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Influence of oxidizing gas on the stability of dry electrical discharge machining process

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Abstract

Due to the absence of a dielectric liquid dry electrical discharge machining (DEDM) can result in comparison to traditional EDM in a simpler and environmentally friendly machine. Driven mainly by this reason several efforts have been made in the past years to understand the erosion mechanism with gaseous fluid and especially with molecular oxygen. The latter is often used due to his enhancement effect on the material removal rate. The effect has been attributed in the literature to the thermal energy surplus resulting from the oxidation of eroded material. This paper presents measurements of material removal rate in function of different flushing gases. Monitoring the voltage and the current values over the erosion gap effective energy specific values of the material removal rate can be calculated. This data shows that the heat energy from the oxidation has only a little effect on the material removal rate and that the main difference between oxygen and less oxidizing gases is to find in different stability and time efficiency of the process. Possible mechanisms driving the observed effects on the material removal rate with oxidizing gases are discussed.

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Keywords: Dry Electrical Discharge Machining; Oxidation; Removal

1. Introduction

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. Kunieda et al. [1] showed that feeding gaseous molecular oxygen into the erosion gap in case of EDM with water based dielectric the material removal rate (MRR) can be increased. The reasons for the MRR enhancement are attributed in the same work to mainly two mechanisms. On one hand the heat release from the oxidation of the eroded material which enhances the mean material removal of the single sparks. On the other hand a higher discharge frequency has been observed when oxygen is introduced into the working gap.

In a later work Kunieda et al. showed that also in case of dry electrical discharge machining a larger amount of oxygen in the erosion gap enhances the material removal rate [2]. Kunieda et al. attributed the higher MRR to the heat energy introduced in the process by the oxidation of the eroded work piece material. In further works from different researchers mostly air or oxygen have been used as flushing gas. The first one thanks to its simplicity and availability and the second one due to the enhancement of the material removal rate [3-9].

Tao et al. [10] tested different gases in the near dry EDM process. This variant of the EDM process is something between traditional EDM with liquid dielectric and dry EDM suggesting a mist as working fluid. Measurement with mixture of water and air, oxygen, nitrogen and helium are presented. On the basis of the results Tao et al. proposed DEDM with oxygen as roughing process and near dry EDM with water nitrogen mixture for finishing process. In this work, material removal rate of dry EDM is measured in dependency of different gases. By the analysis of the voltage and current signals, a statistical evaluation of good sparks, arcing, short circuiting and ignition delay time can be done and the effective power supplied to the process calculated. These data can be used to assess current and power specific material removal rate, which allow a

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better insight in the driving mechanisms of DEDM-process. Comparing the results from different oxidizing gases, such as air, carbon dioxide and oxygen and non oxidizing gases such as nitrogen, we observe a strong influence on the stability of the process and his time efficiency. The oxidation magnitude of the removed material has two main effects on the EDM process. The one increasing the removal rate of single sparks and the latter increasing the time efficiency of the process. Comparing the absolute, the current specific and the energy specific material removal rate of dry electrical discharge machining with the various flushing gases the oxidation effects and their contribution to the material removal rate are elucidated in this work.

Nomenclature	
MRR	Material removal rate [mm^3/min]
CMRR	Current specific MRR [mm^3/minA]
PMRR	Power specific MRR [mm3/minW]
TWR	Tool wear ratio [%]
u	Open voltage [V]
u_e	Discharge voltage [V]
i_e	Discharge current [A]
i_a	Time averaged current [A]
t_e	Discharge duration [µs]
t_o	Interval duration [µs]
P	Flushing pressure [bar]
τ_A	Relative arcing time [%]
τ_S	Relative sparking time [%]

2. Materials and Methods

In this work the same procedures regarding materials and methods are applied as already presented in a previous work [11]. For clarity they are briefly summarized and adapted to the particularity of the experiments presented here.

2.1. Experimental set up

The experimental setup consists in a Spirit II EDM machine from AGIE with a 3R (3R-6.300-EHS16) spindle providing 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 maximum rotation speed of the setup is 2000 rpm and the maximum allowed gas pressure is 35 bars. The gas species can be changed easily replacing the gas bottles. In the DEDM experiments, that are presented here molecular oxygen, nitrogen, carbon dioxide and air have been used as working fluids. A LeCroy Wave Runner 44MXi-A electroscope is used to measure and evaluate the voltage and the current signals over time.

2.2. Electrodes and work pieces

A tubular multichannel copper electrode is used as tool. The cross section of the copper electrode can be seen in Fig. 1. The outer diameter of the copper electrode is 1 millimeter, the inner is 0.44 millimeters and the width of the division bar is 0.13 millimeters which results in a cross section of the tool electrode of 0.69 square millimeters. The multichannel electrode has mainly two advantages in respect to a simple tubular electrode. On one hand the rotation curls the gas flow more leading to a better flushing of the erosion gap. On the other hand, when a pure drilling is performed it avoids the formation of a gudgeon in the middle of the hole. The work piece material used in these experiments is stainless steel SS304.

Fig. 1 - Cross section of 1 mm tubular multichannel copper electrode

2.3. Measurements

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

The electrical behavior during the erosions is measured with the oscilloscope while running the process. 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 time in which normal or arcing discharges, short circuits or ignition delays have occurred is evaluated from the stored data. In order to evaluate this data the voltage signal is scanned for negative pulses, which means signals that go below a defined value for a given time and then rise again. The durations of the scanned pulses is noted. For good sparks the duration of the negative voltage pulse corresponds to the sum of discharge duration t_e and interval duration t_o. 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 circuiting when the voltage signal goes below 8 V and the measured pulse lasts at least $T_1 = 1.5\ (t_e + t_o)$. Arcing times together with short circuiting times are listed when the voltage signal goes below 2/3 of the open voltage u and the pulse lasts at least $T_1 = 1.5\ (t_e + t_o)$. The times of sparks, arcings and short circuits are listed together when the open voltage goes below 2/3 of the open voltage u and the pulse lasts at least $T_2 = 2/3\ (t_e + t_o)$. The right combination of the measured times finally permits to deduce the individual sparking, arcing and short circuiting 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 are enough for a representative time span of the process, because also the servo axis works in the kHz area.

3. Experiments

To evaluate the DEDM process vertical blind holes were machined by means of vertical drilling. Attention has to be paid when the depth of drilled holes becomes too high because instabilities may occur. After a certain depth depending on machining parameters and flushing gas long during short circuits where the tool electrode retracts till the top of the hole are observed. Probably after a given depth the flushing is no more efficient enough to guarantee a sustainable cleaning and debris will accumulate on the bottom of the drilling hole. Blowing this debris up on the side walls may cause longer short circuits till the electrode has retracted enough to ensure the flushing of the accumulated debris. To avoid these phenomena that can lead to bigger variances of the results an upper limit for the machining depth and consequently for the machining time was given for every gas. The range of the erosion time was between 1 and 5 minutes and the depth between 0.5 and 2 mm depending on the flushing gas.

To see how the flushing gases influence the material removal rate a fixed set of DEDM parameters has been chosen – only the flushing gas has been changed. The main parameters are listed in Tab. 1. The electrical parameters as for example interval duration t_o and discharge current i_e have been chosen to have a possibly stable and not too aggressive process for all the different flushing gases and not to optimize MRR.

Tab. 1 – Parameters of the experiments

Parameter	Symbol	Value
Open voltage [V]	u	250
Discharge current [A]	i_e	7
Discharge duration [µs]	t_e	15.4
Interval duration [µs]	t_o	7.5
Flushing pressure[bar]	P	20
Electrode rotation speed [rpm]	Ω	2000
Tool electrode polarization [-]		negative
Tool material		copper
Work piece material		SS304

4. Results

4.1. Material Removal Rate

Fig. 2 shows the MRR measured in the experiments. The lowest MRR is measured with molecular nitrogen as flushing gas. Flushing with carbon dioxide results in a MRR which is about three times the MRR of nitrogen. With air we measure already more then 4 times the nitrogen values. The biggest material removal rate is obtained with molecular oxygen as flushing gas. The value measured with this parameter set is about 4 times the material removal rate with air and more than 16 times the value with nitrogen.

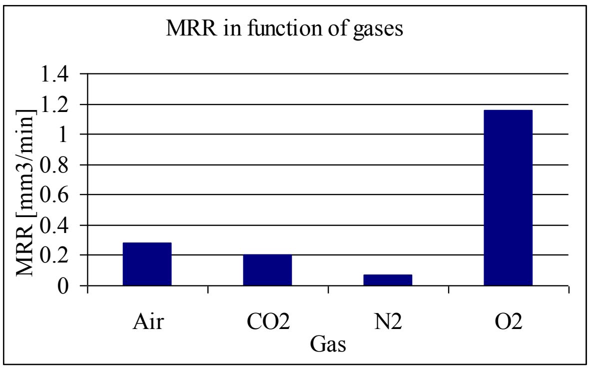

Fig. 2 MRR for different flushing gases

4.2. Discharge behavior

In Fig. 3 the sparking, arcing, short circuiting and ignition delay times are represented for the tested flushing gases. It is notable that there is a major influence from the flushing gas on the discharge behavior in the process. Comparing the share of discharge durations for different gases, it gives a similar picture as the MRR.

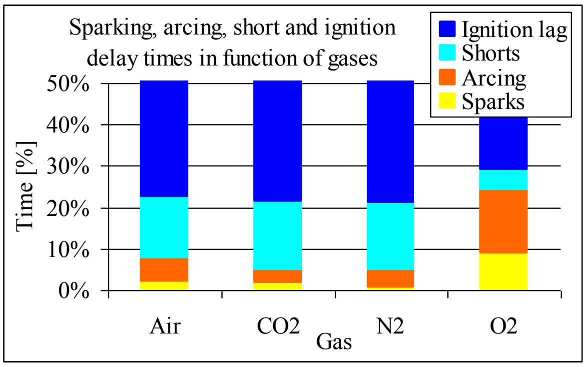

Fig. 3 - Sparking, arcing, shorts and ignition delay times for different flushing gas

4.3. Specific material removal rate

We can represent a current specific material removal rate (CMRR) dividing the MRR with the time averaged current value i_a:

$$i_a = i_e \frac{t_e}{t_t + t_o}(\tau_A + \tau_S) \qquad (1)$$

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 discharge duration t_e divided by the sum of discharge and pause duration t_e and t_o is representing the duty cycle of the process.

In Fig. 4 the current specific MRR is represented for the flushing gases. The current specific removal rate does not change significantly for different flushing gases as long as an oxidizing gas is used, but still a big difference is to be seen between nitrogen and the other gases.

The current specific material removal rate measures the efficiency of the process. Since the current is constant in the process the value of the current specific removal rate is proportional to the mean removal of a single spark which is a good indicator of the spark effectiveness and therefore the flushing efficiency. Furthermore assuming that the mean discharge voltage of the sparks is constant over the measured erosions the current specific MRR would be also proportional to a power specific MRR (PMRR). During the evaluation of measured data quite different discharge voltages have been observed. For this reason a broader evaluation of the discharge voltage for the flushing gases has been made.

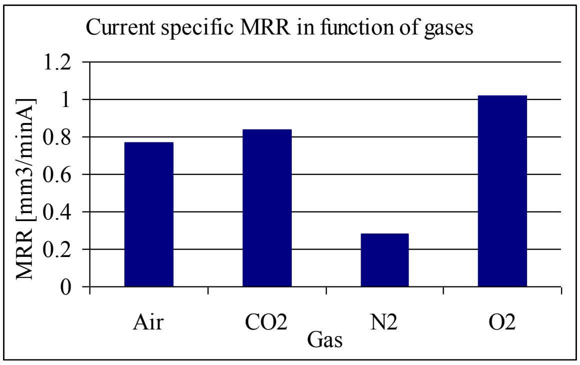

Fig. 4 – Current specific material removal rate for different flushing gases

To evaluate the discharge voltage u_e the mean of all the values measured per gas between 12 and 50 V have been taken into account. The voltage limits have been chosen analyzing the histograms of the voltage signals where a clear range of the occurred discharge voltages can be seen. This simple but effective evaluation leads to the mean discharge voltages for the different gases listed in Tab. 2. The differences between the discharge voltages are not negligible regarding the proportionality between current specific and power specific MRR.

Tab. 2 – Mean discharge voltage for different gases

Gas	**Discharge voltage u_e [V]**
Air	18.5
Carbon dioxide	16.3
Nitrogen	17.3
Oxygen	23.0

Because arcs may have a mean lower discharge voltage then sparks their different proportion of occurrence that can be seen in Fig. 3 may result in the different discharge voltages listed in Tab. 2. Also an influence of the gases itself on the resistivity of the plasma channel as well as different voltage over the gap caused by different distances of the electrodes cannot be excluded. Nevertheless dividing the current specific MRR with the mean discharge voltage the power specific MRR in $mm^3/minW$ is computed, which for the different flushing gases can be seen in Fig. 5. Concerning the specific MRR there is no significant difference between air and oxygen. The power specific MRR of carbon dioxide is even a bit larger than the one with oxygen. The one with nitrogen as flushing gas is still the lowest. Between nitrogen and air or oxygen there is still a difference of factor 2.5, ruling out nitrogen as beneficial media for DEDM.

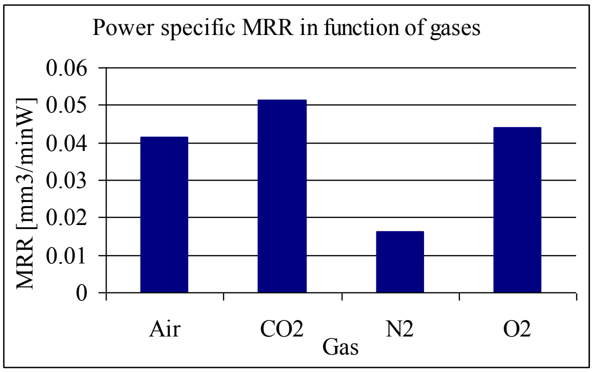

Fig. 5 – Current specific material removal rate for different flushing gases

5. Discussion

The results on MRR in the DEDM experiments show a clear influence of the applied flushing gas. Two different effects that influence the MRR of DEDM with oxidizing gases can be distinguished. The first effect is visible in the absolute MRR and is due a great difference in discharge behavior between strong oxidizing gases as oxygen and less till non oxidizing gases such as air or nitrogen. The second effect is the difference that can be observed between the oxidizing gases and non oxidizing gases in case of current or power specific MRR. The first effect on the stability has the major influence on the absolute MRR and occurs only at large oxygen amounts. The second effect has no big influence on the absolute material removal rate and occurs already at tiny amounts of oxygen. As already mentioned in the introduction an enhancement of the discharge frequency as well as an enhancement of the removed material per spark in function of the amount of oxygen present in the erosion gap has been presented from Kunieda et al. for erosion in water based dielectric in [1]. The work suggests that larger debris particles observed with oxygen supported erosion are leading to a greater gap distance which itself leads, through a higher gap impedance and a decreasing leak current during discharge delay, to a bigger open voltage. Thanks to the latter a higher discharge frequency is obtained. Further it is suggested that the heat energy release of the oxidation enhances the material removed per spark. Although, as suggested in [11] the breakdown mechanism in DEDM is different as the one with liquid dielectrics and potentially other mechanisms may rule the process.

5.1. Influence of the oxidation on the discharge behavior in DEDM

In comparison to oxygen nitrogen drastically increases the amount of short circuits. If too many short circuits occur, the servo regulation reacts enhancing the ignition lag trying to avoid short circuiting and arcing. Because of the narrow nature of the working gap in DEDM this reaction is not effective in case of nitrogen and leads to a time inefficient process. Indeed due to the generally higher dielectric strength of gases the working gap of DEDM is very narrow in comparison to EDM in liquid dielectrics. As already discussed in [11] for the applied voltage in case of traditional EDM machines (< 300 V) theoretically no breakdown of the gas is possible because they operate below the minimum of the Pashen curve. The breakdown is triggered by the electron field emission of the electrodes at very narrow gaps (< 5 μm) which is the same mechanism that triggers sparks in vacuum also at higher voltages. This thesis is supported on one side from the spectrum of the light emitted in case of DEDM which is strongly depending on the electrode material and not on the dielectric gas species as Subbu et al. have shown in [12]. On the other side the thesis is supported from research efforts in the field of micro electrical mechanical systems where the discharge behavior in micrometers gaps is studied. A linear dependency between breakdown voltage and electrode distance has been observed below the minimum of the Pashen curve in case of at least one metallic electrode in [13] and [14].

For these reasons and the results presented in [11], where a strong dependency of the process stability on the work piece material has been shown, it is reasonable to suggest that the stability differences for different flushing gases are mainly due to the different properties of the debris particles in the working gap, namely whether they are oxidized or non oxidized. It is well known that the debris particles have a major effect on the gap width in oil erosion. As already suggested in [11] the debris particles in the very narrow gap of DEDM can lead to frequent short circuits. Usually the servo regulation reacts leading to a bigger working gap. In the case of DEDM and given flushing gas where only a very narrow distance between the electrodes allows a stable process the reaction of the servo control leads to a situation where almost only short circuiting and ignition lag occur. This can be seen in Fig. 3 in case of nitrogen as flushing gas. In case of a major oxidation of the removed material the electrical properties of the latter may change. The SS304 that was used as work piece is an austenitic and therefore non magnetic stainless steel. The observed debris in case of oxygen as flushing gas have ferromagnetic properties and are mainly not conductive. These properties suggest that the main content of the debris eroded with oxygen is iron(II,III) oxide. This is not the case when erosion is performed with air, carbon dioxide or nitrogen. However no quantitative evaluation of these factors has been made till now. The strongly oxidized debris which are no more conductive cannot lead anymore to short circuits and therefore transported outside the erosion gap without disturbing the process. In case of less oxygen in the flushing gas i.e. with air as working fluid, the amount of oxidizing gas is not sufficient to oxidize completely the debris and make them electrically not conductive.

5.2. Influence of the oxidation on mean removal per spark in DEDM

Oxidizing gases have similar power specific MRR values and the only one that shows lower values is nitrogen. As mentioned before the current specific MRR is proportional to the mean removal caused by single sparks as long as the current is kept constant. The difference between the specific MRR of nitrogen and oxidizing gases has to be caused by a greater removal per spark and/or a better flushing efficiency of the process. The first one can be caused by the heat release of the oxidation and the second one can be caused by the different properties of the debris and the work piece surface that avoid the reattachment on the work piece enabling a better flushing of the crater. Regarding the heat release caused by the oxygen a simple estimation of the maximal released reaction energy in case of a complete oxidation of the eroded material shows that the chemical heat is only a little percentage of the electrical energy in the process. Also considering that only a fraction of the energy will be released in a region where it really can support the melting of the work piece (i.e. by the discharge) and not only be transported away due to heat conduction or with the debris it becomes clear that the heat release cannot be the major cause of the mean removal enhancement of single sparks. Therefore we suggest that the different physical properties of oxidized particles and their capability to reattach on the work piece play a major role in the process.

6. Conclusion

MRR and discharge behavior of DEDM has been systematically analyzed for different more or less oxidizing gases. Current specific and power specific MRR are presented and hypothesis of the ruling mechanisms regarding the influence of oxygen in DEDM are elucidated. The results show an already known major influence on the MRR where oxygen is used as flushing gas. The influence is given by two different mechanisms. The first one occurs only at high oxidation capability of the flushing gas acting on the stability of the process. According to [11] this effect probably depends mainly on the electrical properties of the debris particles in the erosion gap. The second effect of the oxidation results in different specific MRR values and saturates already with little oxidation capability of the flushing gas. This mechanism enhances the removed material per spark and is probably ruled mainly by the physical properties of the oxidized particles which reattach less to the work piece enhancing the flushing efficiency of the process.

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