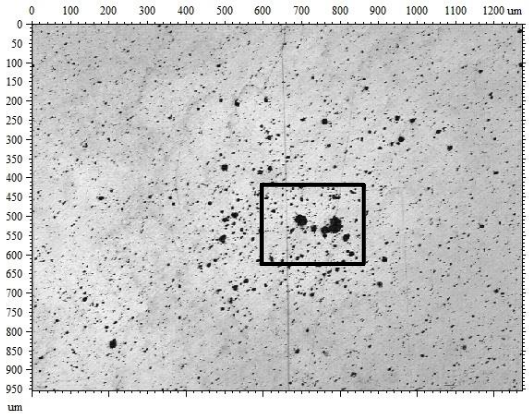


Figure 7: Craters left by a 316 µs single discharge in argon (U = 250 V; I = 20 A; Positive tool electrode)

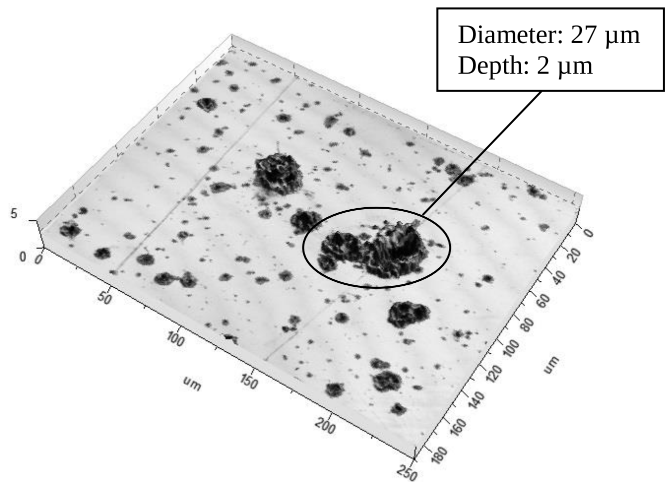


Figure 8: Amplification of craters from Figure 7 left by a 316 µs single discharge in argon (U = 250 V; I = 20 A; Positive tool electrode)

### 3.2. Plasma expansion

High-speed imaging experiments were done to measure the plasma expansion and provide a relation between plasma dimensions and craters left on material surface. Electrode gaps of 8 and 12 µm were adopted and pre-set on the electrical discharge machine for sparks in argon. The pre-set gaps are small enough for the occurrence of a gas discharge.

The vacuum breakdown mechanism just occurs when the gap is smaller than the ionization free path. Since the gap distance is too small to be pre-set in the EDM machine, the discharges in air were performed moving the tool towards the work piece with an open voltage. Thus, the spark takes place when the electric field is high enough to the occurrence of the breakdown.

Movement and expansion of the plasma during electrical discharges in air are restricted to the tool electrode borders. The behaviour of the plasma expansion is considerably different in discharges made in argon, with plasma expanding beyond the tool electrode edges. Such expansion behaviour of the plasmas is shown in Figures 9a and 9b.

The average and deviation of the plasma expansion during the time are larger for big gaps in argon as dielectric. The Figure 10 shows the dimensions of the plasma expansion in function of time. No significant differences concerning the plasma expansion behaviour were identified inverting the polarity between tool and work piece.

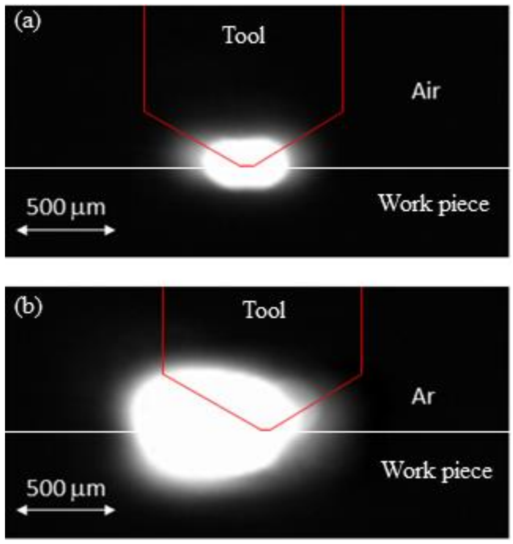


Figure 9: (a) Plasma expansion in air; (b) Plasma expansion in argon

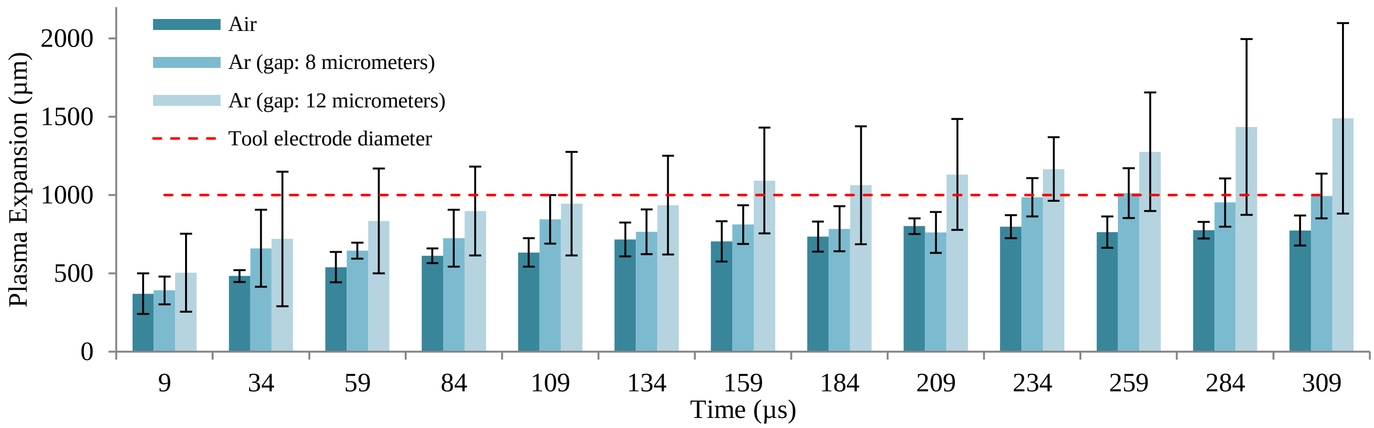


Figure 10: Plasma expansion in function of time for discharges in air and argon

### *3.3. Time-resolved emission spectroscopy*

Time-resolved emission spectroscopy provides information about species present in different analysed plasmas. The results show that the majority of intense lines in the spectra of discharges performed in argon are Cu I, Cu II, Ar I and Ar II, whereas the spectra of sparks in air show mainly Cu I lines. Emission spectra of discharges in air and argon are presented in Figures 11a and 11b with some characteristic lines.

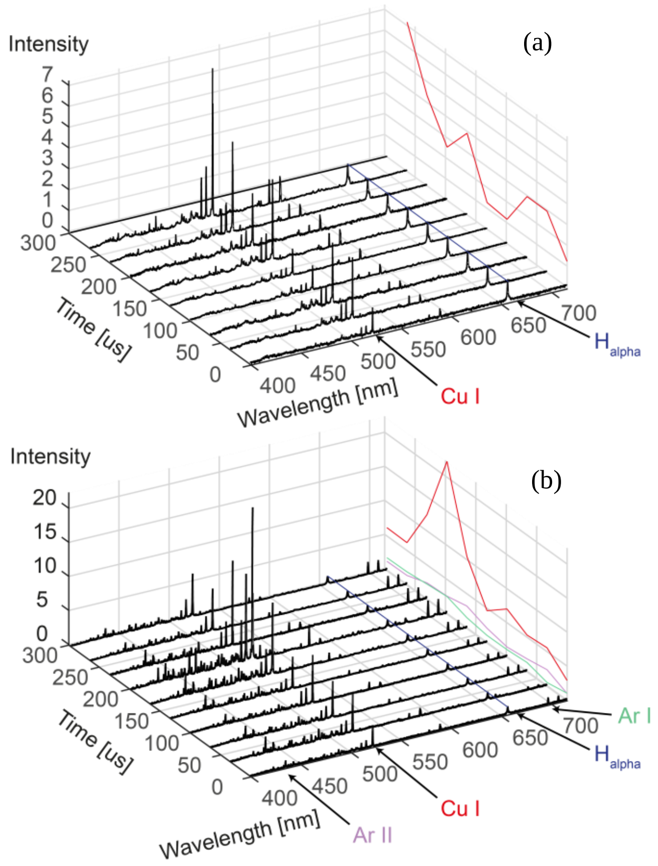


Figure 11: (a) Spectrum of single discharge in air; (b) Spectrum of single discharge in argon
(t = 316 μs; U = 250 V; I = 20 A)

The spectra clearly show the $H_\alpha$ line at 656.28 nm, particularly strong for discharges in air. Discharges made in argon also have the $H_\alpha$ line, although with lower intensity. The reason is most probably presence of humidity in air, which leads to cracking $H_2O$ molecules during development of the sparks. Discharges made in argon also have $H_\alpha$ line, possibly due to some remaining air in the gap.

The 3D spectra graphs are normalised to the $H_\alpha$ line. The normalization provides information about concentration of metallic contamination in the plasma during the time. Metallic lines increase was registered for both discharges after 200 μs, which indicates higher content of metallic species for long pulses. The projected red curves show light intensity behaviour originating from Cu I emission at 521.82 nm wavelength for both single discharges. Moreover, electrical discharges in argon dielectric present Ar I and Ar II lines. The intensity lines behaviour is shown in the green and purple projected curves at 696.54 and 434.81 nm wavelengths from Ar I and Ar II respectively. These curves indicate that the gas plasma content does not change significantly during the time.

## 4. Discussion

Spectroscopy of electrical discharges in air show mainly Cu I lines. Spectra dominated by metallic lines were also reported by Subbu et al. (2011) for dry EDM in air [10]. However, this does not necessarily mean that large amount of Cu species is present in the plasma. Abundance and relatively high intensity of the Cu I lines in the spectra can be just due to low excitation energy of Cu atoms, around 2.5 eV, whereas their ionization energy is approximately 7.7 eV [11]. It is known from arc discharges that the light emission is dominated by metallic lines with just a few per cent of metal in the plasma [12]. Large amount of Cu species in the plasma can be supported by the vacuum breakdown mechanism.

The high-speed imaging experiments show plasma expansion of discharges in air normally restricted to the tool electrode borders. The plasma expands smoothly during around 200 μs after the breakdown, reaching diameter of about 800 μm. This value keeps relatively constant for longer pulses. The area of craters formation is normally limited to diameters of around 300 μm, which indicates concentration of the discharge to the hot spot and vaporization of the electrode material as source of metallic species to the plasma [8, 13].

As beforehand presented in Figures 5 and 6, pulsed discharges in air with durations between 4.9 and 32 μs provide craters with relatively small depth and material removal. Izquierdo et al. (2009) [14] reported that craters made by short pulsed discharges in liquid, of around 5 μs, are mostly generated by evaporation of electrode material, with part of the material expelled through electrostatic forces. Moreover, homogeneous form of the craters suggests that the surface is heated by equilibrium effects, such as low-energy electrons and joule heating from emitted charged particles [8].

Crater depths and material extractions have sharp increase starting for 75 μs pulses, followed by a small decrease for 100 μs pulses. Similar results concerning crater depth have also been published for the erosion phenomena in liquid dielectric media [15]. It probably occurs due to expansion of the plasma and reduction of the electrostatic forces, distributing the energy over a larger area. The electrostatic forces are much weaker for longer pulses, such as 100 μs duration, reducing their erosion effect to negligible values [16]. The volume of the craters is higher for long pulses; however, the relation between the crater and resolidified layer is much smaller, with an inefficient material ejection mechanism [17]. Variations of the pressure above the hot spot during the discharge and impulsive forces due to shock waves can also play an important role in the material removal phenomenon [18]. Moreover, possible reasons for several appearances of complex craters made by single sparks can be plasma density fluctuations and thermal spikes due to overlap of “showers” and clusters of charged particles during the random movement of the anode spot [8, 13].

The results obtained from electrical discharges in argon are considerably different than the ones provided by discharges in air. Pre-set 8 and 12 μm gaps lead to gas discharges, governed by the streamer mechanism. Spectroscopy results show atomic and ionic Cu and Ar lines. The spectra normalized to the $H_\alpha$ line have low intensity Cu lines in the beginning of the discharge, increasing after 200 μs. This behaviour was also registered for sparks in air. It indicates enhance of Cu vapour in the plasma with increasing pulse duration, suggesting transition of the spark to an arc discharge. Maradia et al. (2015) [19] reported similar results for EDM in oil dielectric.

High-speed imaging registered expansion of the plasma in 8 µm gaps until around 230 µs. The plasma reaches diameter of about 1000 µm, just smoothly varying for longer pulses. The plasma diameter rises during the whole development of single sparks in 12 µm gaps, reaching average of nearly 1500 µm. Differently than electrical discharges in air, discharges in argon under the referred conditions are not concentrated to a hot spot; thus the plasma expansion depends on the volume of dielectric available for ionization, which increases with the gap distance. Therefore, due to the different natures of the discharges in argon and in air, their plasma dimensions cannot be simply compared based just on the gap distance.

Applying the tool electrode as cathode in argon, the surface of the work piece material was just smoothly burned, possibly due to the large plasma expansion and the low weight of electrons bombarding the material during the discharge. The sparks generated with the tool as anode are able to form several small craters due to ion collisions, since they are much heavier than electrons, although there is also high plasma expansion [15]. The craters are spread over the work piece surface with small material removal, between $10^2$ and $10^3$ $\mu m^3$, similarly to results obtained from short pulses in air. These small craters are probably the main source of Cu plasma species and are progressively created during the discharge. The measured plasma dimensions are around 100% larger than the area of craters formation for pulse durations until 75 µs; such relation decreases to approximately 30% for pulses longer than 100 µs.

The different crater formation by electrical discharges in air and argon as dielectric can explain the reported higher material removal rate obtained by dry EDM in air, compared with the same process in argon as dielectric [20].

## 5. Conclusions

Erosion phenomena in dry EDM under different breakdown mechanisms are characterized in the present work.

Plasma of discharges in air is mostly composed of Cu species from the electrodes due to the vacuum breakdown mechanism. The dimensions of the plasma are restricted to the tool electrode borders and its interaction with the work piece tends to be concentrated in small spots, generating relatively large craters not very spread over the surface.

Single sparks in air produce single or several craters on the anode surface. The craters depth and volume of material expelled from them are relatively stable for short discharges, abruptly increasing for pulse durations longer than 75 µs.

The breakdown of discharges in argon is governed by the streamer mechanism. Cu and Ar lines are visible in the spectroscopy results. The plasma expands beyond the tool electrode borders. Ions bombardment occurs in larger spots of the cathode surface, providing small material removal.

Thus, the different breakdown mechanisms are probably the main reason for the different material removal efficiencies of the two gases in dry EDM.

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## References

[1] Leão FN, Pashby IR. A review on the use of environmentally-friendly dielectric fluids in electrical discharge machining. Journal of Materials Processing Technology. 2004;149:341-6.
[2] Kunieda M, Miyoshi Y, Takaya T, Nakajima N, ZhanBo Y, Yoshida M. High Speed 3D Milling by Dry EDM. CIRP Annals - Manufacturing Technology. 2003;52:147-50.
[3] Raizer YP. Gas discharge physics. Berlin; New York: Springer-Verlag; 1991.
[4] Torres JM, Dhariwal RS. Electric field breakdown at micrometre separations. Nanotechnology. 1999;10:102.
[5] Roth R, Balzer H, Kuster F, Wegener K. Influence of the Anode Material on the Breakdown Behavior in Dry Electrical Discharge Machining. Procedia CIRP. 2012;1:639-44.
[6] Radmilovic-Radjenovic M, Radjenovic B, Klas M, Bojarov A, Matejcik S. The breakdown mechanisms in electrical discharges: the role of the field emission effect in direct current discharges in microgaps. Acta Physica Slovaca. 2013;63.
[7] Klas M, Š M, Radjenović B, Radmilović-Radjenović M. Experimental and theoretical studies of the breakdown voltage characteristics at micrometre separations in air. EPL (Europhysics Letters). 2011;95:35002.
[8] Timko H, Djurabekova F, Nordlund K, Costelle L, Matyash K, Schneider R, et al. Mechanism of surface modification in the plasma-surface interaction in electrical arcs. Physical Review B. 2010;81:184109.
[9] Naidu S, Kamaraju V. High Voltage Engineering: Tata McGraw Hill Education Private Limited; 2009.
[10] Kanmani Subbu S, Karthikeyan G, Ramkumar J, Dhamodaran S. Plasma characterization of dry µ-EDM. Int J Adv Manuf Technol. 2011;56:187-95.
[11] Liu F, Tong J, Mao J, Bohn R, Messina J, Badger L, et al. NIST Cloud Computing Reference Architecture: Recommendations of the National Institute of Standards and Technology (Special Publication 500-292): CreateSpace Independent Publishing Platform; 2012.
[12] Descoeudres A. Characterization of electrical discharge machining plasmas: EPFL; 2006.
[13] Djurabekova F, Samela J, Timko H, Nordlund K, Calatroni S, Taborelli M, et al. Crater formation by single ions, cluster ions and ion "showers". Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms. 2012;272:374-6.
[14] Izquierdo B, Sánchez JA, Plaza S, Pombo I, Ortega N. A numerical model of the EDM process considering the effect of multiple discharges. International Journal of Machine Tools and Manufacture. 2009;49:220-9.
[15] Klocke F. Fertigungsverfahren 3 Abtragen, Generieren Lasermaterialbearbeitung. 4., neu bearbeitete Auflage ed. Berlin, Heidelberg: Springer Berlin Heidelberg; 2007.
[16] Singh A, Ghosh A. A thermo-electric model of material removal during electric discharge machining. International Journal of Machine Tools and Manufacture. 1999;39:669-82.
[17] Takezawa H, Kokubo H, Mohri N, Horio K. A Study on Single Discharge Machining with Low Melting Temperature Alloy(1 st report)-The Relationship between removal volume of crater and single dischage conditions. Journal of The Japan Society of Electrical Machining Engineers. 2008;42:5-11.
[18] Zhang Y, Liu Y, Shen Y, Ji R, Li Z, Zheng C. Investigation on the influence of the dielectrics on the material removal characteristics of EDM. Journal of Materials Processing Technology. 2014;214:1052-61.
[19] Maradia U, Hollenstein C, Wegener K. Temporal characteristics of the pulsed electric discharges in small gaps filled with hydrocarbon oil. Journal of Physics D: Applied Physics. 2015;48:055202.
[20] Liqing L, Yingjie S. Study of Dry EDM with Oxygen-Mixed and Cryogenic Cooling Approaches. Procedia CIRP. 2013;6:344-50.