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Influence of the Anode Material on the Breakdown Behavior in Dry Electrical Discharge Machining

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Abstract

In the last years dry electrical discharge machining (DEDM) has been proposed as an alternative to the traditional EDM. The main reason for these efforts is the absence of a liquid dielectric which results in a simpler and environmentally friendly machine. This paper presents measurements of the material removal rate in function of different tool electrode and work piece material put in relation with the breakdown behavior of the process .Whit this data it is shown that the breakdown mechanism in the gas filled work gap is different as in traditional EDM, where the gap is filled with liquid dielectric.

Keywords: Electrical discharge machining (EDM), Removal, Breakdown

1. Introduction

Electrical discharge machining (EDM) is a well established machining process characterized by its high precision and ability to machine materials considered hard to machine. Dry electrical discharge machining (DEDM) is a new process based on the traditional EDM with the particularity that gaseous dielectric is utilized instead of liquid dielectric. The advantage in respect to traditional EDM is first of all that no liquid is needed for the process. This allows a simpler EDM machine which does not need to take care of keeping the liquid inside. Another advantage is, that in comparison to die sinking EDM usually performed in mineral oil, the process is environmental friendlier. Other advantages as higher removal rate and very little tool wear ratio have been attributed to DEDM [1]. Furthermore the capability to combine EDM with other processes, to design process chains with EDM can be enhanced.

In the traditional process the main function of the liquid dielectric is to isolate electrode and work piece to cool them and to flush the working gap ensuring a stable process. To ensure these functions without liquid dielectric some measures need to be taken in the dry version of the process. Kunieda proposed to use a rotating tube electrode flushed from the inside [2], which became a standard for DEDM. The pressurized gas coming from the inside of the electrode carries away the eroded material particles from the working gap. The rotation of the electrode helps flushing creating a vorticity and leads to a more stable process. Usually oxygen is used as working gas because of its good effect on material removal rate. Efforts have been made to characterize this new process and optimize it, trying to reach higher removal rates, lower tool electrode wear and better surface characteristics [3].

The removal mechanism of EDM is a stochastic microscopic elementary phenomenon which is repeated at high frequencies and thus leads to a macroscopic predicable process. The models of EDM removal mechanism usually base on the thermal energy introduced into the work piece through the point where the plasma channel is in contact with the metal. The microscopic nature of the space and time scale of the process makes it hard to have an insight to the process mechanisms.

For the EDM process it is important to have a stable gap control able to maintain the ideal distance from tool

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electrode to the work piece. Parameters that influence the breakdown distance of the gap are mainly the applied voltage, the breakdown strength of the dielectric fluid, the pollution of the gap, the electrode surface, the material and the geometrical form of the tool electrode. In traditional EDM the breakdown tension of the dielectric fluid is small enough that gaps from few micrometers till hundreds of micrometers are possible. On the contrary in DEDM only very little gaps are possible because of the high breakdown tension of the gases applied. This is a big challenge for the technology because the small gap is harder to control. The servo control is not able to avoid a lot of short circuit on one side and longer ignition delay times on the other side. This paper shows how the work piece material is crucial for the process stability and affects the removal rate not only due to its different physical properties affecting the molten zone of a spark, but mostly because of the properties that affect the discharge behavior of the process.

Nomenclature

MRR	Material removal rate [mm^3/min]
SMRR	Specific material removal rate [mm^3/minA]
TWR	Tool wear ratio [%]
U	Open voltage [V]
U_B	Burning voltage [V]
I	Current [A]
I_a	Time averaged current [A]
T_S	Spark time [μs]
T_P	Pause time [μs]
p	Flushing pressure [bar]
τ_A	Relative arcing time [%]
τ_S	Relative sparking time [%]
Cu	Copper
CC	Cemented Carbide

2. Materials and Methods

2.1. Experimental set up

The experimental set up consists in a Spirit II EDM machine from AGIE. An additional spindle from 3R (3R-6.300-EHS16) provides a high speed rotation of the tool electrode. High pressure gas is provided from gas bottles through a pressure regulator and a mass flow measurement system into the spindle and then from the inside of the tool electrode to the work gap. The setup efforts tool electrode rotational speed up to 2000 rpm and gas pressures up to 35 bars. The working gas can be easily changed by changing the gas bottle. In the DEDM experiments, that are presented here, only oxygen has been used as working fluid. A LeCroy Wave Runner 44MXi-A electroscope is used to monitor and evaluate the voltage and the current signals over the time.

2.2. Electrodes and work pieces

The used electrode materials are pure copper and cemented carbide multichannel electrode from Balzer Technik. The copper electrode is a two channel electrode and the cemented carbide is a four channel electrode. The cross sections are shown in Fig. 1.

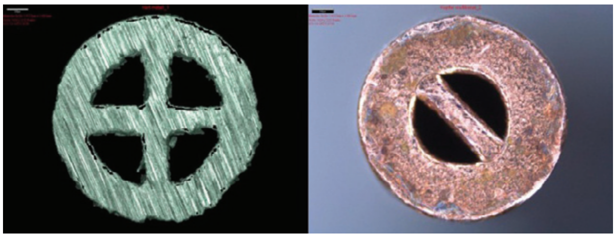

Fig. 1 - Cross section of cemented carbide electrode (left) and copper electrode (right)

The outer diameter of both electrodes is 1 millimeter. The inner diameter of the copper electrode is 0.44 millimeters and the width of the division bar is 0.13 millimeters which results in a cross section of the copper electrode of 0.69 square millimeters. The cemented carbide electrode has an inner diameter of 0.6 millimeters and division bars with a width of 0.135 millimeters. This corresponds to a cross section of the cemented carbide electrode of 0.64 square millimeters. The multichannel electrode with two or four channels has mainly two advantages. On the one hand during rotation it curls the gas flow more than a one channel electrode leading to a better flushing of the working gap. On the other hand, if a pure drilling operation is executed it avoids the formation of a gudgeon in the middle of the hole.

The utilized work piece materials are the stainless steel SS304 and cemented carbide.

2.3. Measurements

During the erosions the machining time is measured and noted. The eroded volume is evaluated after the erosion with a 3 dimensional data set of the work piece, generated with an Alicona Infinite Focus microscope. Dividing the eroded volume with the erosion time the material removal rate (MRR) in mm^3/min can be calculated.

The tool wear is measured directly after the erosion, measuring the difference of the electrode length before and after the erosion process. Multiplying the worn length with the cross section of the electrode the worn volume is obtained. The tool wear ratio (TWR) is calculated by dividing the worn volume of the electrode with the eroded volume of the work piece.

During the erosion also the electrical behavior of the process is monitored and measured on the electroscope. A minimum of two seconds with a resolution of 20 MHz of voltage and current signal over the working gap are stored for every erosion test. The stored data is analyzed evaluating the duration of the time in which normal discharges, arcing discharges, short circuits or ignition delays have occurred. In order to evaluate this data the voltage signal is scanned for negative pulses, which means signals that goes below a defined value for a given time and then rises again. The duration of the scanned pulses is noted. In case of normal sparks this length of time corresponds to the sum of spark time T_S and pause time T_P. Filtering several voltage levels and pulse lengths, a list of all the sparks, arcings and shorts with their respective length is extracted. The signal is considered to be a short when the voltage signal goes below 8 V and the measured pulse lasts at least $T_1 = 1.5 (T_S + T_P)$. Arcing together with short times are listed when the voltage signal goes below 2/3 of the open voltage U and the pulse lasts at least $T_1 = 1.5 (T_S + T_P)$. The spark time, arcing time and short times are listed together when the open voltage goes below 2/3 the open voltage U and the pulse lasts at least $T_2 = 2/3 (T_S + T_P)$. The right combination of the measured times finally permits to educe the individual sparking, arcing and shorting times. Putting the results in relation with the total measurement time of two seconds the partitions of the occurred spark, arcs, shorts and ignition delay times can be calculated. Two seconds may look not representative for an erosion that can last several minutes, but in comparison to the regulation times of the working axis, which happens in the kHz range it becomes clear that in a couple of seconds enough cycles have occurred.

3. Experiments

As experiments vertical drilling of holes of at least 1 millimeter depth are performed. To see how the tool electrode and work piece material influences the material removal rate a fixed set of dry electrical discharge machining parameters has been chosen – only the materials have been changed. The main parameters are listed in Tab. 1.

The electrical parameters have been chosen to guarantee a stable and not too aggressive process for the combination of several electrode materials. For this reason parameters as for example pause time T_P and current I are not set to reach the maximum of the removal rate.

The combinations of the tool electrode and work piece materials which have been tested are listed in Tab. 2.

Tab. 1 – Fixed DEDM Parameters of the experiments

Parameter	Symbol	Value
Tool electrode polarization [-]		negative
Open voltage [V]	U	250
Current [A]	I	6
Spark time [μs]	T_S	15.4
Pause time [μs]	T_P	15.4
Flushing pressure[bar]	p	20
Electrode rotation speed [rpm]	Ω	2000
Flushing fluid		Oxygen

Tab. 2 – Materials combination of the experiments

Experiment	Tool electrode	Work piece
1	Copper	SS304
2	Cemented Carbide	SS304
3	Copper	Cemented Carbide
4	Cemented Carbide	Cemented Carbide

To have a comparison of the discharge behavior in a liquid dielectric the same experiment has been conducted in oil. The aim was not to compare the material removal rate which has not been optimized for none of the two processes but to have a comparison of the electrical behavior of the two processes. For this reason the same parameters which have been used in DEDM have been used for the oil erosion. Just the rotational speed and the flushing pressure of the working fluid have been changed because the experimental set up for erosion in oil did not afford the same values. In Tab. 3 the Values of the parameters which have been different are listed.

Tab. 3 – Changed parameters of the experiment with oil

Parameter	Symbol	Value
Flushing pressure [bar]	p	1.5
Electrode rotation speed [rpm]	Ω	40
Flushing fluid		Oil

The aim is to evidence the difference between the different electrode materials and not to compare directly the machining result in oxygen and oil. The comparison is still interesting also if a few parameters change, as long they are fixed for all the experiments in oil.

4. Results

4.1. Material removal rate

The result of the experiment shows a little higher material removal rate when cemented carbide tool electrode is utilized instead of the copper electrode. In Fig. 2 the measured material removal rate is represented in dependence on the several material combinations.

When cemented carbide is used as work piece the material removal rate is clearly less than the one with stainless steel. So it becomes obvious that the work piece material has a major influence on the material removal rate. On the other hand the influence of the tool electrode material on the material removal rate is very little in comparison to the work piece material.

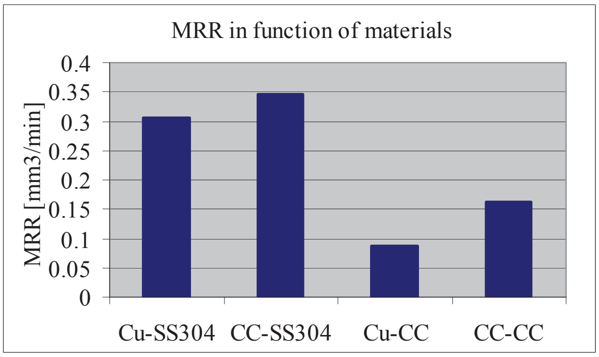

Fig. 2 - MRR depending on anode and cathode material combinations

4.2. Tool wear ratio

In Fig. 3 the tool wear ratio is represented in dependence of the several materials that have been combined.

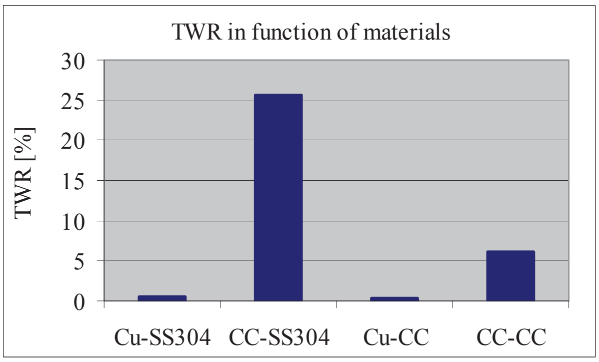

Fig. 3 - Tool wear ratio in function of anode and cathode material combinations

We assume that the reason for this behavior is the different heat conduction coefficient of the two materials. The copper takes away heat faster from the working area preventing the erosion of the tool electrode. The reason for the difference between the CC-SS304 and the CC-CC tool wear ratio can be found looking at the discharge behavior (see chapter 4.3). With cemented carbide work piece the frequency of the shorts becomes larger, so the ratio of time where energy is converted in the gap drops. The cemented carbide has more time to take away the heat and wears less.

4.3. Discharge behavior

In Fig. 4 the sparking, arcing, shorting and ignition delay times are represented in function of the several material combinations. Here it is notable – as has already been shown for the material removal rate – that there is a major influence from the work piece material and only a little influence from the tool electrode material.

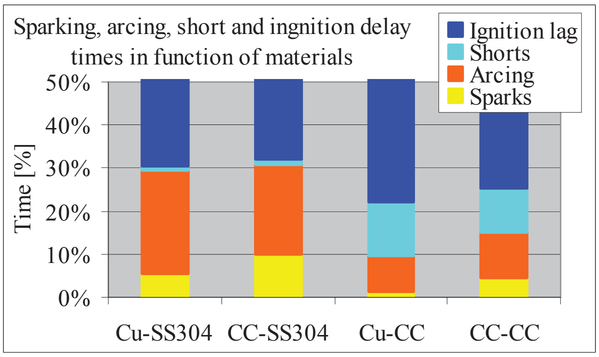

Fig. 4 - Sparking, arcing, shorts and ignition delay times in function of anode and cathode material combinations

4.4. Current specific material removal rate

We can represent a specific material removal rate (SMRR) dividing the MRR with the time averaged current value I_a. The time averaged current value I_a is calculated as follows:

$$I_a = I \frac{T_S}{T_S + T_P} (\tau_A + \tau_S) \qquad (1)$$

The time averaged current is calculated with the relative sparking time τ_S and the relative arcing time τ_A because these are the only times where the flowing current is supplying energy to the working gap. In case of short circuiting the gap voltage is vanishing, so no power is converted over the gap. In case of ignition delay obviously no power is converted too because the current is not flowing. The spark time T_S divided by the sum of spark and pause time T_S and T_P is representing the duty cycle of the process. Assuming that the burning voltage of the sparks is the same for the material combinations the SMRR is also proportional to a power specific material rate. Anyway only the current specific material removal rate is presented here.

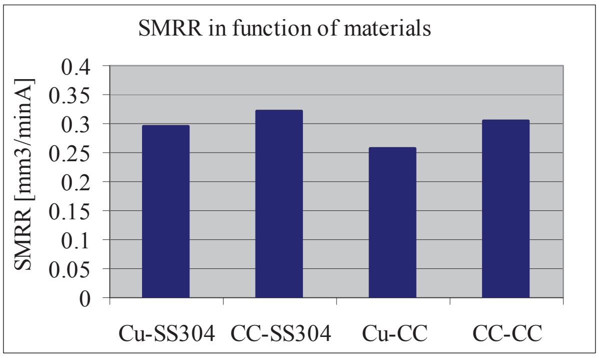

Fig. 5 – Current specific material removal rate in function of the anode and cathode material combinations

In Fig. 5 the SMRR is represented in function of several anode and cathode material combinations. It becomes clear that the current specific removal rate does not change significantly in function of the work piece material.

4.5. Discharge behavior in oil

In Fig. 6 the discharge behavior in dielectric oil is presented. Also here a clear influence of the tool electrode and work piece materials is noticeable. The negative tool electrode polarization which is not ideal for copper-steel erosion, the short pause time T_P as well as the different flushing of the working gap lead to high short circuit rates.

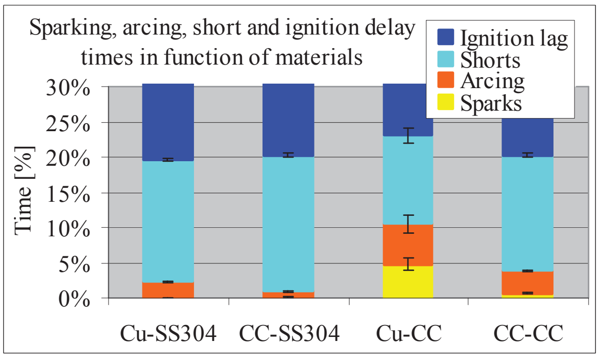

Fig. 6 - Sparking, arcing, shorts and ignition delay times in dielectric oil in function of anode and cathode materials' combinations

Because it is important to have the same polarization of the electrodes, here we neglect the poor sparking and arcing times – but just look at the relative behavior in function of the materials. By contrast with the DEDM results the influence seems not to be clearly in function of the work piece electrode.

5. Discussion

The results on material removal rate in the DEDM experiments show a clear influence of the anode. In traditional EDM this behavior is expected and mostly depends on the different physical properties of the eroded material, especially on heat conduction coefficient and melting temperature. The reason of this dependency is that a given energy input of a spark will lead to different craters on the work piece due to the different physical properties.

The specific material removal rate is nearly not affected by the material combination. This means that what significantly changes the process are not physical properties as heat conduction coefficient or melting temperature which show their effect when a discharge occurs, but more likely material properties which influence the discharge frequency and the stability of the process.

Using traditional EDM generators the maximal open voltage is around 250 V. In the Paschen's diagram of the applied gases the minimum breakdown voltage is over 300V. This means that in these experiments we haven't reached the minimum values of the Paschens's diagram for the flushing gas. In the last years several efforts have been made to characterize electrical breakdown over micro gaps because of their applications in micro electro mechanical systems. It has been shown that in case of gaps less than 5µm in atmospheric air and with at least one metallic electrode there is a discrepancy with the Paschen's curve [4]. There is a linear dependency between gap distance and breakdown voltage till the Paschen's curve is reached. In larger gaps an electron avalanche triggers the breakdown, ionizing the gas molecules present in the gap. But in case of very small gaps the free path of gas molecules is too big in comparison to the gap distance. Only few molecules will be present in the gap. The cause of the increasing breakdown voltage of the Paschen's curve by very small gaps is the lack of gas molecules. In case of at least one metallic electrode, and gaps that are small enough (<5µm) an electron field emission can trigger the discharge at lower voltages rather than the electron avalanche through the gas would do [5]. This mechanism is more similar to a vacuum discharge than a gas discharge.

This means that the ignition mechanism of the DEDM discharge is not the same as the one known from traditional EDM in oil or deionized water.

Subbu et al. [6] measured the light emission of sparks during DEDM and evaluated plasma temperature and electrode density using the line pair method. In this publication images of several spectral measurements are shown and it is clearly visible that there is mostly a metal plasma and not gas atoms scattering the light. On the other hand Descoudres [7] published spectral measurements of EDM plasma in deionized water. The results show a spectrum where hydrogen and oxygen are the principal lines.

The comparison with the measurement in oil shows that also in oil EDM the influence of the materials is obviously present, but it is completely different. The dependency is not clearly on the side of anode or cathode but more likely a combination of the two.

Because the discharge mechanism needs an evaporation of the metal phases to create a plasma channel, a material with a slightly greater resistance to this phenomenon can lead to an even smaller gap, which is harder for the machine to control. On the other side from traditional EDM we know that eroded particles in the dielectric fluid can have a great influence on the gap distance and the discharge behavior. So also the different behavior of the eroded particles of the work piece materials can affect the erosion process leading to frequently short circuiting. Further experiments will be done to gain more information of the mechanisms which occur in the dry electrical discharge machining.

6. Conclusion

A comparison of material removal rate and tool wear ratio of dry electrical discharge machining with different tool electrode and work piece materials by fixed EDM parameters has been presented. The results have been compared to the discharge behavior. The comparison shows that the major influence on the material removal rate is caused by the work piece material on the discharge behavior. This is supported by the evidence that the specific material removal rate is quite independent from the tested work piece material and in addition by the fact that we have metallic plasma similar to vacuum plasma and not plasma formed out of the dielectric fluid present in the gap. This fact necessitates different measures to enhance the process efficiency of DEDM than in traditional EDM. Thus DEDM mechanism and behaviors cannot be only explained on the basis of models developed for traditional EDM.

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