Some aspects of the research on electro-erosion machining

Citation for published version (APA):
Heuvelman, C. J. (1968). *Some aspects of the research on electro-erosion machining*. (TH Eindhoven. Afd. Werktuigbouwkunde, Laboratorium voor mechanische technologie en werkplaatstechniek : WT rapporten; Vol. WT0204). Technische Hogeschool Eindhoven.

Document status and date:
Published: 01/01/1968

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

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technische hogeschool eindhoven
laboratorium voor mechanische technologie en werkplaatstechniek

blz. 0 van 11 bl
rapport nr. 0204

rapport van de sectie:

titel:

Some aspects of the research on electro-erosion machining.

codering:

P.7.b.12

auteur(s):

Ir. C.J.Heuvelman

trefwoord:

vonkverspane

sectieleider:

hoogleraar: Prof.dr.P.C.Veenstra

samenvatting

This paper mainly deals with two models based on the thermal-erosion theory, and the influence of flushing.
These models permit the prediction of erosion properties of workpiece and tool. It is also possible to derive the values of the electrical parameters of the energy applied so as to obtain optimum results. Finally the effect of flushing of the dielectricum on electro-erosion machining is described.

prognose

Note presented at the 18th General Assembly of C.I.R.P., Nottingham, September, 1968

datum:
Aug.1968

aantal blz.
12

geschikt voor publicatie in:

Annales of C.I.R.P. , Nottingham.

SOME ASPECTS OF THE RESEARCH ON ELECTRO-EROSION MACHINING

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for presentation at the
18th GENERAL ASSEMBLY OF C.I.R.P.
Nottingham, September, 1968

Summary

This paper mainly deals with two models based on the thermal-erosion theory, and the influence of flushing.
These models permit the prediction of erosion properties of workpiece and tool. It is also possible to derive the values of the electrical parameters of the energy applied so as to obtain optimum results. Finally the effect of flushing of the dielectricum on electro-erosion machining is described.

Sommaire

Dans cet article deux modèles basés sur la théorie d'erosion thermique, ainsi que l'influence de l'écoulement du diélectrique sont principlament discutés.
Ces modèles permettent la prédiction des propriétés d'érosion de la pièce et de l'électrode. Il est aussi possible de dériver les caractéristiques de l'impulsion afin d'obtenir des résultats optimaux. Finalement, l'effet de l'écoulage sur le machinage par électroérosion est eclairci.

Zusamenfassung

In diesem Aufsatz werden hauptsächlich zwei auf die thermische Erosionstheorie basierte Modelle wie auch der Einfluss auf die Spülung besprochen.
Diese Modelle ermöglichen die Vorhersage über die Erosionseigenschaften des Werkstückes und der Werkzeugelektrode. Es ist auch möglich die Entladeparameter abzuleiten damit maximale Erfolge erreicht werden können. Schliesslich werd der Effekt der Spülung auf die elektroerosieve Bearbeitung beleuchtet.

Some aspects of the research on electro-erosion machining

Introduction

Since the physical background of the electro-erosion process is still rather unknown, a lot of research in this field is still going on. This research diverges into several directions.

In the emperic research a lot of experiments are carried out in order to find an optimum if one or more process-dependent parameters are varied. This optimum is mostly the maximum productivity and minimum tool wear together with a high-quality surface. From the emperic results a number of physical properties of the erosion process were succesfully derived. The properties generally refer to the physical background of the well-known high-pressure ionized gas discharge.

Another way of explaining the properties of the erosion process is to create a model and to verify this model experimentally. This method is sometimes rather difficult since the experiments required for theoretical verification, are hardly feasible. Problems usually arise owing to lack of suitable electrical generators and measuring equipment, since there is a great divergence between theoretical models and practical experiments.

An intermediate type of research is to carry out special experiments in order to find possible new effects that may explain the process or how a new model can be created. This procedure sometimes proves to be very succesful.

This paper deals with some interesting investigations and their results which may not be widely known.

An erosion model

A number of theories on the mechanism of electro-erosion have been developed in order to explain the metal-removal process of workpiece and tool.

The theories are dependent on the energy level of the spark. Mechanical impacts of particals on the workpiece material will probably play a role at high energies (10 J and above). At lower energies, however, the thermal erosion theory is more probable. This theory is based on the fact that, when passing electrical current through the gap, energy is fed into the arc channel, since there exists a burning voltage across the gap. As the radiation energy and the heat energy transported by the dielectricum can be assumed to have a rather low value, the greater part of the electrical energy is transferred into heat which is delivered to workpiece and tool. The energy distribution on both surfaces depends on the voltage distribution across the gap, and is a function of the polarity, current density and the physical properties of the material together with those of the dielectricum. Several investigaters have tried to find out this distribution; according to Zingerman (1) the drop of potential at the anode is linear to the current density, but at lower values of the current this rule is probable not valid. In many cases not too large a mistake is made when assuming an equal division of the voltage. The heat distribution in the material can be calculated with the aid of the physical properties and on the supposition that all electric energy will be transferred into heat on the material surface. It is then possible to calculate the amount of melted and evaporated material that will be removed. However, this thermal erosion model is not complete: one of the most important figures to know is the distribution of the heat density as a function of its position on the surface and of the time. This distribution is still rather unknown.

Leemreis (2) created a simple model with which he could calculate the material removal of the workpiece in relation to the removal from the tool. He assumed a point-source working on the surface with a constant power N, during a time t_f (rectangular pulse), so that the energy during that pulse is $A_f = t_f.N$. He calculated the temperature in the material at the end of the pulse and subsequently the optimum pulse duration at a given energy. The solution of the Fourier differential equation for a non-stationary heat problem gives the temperature T in a spherical space at a distance r from the origin (source on the surface). The temperature at the end of the pulse is:

$$T(r,t_f) = \frac{A}{2\pi k} \cdot \frac{1}{r t_f} \left(1 - \operatorname{erf} \frac{r}{\sqrt{4a.t_f}}\right) \qquad (1)$$

in which k = heat conduction coefficient, and

a = thermal diffusivity.

Equation (1) is only valid at temperatures below melting point (T_m) and based on the supposition that k and a have a constant value in the whole temperature range. However, joining the melting heat (m) to the specific heat (c) the validity can be extented to over the melting temperature. The thermal diffusivity has to be replaced by:

$$a' = \frac{k}{\rho} \cdot \frac{1}{c'}$$

ρ = specific mass, and

$c' = c + \frac{m}{T_m}$

Leemreis defined the optimum pulse duration being the pulse time at which the polar radius of the meltingsphere will be maximum as a function of the material properties. For the optimal pulse duration he found:

$$t_{f,opt} = \left[\frac{1}{14.42.\pi} \cdot \frac{1}{kT_m\sqrt{a'}} . A_f\right]^{2/3} \qquad (2)$$

and for the polar radius:

$$r_m = \left[\frac{1}{3\pi \cdot T_m \rho c'} . A_f\right]^{1/3} \qquad (3)$$

The eroded volume will be linear to r_m^3; according to equation (3) the eroded volume is linear to the pulse energy, which is well-known. Pulses having low current and long pulse duration do not erode: the momentary power will not be large enough to melt the material. However, in equation (1) the temperature at the origin ($r \rightarrow 0$) will be infinitely high, irrespective of the pulse duration. In this case the model fails since a point heat-source is supposed.

With the aid of a model where the heat source is an infinitely large plane on the material surface with an energy density of e, (J/m^2), Leemreis calculated the maximum (critical) pulse duration at which the material just melts. The critical pulse time is:

$$t_{i,cr} = \frac{4}{\pi} e^2 \frac{1}{k\rho c T_m^2} \tag{4}$$

The factor $k\rho c T_m^2$ is called the erosion-strength. A high erosion-strength is desired for tool material. The physical factors appearing in the formulas (2), (3), (4), are calculated from constants that are not always exactly known. Moreover, many of them are functions of the temperature.
In table I the values of $kT_m\sqrt{a'}$, $T_m\rho c'$ and $k\rho cT_m^2$ are given for a number of materials.

	$kT_m \quad a'$	$T_m \quad c'$	$k \quad cT_m^2$
Unit	$Js^{-3/2}$	$x10^8.Jm^{-3}$	$x10^{13}.J^2m^{-4}s^{-1}$
Copper	3200	57	150
Aluminium	1400	29	32
Cobalt	370	78	56
Tungsten	2900	139	510
Graphite	3700	50	200
Steel (0,1% C)	210	79	40.6
Cast Iron	190	53	2.5
Tungsten Carbide (GT20)	860	82	150

Table I,values for significant erosion constants for some materials (after Leemreis)

When using copper as electrode and steel as workpiece,the ratio of the optimum pulse times for both metals can be calculated from (2):

$$\frac{t_{f,opt}\ (\text{steel})}{t_{f,opt}\ (\text{copper})} \approx 10$$

At an energy level (at steel side) of 1J the (desired) pulse time must be:

$$t_{f,opt}\ (\text{steel}) \approx 2380 \mu s$$

In the range of 1mJ the optimum pulse duration will be about 20μs.

The relative electrode wear

The relative electrode wear is defined as the quotient of material mass removal of tool and workpiece.

From equation (4) it can be derived that no tool wear will occur if at a certain energy for the tool material the pulse duration is larger than the critical pulse time. At an energy level of 50mJ the optimum pulse time for steel is about 100µs (equation 2). At that level the critical pulse time for graphite is below 100µs, so that no tool wear will occur; which has indeed been established in practice.

The low-energy range is becoming important for finishing work, and for machining of tungsten-carbide in order to prevent hair cracks. However, at an energy level of about 10mJ and lower, the optimum pulse times become shorter than the critical pulse duration of most tool materials, so that the relative tool wear will increase.

With the thermal erosion theory the energy distribution in the spark gap plays an important role. For low tool removal at low energy it is necessary to keep the drop of potential near the tool surface low in order to maintain the critical pulse duration at a low value.

De Bruyn (3) reached a rather low relative wear (down to 0.1%) by using trapezoidal pulse forms instead of rectangular forms and by carefully keeping the gap between workpiece and tool at a constant value by having the tool servo-mechanism actuate on the firing voltage of the applied pulse. De Bruyn has a reasonable explanation for the success of the trapezoidal wave form: according to the theory of the ionised gas discharges the cross-section of the discharge channel increases during discharge. If at the same rate the current is increasing, the current density on the surface will be constant. On the other hand, it seems reasonable to suppose that an optimum material-removal process will occur at a given current density: the voltage distribution might be constant at a constant energy density, which is corroborated by the exigency of keeping the length of the discharge path as constant as possible. However, with very short pulse times (0.2µs-2µs) there are phenomenae that are not so easy to explain with the thermal erosion theory, where the energy distribution is rather essential.

Veroman(4) found a rapidly decreasing relative wear when the pulse duration is decreasing (sinusoidal wave forms) if the tool has a negative polarity. With longer pulses the polarity has to be altered in order to keep the electrode wear at a low value. Pahlitzsch, Visser and Funk (5) reported on this as well; they explain the phenomenae by distinguishing the erosion in electron-impacts and in positive ion-impacts on the surface of the electrodes: at the beginning of the pulse the number of electrons is larger than the number of ions. The electrons are attracted by the anode and cause material removal of the anode. According to the thermal erosion theory the drop of potential at the anode is rather large during the first μs. During the pulse, the number of generated ions is increasing. These ions are bombing the cathode, causing there material removal; so the drop of potential at the cathode must increase.
Pahlitzsch et al. change polarity when the ion current has become predominant, thus obtaining a low relative tool wear.
It is obvious that these phenomenae are connected with the ignition mechanism which is not fully clear as yet. The semi-quiescent current is reached after some μs. The relationship of the voltage applied to the gap and the length of the gap is known, but preceding sparks will facilitate the ignition.
Experiments show that a much higher field strength (shorter distance between the electrodes) is required for ignition if a single pulse is applied than if a series of pulses is passing.
In the lather case pollution of the dielectrical fluid will probable help the ignition. This pollution may consist of electrically conducting tar products originating from the dielectricum, small metal particals or even not yet recombined ionized atoms. In relation to this the importance of the flushing has also to be considered.

The influence of the flushing on the electro-erosion process

Svan (6) has carried out a lot of experiments in order to trace the influence of the flushing on the material removal, the tool wear and the roughness.

He experimented with pressing or sucking the fluid through the work-gap. He found a dependance of the fluid-velocity on the material removal. The experiments were carried out with a lot of different dielectric fluids.

Svan points out that, generally, the fluid has to be pressed into the gap with coarse machining. In high-energy maching large gas-bubbles arise out of the arcs. With underpressure these bubbles, together with turbulence phenomenae cause a change of the electrical properties of the fluid, in such a way that the gap width is decreasing. Hence, short circuiting more often occurs, owing to the particles produced. This results in a bad surface. Pressing the fluid into the gap causes no turbulency and consequently the surface quality will be better.

With fine machining the pulse energy and gap width are small. In this case sucking is more suitable because the particals generally pass a shorter distance through the gap, so that the risk of short-circuiting is smaller. This is especially of importance with machining of deep holes. From the experiments on short-circuiting and turbulency is appeared that there was no difference as to workpiece removal and relative tool wear if sucking or pressing was applied with equal fluid velocity.

In order to obtain maximum material removal, the fluid velocity must have a low value. However, the velocity must not be kept too low so as to avoid short-circuiting by accumulation of particals.

At high velocities the gap width is decreasing, which may cause short-circuits again. On the other hand, the ignition becomes difficult owing to the increased absence of pollution of the fluid.

In Fig. 1 an example is given of the dependence of the material removal as a function of the velocity (coarse machining).

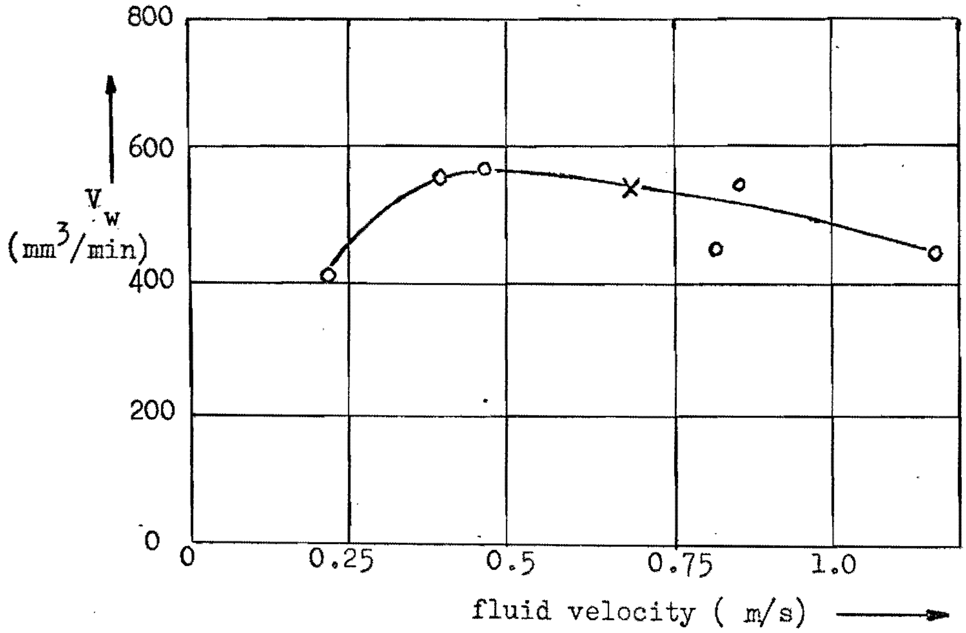

Fig. 1. - The influence of the velocity of the dielectric fluid on the workpiece-material removal (after Svan).

Anode:	graphite	t_f = 226µs
Cathode:	Steel SIS 2312	t_p = 333µs
Dielectricum:	Shell Sol-H	I = 60A

o o o : pressing of the fluid
x x x : sucking of the fluid

In Fig. 2 the effect of the flushing on the gap width is given for the same conditions as described in Fig. 1.

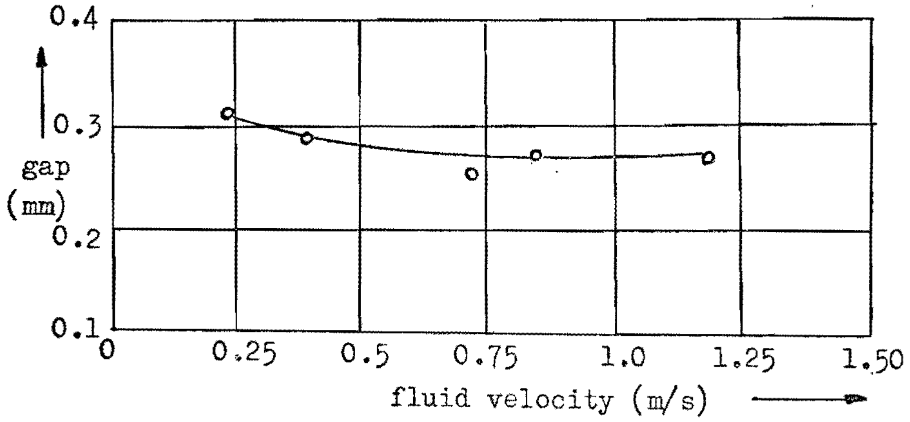

Fig. 2. - The gap-width dependence of the fluid velocity (after Svan). Conditions as in Fig. 1.

Fig. 3 shows that the relative tool wear is not very much affected by the velocity of the dielectric fluid. A maximum occurs at the said velocity where the workpiece-material removal is maximum.

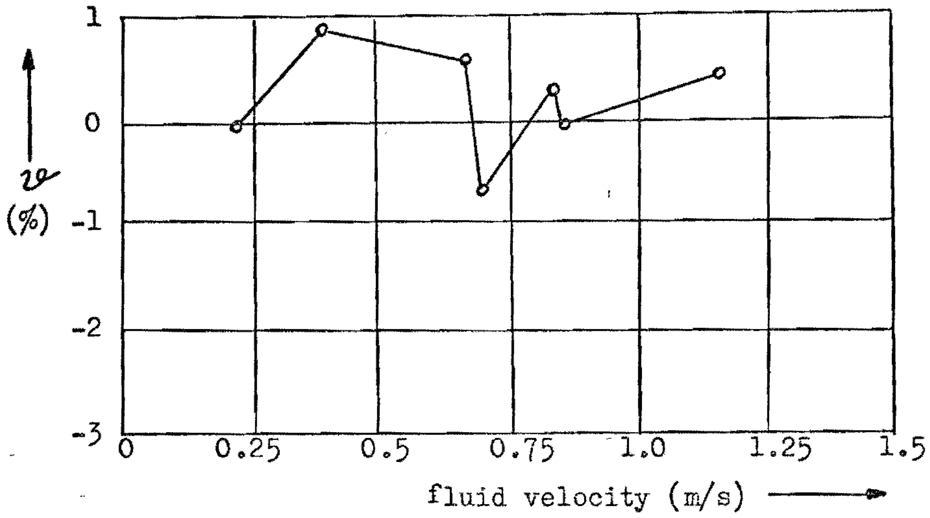

Fig. 3. - The relative tool wear as a function of the fluid velocity (after Svan). Conditions as in Fig. 1.

With machining of deep holes the velocity of the dielectric fluid has much influence on the conicity of the hole. In Fig. 4 the difference of the diameters of a hole is given as a function of the velocity. The fluid is sucked through a concentric hole at the bottom of the machined hole.

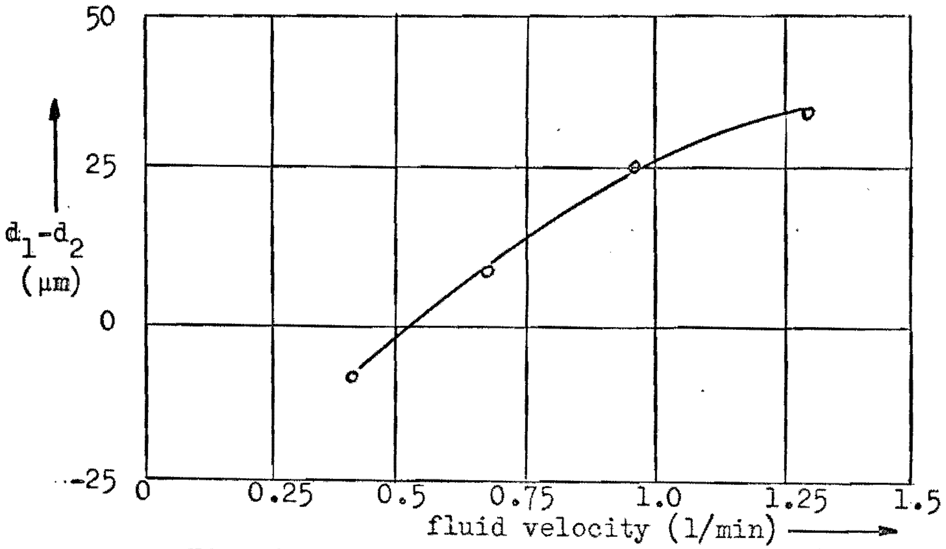

Fig. 4. - The conicity of a machined hole as a function of the fluid velocity. (Finishing machining)

d_1 = diameter at the top (d_1 = 30 mm)

d_2 = diameter at the bottom.

The depth of the hole was 40 mm.

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