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On precision improvement by ultrasonics-aided electrodischarge machining

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Abstract. The paper deals with increasing the precision by electrodischarge machining, aided by ultrasonic longitudinal vibration of the electrode tool. Increasing the dimensional precision of machined surfaces is strongly related to the decrease of volumetric relative wear. This essential parameter of electrodischarge machining depends on several input parameters, which are described in detail. Several optimization conditions, concerning the technological input parameters, are elaborated, aiming at the maximization of the dimensional precision through volumetric relative wear. These conditions address overall parameters as acoustic pressure, discharge energy level and power supply of the ultrasonic chain. Several technological solutions are elaborated like the synchronization of pulses with tool oscillation semiperiods, decreasing the supply power of the acoustic chain and working with frontal flat surfaces of electrodes by generating complex surfaces through 3D technological movements provided by CNC machines. All these can lead to up to 50% decrease of volumetric relative wear.

Key words: electrodischarge machining, ultrasonics, finishing, precision.

1. INTRODUCTION

Using of ultrasonics, i.e. longitudinal vibrations of the electrode-tool with ultrasonic frequency, by finishing electrodischarge machining (EDM+US) aims to eliminate the specific instability of the process and increases its performance relative to precision, surface quality and machining rate. Under normal conditions, EDM finishing occurs in a very narrow working gap (interelectrode gap), which determines frequent short-circuits and difficult evacuation of removed particles, affecting volumetric relative wear and implicitly the precision of the machined surface. Controlled cavitational phenomena, ultrasonically induced within the gap, solve these problems and improve not only the precision but all technological parameters mentioned above [1–4]. Starting from the analysis of the phenomena, related to volumetric relative wear, several technological solutions are elaborated.

2. WORKING PARAMETERS INFLUENCING ELECTRODE WEAR

Precision of a machined surface is directly related to electrode wear and also to one of the main EDM output parameters, volumetric relative wear ϑ, defined as

$$\vartheta = V_e / V_p, \ \% \tag{1}$$

where V_e is the volume, removed from the electrode during machining in mm^3 and V_p is the volume, removed from the workpiece during machining.

According to the van Dijck and Snoeys model [5], in EDM processes the current density J within the plasma channel, produced by discharge, determines the anode/cathode ratio and consequently, the volumetric relative wear. Power P_c, dissipated on the cathode surface, can be determined with the formula:

$$P_c = i_{c^+}(U_c + U_{i^+} - \Phi) - i_{c^-}\Phi, \ \text{W} \tag{2}$$

where i_{c^+} is the ionic current (A), i_{c^-} is the electronic current (A), U_c is the potential fall at the cathode (V), U_{i^+} is the ionization potential of positive ions (V), Φ is the extracting tension, corresponding to the cathode metal (V) and $i_{c^-}\Phi$ is a factor, contributing to the cathode cooling due to electronic emission (W).

Power, dissipated at anode, P_a, can be determined from the following relation:

$$P_a = P_{tot} - P_c - P_{col}, \tag{3}$$

where P_{tot} is the power, corresponding to a discharge

$$P_{tot} = W_e / t_i, \tag{4}$$

W_e is discharge energy (J), P_{col} is the power, dissipated in the plasma channel (estimated lower than 1% of P_{tot} [5]) and t_i is the pulse time (s).

A qualitative synthesis of working parameters, influencing anode/cathode distribution power is presented in Fig. 1. It can be noticed that at short times of discharges, plasma channel has not sufficient time to develop and thus the discharge energy is reported on small transversal section of the plasma channel, resulting in high current density. In this case, electronic current i_{c^-} is dominant due its lower extracting tension Φ and therefore, a growing of current ratio

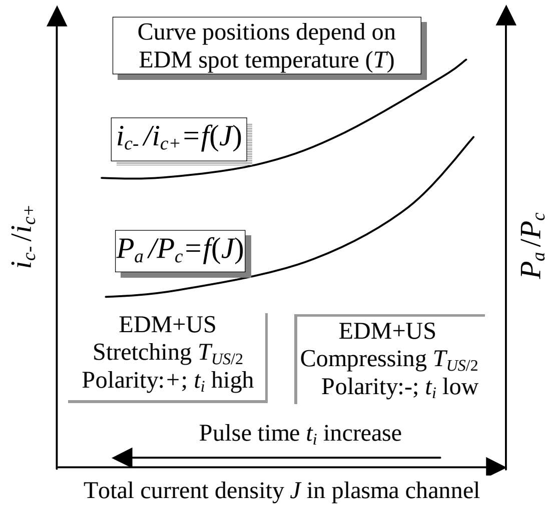

Fig. 1. Qualitative variation of working parameters influencing electrode wear.

i_{c^-}/i_{c^+} is produced. In Eq. (2), the factor $i_{c^-}\Phi$ has a high value, ionic current i_{c^+} is low and thus, taking account of relations (2) and (3), the anode/cathode power ratio P_a/P_c grows.

In this context, an important aspect to be analysed is the polarity effect. As the finishing mode is characterized by low pulse time, it is advantageous to work with negative *e* polarity (the tool is the cathode), resulting in low density J within the plasma channel. Moreover, relaxation pulses, usually used in this case, are able to get a superior quality of surface due to the crater shape, which is more flat than in case of commanded pulses [4].

When commanded pulses are used, having greater pulse durations, plasma channel has time to develop decreasing density J. Ratio P_a/P_c becoming low, using of positive polarity is advantageous, taking into account tool wear and precision. These phenomena are involved in the EDM+US process as it will be further explained.

Flushing pressure p_{fl} is another parameter related to wear ϑ. High flushing pressure determines easier evacuation of gas bubbles from the working gap and thus inertia forces of the dielectric liquid with high purity degree restrict the development of the plasma channel, producing high J density. When working with positive polarity, the P_a/P_c ratio increases and implicitly, great ϑ values are recorded.

The pause time t_o also influences ϑ as reported by Joeres and Semon [6]. For small values of t_o, inertia forces of the dielectric liquid are low due to its pollution and plasma channel extents. Thus the density J decreases with consequences on related working parameters mentioned above. But at too small t_o, EDM finishing process could degenerate in continuous arcs due to specific narrow gap.

In addition, the importance of the tool material characteristics must be underlined; during the EDM process the electrode material has lower wear than the workpiece material, being proportional to the C_{PZ} coefficient – the Palatnik and Zingermann criterion involving its thermo-physical characteristic [4].

3. PHENOMENA INFLUENCING TOOL WEAR DURING DISCHARGE

The pressure in the gas bubble, developed around the plasma channel produced by discharge, limits transversal section of the plasma channel, influencing density J within the plasma channel.

As it is shown in Fig. 2, gas bubble dynamics comprises four stages:

(a) *initial stage*, characterized by very high pressure p_{ib} in the gas bubble due to great inertial forces of dielectric liquid, which are opposed to bubble development;

(b) *development stage* – pressure p_{ib} lowers gradually because of bubble volume growing;

(c) *intermediate stage* – sudden fall of inner pressure p_{ib} due to the pulse end;

(d) *final stage* of bubble implosion – great increase of inner pressure p_{ib} as a result of adiabatic gas compression and gas elastic distend.

In Fig. 2, p_{ib} values for a particular case are presented.

Other researchers have reported relatively close values corresponding to these development stages of the gas bubble [2,7,8].

These four stage analysis leads to correspondent phases of volumetric relative wear dynamics, considering the polarity effect.

The analysis below corresponds to *positive polarity* working (tool to plus).

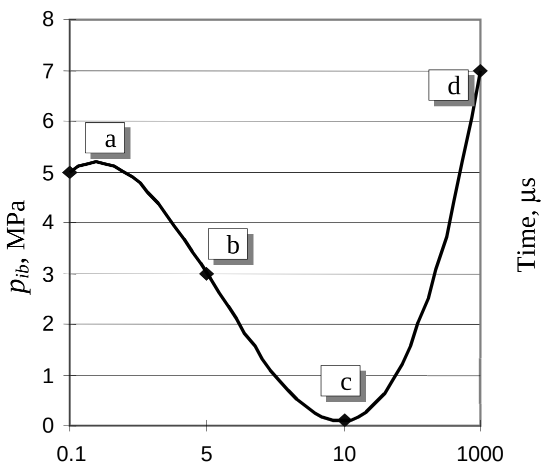

Fig. 2. Pressure variation within the gas bubble for a pulse time of 10 µs.

In the first phase, corresponding to stage (a), great pressure in the gas bubble determines high value of density J in the plasma channel. Therefore the anode-cathode ratio P_a/P_c is great and thus the electrode wear grows.

In the second phase, matching stage (b), the density J is lower due to the inner pressure decrease; thus P_a/P_c ratio is low and, consequently, electrode wear lowers.

In the third phase (c), sudden fall of p_{ib} at the pulse final determines a quick boiling, mainly in the workpiece material, the main mechanism of the removal process at EDM [5], and low volumetric relative wear, because material couple was selected using the Palatnik and Zingermann criterion.

In the fourth phase (d), at the classical EDM, the probability to remove material through bubble implosion is very low, because this moment is very far in time from the pulse end, unlike at EDM+US, when bubble implosion occurs at each end of the oscillation period. The hydraulic forces can not remove great volumes of the material, because it is already solidified by this moment. Cavitational phenomena due to bubble implosion can remove material, and relative wear ϑ is assessed as high.

The analysis of *negative polarity* working (tool to minus) is the following.

In the first phase (a), because of high values of p_{ib}, current density J is high, P_a/P_c ratio grows, determining low tool wear.

In the bubble development phase (b), inner pressure p_{ib} as well as density J become low; due to diminishing P_a/P_c, electrode wear increases. The analysis of the next phases does not emphasize the polarity effect, the observations above being correct for the negative polarity too.

To conclude, positive polarity produces low wear electrode, when bubble development is sufficient (phase b) and negative polarity determines low wear at short pulse times (phase a). The analysis of gaseous and hydrodynamics phenomena are in agreement with the van Dijck–Snoeys model, experimentally confirmed [6]. If the results from classical EDM phenomena analysis are transferred to the specific mechanism of ultrasonically aided EDM, the solution of the pulse generator, synchronized with the time intervals when current density is high or low, becomes very effective in order to reduce relative wear ϑ.

4. CARBON LAYER DEPOSITING

Carbon depositing, as a surface layer on electrode-tool when using dielectric liquid, consisting of hydrocarbons with high content of carbon, is a known phenomenon. Taking account of very high melting point of this deposited material, it is necessary to analyse this phenomenon in connection with the tool wear.

Mohri et al. [9] reveal an interesting occurrence, studying on-line the wear of the frontal plate zone of the electrode. The total wear on this region is lower at the beginning of machining and increases gradually up to a value that depends on machining and material conditions.

At start, the plate region wear becomes even negative as a result of carbon depositing on this area, determined by cracking reactions of the dielectric liquid with hydrocarbons content during EDM, because of about 10 000 °C around the plasma channel.

Experimentally, at finishing/superfinishing modes with low machining time 10–15 min, we noticed a very low, even negative volumetric wear ϑ [6].

After these first phenomena, depositing process begins to balance the EDM material removal process. On electrode edges, the wear dynamics is explained by the fact that carbon depositing is not apparent as long as their radii are very small. The depositing process occurs as machining progresses and edges become more round.

Moreover, by carbon steel machining, in some cases carbon adheres very well on the electrode surface and in other cases it is very easily removable. X-ray analysis suggests that in the first case, the carbon layer is turbolayered, i.e. laminated layer of bidimensional carbon crystals with random phase. At machining of steels with high carbon content, adhering process is considered to be the result of carbon precipitation, similar to graphite precipitation phenomenon at steel cast.

Carbon layer depth is proportional to equivalent carbon content from the workpiece material and hence with electrode wear. But by machining of materials with relatively high content of Ni or Cr, the electrode wear is very low and even their carbon content is reduced. It is considered that elements like Ni, Cr and Fe have a catalyzing role in carbon precipitation [10].

We also consider a strict connection between temperature during the EDM process and carbon depositing. In different phases of the EDM+US process, we emphasize some phenomena that sustain carbon deposition and, consequently, reduce electrode wear (a hypothesis in agreement with our experimental results). On this basis, technological solutions are elaborated to increase dimensional precision.

5. EDM+US PHENOMENA INFLUENCING ELECRODE WEAR

An oscillation period T_{US} at EDM, aided by longitudinal vibrations (normal to the machined surface) of the electrode-tool, comprises two semiperiods with distinctive cavitational phenomena, influencing electrode wear (Fig. 3). Numerical values are calculated with Eqs. (5) and (6) and experimentally confirmed in [6].

In the first semiperiod, lasting from 0 to 25 μs (at usual frequency of 20 kHz), the *compression* of dielectric liquid from the frontal working gap is produced.

Thus gas bubbles from previous electric discharges are dissolved when elongation y is positive due to acoustic pressure p_{ac}, created within frontal gap, determined with formula [1]:

$$p_{ac} = 2\pi f_{US} A\rho c_s, \ \text{Pa} \tag{5}$$

where f_{US} is ultrasonic oscillations frequency on normal direction (Hz), ρ is dielectric liquid density (kg/m^3), A is ultrasonic oscillation amplitude (m) and c_s is sound velocity in the dielectric (m/s).

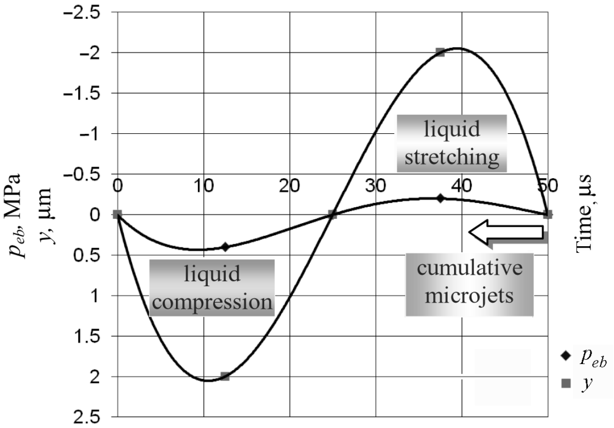

Fig. 3. Cavitational phenomena ultrasonically induced at EDM+US.

To produce cavitation, p_{ac} must be greater than cavitation threshold that depends on existing conditions [6]. In our experiments, cavitation was obtained using $f_{US} = 20$ kHz, A from 1 to 2 μm in a dielectric liquid with density $\rho = 840$ kg/m^3.

During compression, inertial forces of the dielectric liquid are great and they restrict the development of the plasma channel. Hence discharges, occurred within the first semiperiod, are characterized through great current density J in the plasma channel. When working with *positive polarity*, density J determines high electrode wear.

However, the volumetric relative wear, defined by Eq. (1), can be maintained in suitable limits even in this semiperiod. The solution could be machining with *negative polarity*. In this case, high values of density J within the plasma channel determine low values of electrode wear, because cathode power P_c is reduced.

The second semiperiod, lasting from 25 to 50 μs at 20 KHz frequency, produces *stretching* of the dielectric liquid from frontal working gap, explained by Eq. (5). Total hydrostatic pressure p_{ht} is equal to pressure from gas bubble exterior p_{eb}, surrounding plasma channel and determined by

$$p_{eb} = p_{ac} \sin \omega t + p_h, \text{ MPa} \tag{6}$$

where $\omega = 2\pi f_{US}$ (s^{-1}) and p_h is local hydrostatic pressure (MPa).

Thus dielectric pressure from the working gap becomes negative and the volume of the gas bubble, created by a previous electric discharge, grows up to a value, corresponding to high dielectric pressure at the end of an oscillation period. At this moment, *cumulative microjets* are produced, resulting from implosion of gas bubbles from the working gap. This phase is characterized by pressures of about 100 MPa, much higher than those from phase (d) at classical EDM, producing low values of relative wear ϑ due to great material volume, removed by additional ultrasonic aiding.

During the stretching semiperiod, discharges could be produced mainly in the predominant gaseous medium due to gas bubble development (Fig. 3). In these conditions, current density within plasma channel is very low, favouring electrode wear decrease when working with positive polarity.

Gas bubbles implosion in cumulative microjets phase produces a temperature of around 10 000 °C. These secondary phenomena intensify cracking reactions in dielectric liquid, increasing carbon depositing on the tool surface and, consequently, decreasing tool wear [6].

Luminescent phenomena also take place during the second semiperiod, according to Negiski [7]. When gas bubble walls are still close (at around 1/5 of the developing time), electric discharges occur between opposite walls, locally ionizing the working medium and contributing to carbon depositing on the tool surface by liquid cracking reactions.

6. OPTIMIZATION OF WORKING PARAMETERS

We obtained dimensional precision increase up to 50% [6] by volumetric relative wear ϑ decrease, based on some optimization conditions concerning input technological parameters. These conditions follow from the previously presented analyses.

1. Minimization of flushing pressure and pause time t_o, still avoiding degeneration of the EDM process; t_o is related to the maximization of the number of discharges within an oscillation period [4].
2. Short time pulses must be used when working with negative polarity and relaxation pulses, advantageous in EDM finishing by producing flat craters (i.e low roughness (R_a); in order not to damage the craters margins that are very sensitive to cavitational shock waves, the power supply of ultrasonic chain has to be 30% lower than that used for commanded pulses, which produce more deeper craters [4].
3. When using positive polarity, long time commanded pulses must be utilized; they must be located within the stretching semiperiod. On the contrary, when negative polarity is used, short commanded pulses must be used inside the compressing semiperiod.
4. Carbon depositing layer is favoured by long time pulses and intensification of cavitational effect trough increasing power supply of acoustic chain (P_{cUS}); this is in contradiction with condition 2. Therefore an optimum must be found experimentally, depending on real working conditions; $P_{cUS} = 70$ W was appropriate in our experiments when using relaxation pulses, and 100 W for commanded pulses.
5. Machining high carbon steels alloyed with Ni, Cr assures tool protection by carbon depositing.

Some possible technological solutions using computer integrated machining (CIM) system for EDM+US are presented in Fig. 4.

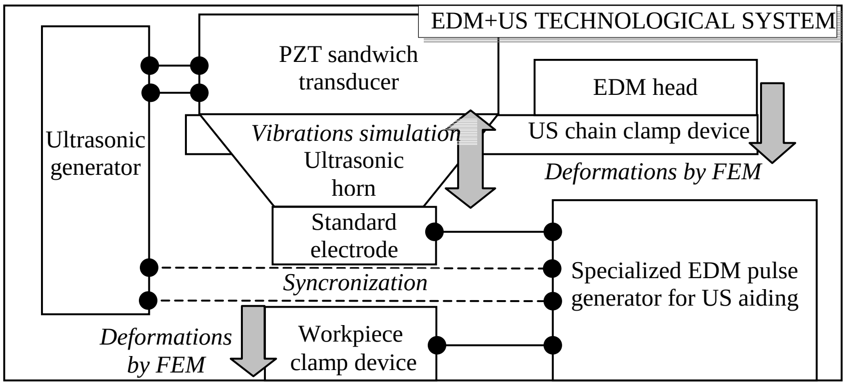

Fig. 4. CIM system for EDM+US.

The decreasing of ϑ can be achieved through a dedicated pulse generator and computer control of deformations through the finite element method. The CIM system achieves simulation of machining under process stability and resonance conditions [[4,6]]. Thus the components of a technological system can be optimized in the CAD/CAE phase and then machined with maximum precision by CNC machines.

7. CONCLUSIONS

The analysis of the removal mechanism at EDM+US emphasizes some technological solutions in order to increase the precision of machined surface through relative electrode wear. The main solutions could be: decreasing the power supply of acoustic chain, nevertheless with the acoustic pressure over the cavitation threshold; synchronization of commanded pulses with tool oscillation semiperiods; working as much as possible with frontal flat surfaces of standard electrodes and 3D CNC for generating complex surfaces.

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Lahendused ultrahelielektroerosioontöötlemise täpsuse parandamiseks

Daniel Ghiculescu, Niculae Ion Marinescu, Gheorghe Jitianu ja George Seritan

On käsitletud elektroerosioontöötlemise täpsuse tõstmist elektroodi pikisuunaliste ultrahelivõnkumistega. Töödeldud pindade mõõtmelise täpsuse suurendamine on olulisel määral seotud suhtelise mahulise kulumise vähenemisega. See elektroerosioontöötlemises oluline parameeter sõltub sisendparameetritest, mida on artiklis detailsemalt kirjeldatud. On välja töötatud tehnoloogiliste sisendparameetrite optimeerimistingimused, mis võimaldavad mõõtmelist täpsust maksimeerida. Nende tingimused puudutavad üldisi parameetreid, nagu helirõhk, sädelahendusenergia tase ja ultraheliahela elektritoide. Nii on saadud tehnoloogilised lahendused: impulsside sünkroniseerimine võnkumiste poolperioodidega, akustilise ahela elektritoite vähendamine ja töötamine elektroodide eesmiste tasapindadega, genereerides 3D tehnoloogiliste siiretega keerukaid pindu. Kõik see võimaldab vähendada suhtelist mahulist kulumist kuni 50%.