PRECISION INCREASING AT ULTRASONICS AIDED ELECTRODISCHARGE MACHINING

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Abstract: The paper deals with technological solutions of precision increasing at electrodischarge machining aided by ultrasonic longitudinal vibration of electrode tool (EDM+US), based on specific phenomenology. Growing of dimensional precision of machined surfaces is strongly related to decrease of volumetric relative wear ($\vartheta$). This essential parameter at EDM finishing depends on some input working parameters, which are described in detail. Some optimisation conditions concerning the input technological parameters are elaborated, aiming maximisation of dimensional precision through $\vartheta$. These conditions address overall parameters as acoustic pressure, discharge energy level, power supply of ultrasonic chain. Thus, some technological solutions are revealed: synchronization of pulses with tool oscillation semiperiods; decreasing the supply power of acoustic chain; working with frontal flat surfaces of electrodes by generating complex surfaces through 3D technological movements provided by CNC machines.

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

1. INTRODUCTION

The ultrasonics aiding, i.e. longitudinal vibrations of electrode-tool with ultrasonic frequency, of finishing electrodischarge machining (EDM+US) aims to eliminate the specific instability of the process and increase its performances of precision, surface quality and machining rate. In normal conditions, EDM finishing occurs in very working gap (interelectrode gap), which determines frequent short-circuits and difficult evacuation of removed particles, affecting volumetric relative wear and implicitly precision of machined surface. Controlled cavitation phenomena ultrasonically induced within the gap solve these problems and spectacular improves not only precision but all technological performances mentioned above. Starting from analysis of phenomena connected to volumetric relative wear, some technological solutions are established.

2. WORKING PARAMETERS INFLUENCING ELECTRODE WEAR

Precision of machined surface is direct related to electrode wear and also by one of the main EDM output parameter, volumetric relative wear ($\vartheta$), defined by:

$$\vartheta = \frac{V_e}{V_p} \text{ [\%]} \quad (1)$$

where: $V_e$ is volume removed from electrode during machining [mm$^3$]; $V_p$ - volume removed from workpiece during machining [mm$^3$].

In EDM processes, current density within the plasma channel ($J$) produced by discharge determines the anode/cathode ratio and consequently, the volumetric relative wear ($\vartheta$), according to F. Van Dijck and R. Snoey’s model [1].

Power dissipated on cathode surface $P_c$ can be determined with the formula:

$$P_c = (i_{c+})(U_{c}+U_i-\Phi) - (i_c)\Phi \text{ [W]} \quad (2)$$

where: $i_{c+}$ is ionic current [A]; $i_c$ – electronic current [A]; $U_c$ – potential fall
at cathode [V]; \( U_{i+} \) – ionization potential of positive ions [V]; \( \Phi \) – extracting tension corresponding to cathode metal [V]; \( (i_c)\Phi \) factor contributing to cathode cooling due to electronic emission [W].

Power dissipated at anode \( (P_a) \) can be determined from the following relation:

\[
P_a = P_{tot} - P_e - P_{col} \quad [W] \tag{3}
\]

where \( P_{tot} \) is power corresponding to a discharge, respectively:

\[
P_{tot} = W_e / t_i \quad [W] \tag{4}
\]

where \( W_e \) is discharge energy [J]; \( P_{col} \) – power dissipated in plasma channel, estimated lower than 1\% \( P_{tot} \) [1].

In fig.1, a qualitative synthesis of working parameters influencing anode/cathode distribution power is presented. It can be noticed that at short times of discharges, plasma channel has not sufficient time to develop and thus discharge energy is reported on small transversal section of the plasma channel, resulting high current density. In this case, electronic current \( (i_{e-}) \) is dominant due its lower extraction tension \( (\Phi) \), and therefore, growing of currents ration \( (i_{e-} / i_{e+}) \) is produced. In formula (1), the factor \( (i_{e-})\Phi \) has high values, ionic current \( (i_{e+}) \) is low and thus, taking account of relations 2-3, anode/cathode power ratio \( (P_a / P_e) \) grows.

In this context, an important aspect, which is necessary to be analyzed is polarity effect. As finishing mode is characterized by low pulse time, it is advantageous to work with negative polarity (the tool is the cathode), resulting low density \( J \) within plasma channel. More over, 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 [2].

When commanded pulses are used, having greater pulse durations, plasma channel has time to develop, density \( J \) decreasing. Ratio \( (P_a / P_e) \) becoming low, positive polarity using is advantageous, taking into account tool wear and implicitly, precision. These phenomena are involved in EDM+US ones as will be further detailed.

Flushing pressure \( (p_{fl}) \) is another parameter related to wear \( \vartheta \). When working with positive polarity, high flushing pressure determines easier evacuation of gas bubbles from working gap and implicitly, great \( \vartheta \) values. Thus, inertia forces of dielectric liquid with high purity degree restrict development of plasma channel, producing high \( J \) density and \( P_a / P_e \) ratio.

The pause time \( (t_o) \) also takes action upon \( \vartheta \) as reported by Jøeres and Semon [3]. For small values of \( t_o \), inertia forces of dielectric liquid are low due to its pollution and plasma channel extents, thus density \( J \) decreasing with consequences on related working parameters mentioned above. But at small \( t_o \), EDM finishing process could degenerate in continuous arcs due to specific narrow gap.

In addition, it must be mentioned the importance of tool material characteristics; electrode material has lower wear during EDM process than workpiece material, being proportional with \( C_{pz} \) coefficient - Palatnik and Zingermann’s criterion [2]:

\[
C_{pz} = c \cdot \rho \cdot K \cdot t_{melt} \quad [J^2 / m^4 s \deg C] \tag{5}
\]

where: \( c \) is specific heat \( [J / kg \ deg C] \); \( \rho \) - density \( [kg / m^3] \); \( K \) - thermal conductivity \( [W / m \ deg C] \); \( t_{melt} \) - melting point \( [\deg C] \).
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 plasma channel, influencing density (J) within 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 of bubble development;
(b) **development stage** - pressure $p_{ib}$ lowers gradually because of bubble volume growing;
(c) **intermediate stage** – sudden fall of inner pressure $p_a$ 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 researches as D. Kremer, C. Lhiaubet, K. Isuzugawa and I. Anton reported relative close values correspondingly to these development stages of the gas bubble [3].

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

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

(1) in this phase, corresponding to stage (a) the great values in the gas bubble determine high values of density J in the plasma channel. Therefore the anode-cathode ratio ($P_a/P_c$) has great values and thus the electrode wear grows.

(2) in this phase, matching to stage (b), the density J is lower due to $p_{ib}$ inner pressure decrease; thus $P_a/P_c$ ratio has low values and consequently, electrode wear lowers.

(3/c) sudden fall of $p_{ib}$ at pulse final determines a quick boiling, mainly in workpiece material - the main mechanism of removal process at EDM [1] – and low volumetric relative wear because material couple was selected on Palatnik and Zingermann’s criterion.

(4/d) at classic 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 oscillation period. The hydraulic forces can not remove great volume of material because it is already solidified by this moment [1]. Cavitation phenomena due to bubble implosion can remove material, and relative wear 9, difficulty quantified, is assessed as high.

The analysis of **negative polarity** working (tool to minus) highlights:

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

(2’) in the bubble development phase (b), inner pressure $p_{ib}$ gets low values as well as density ($J$); due to $P_a/P_c$ ratio diminishing, electrode wear increases.

The analysis of phases (3’) and (4’) does not emphasize the polarity effect, the observations from above being correct for 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 Van Dijck - Snoeys model, experimentally confirmed [3].
4. CARBON LAYER DEPOSITING

Carbon depositing, as a surface layer on electrode-tool when using dielectric liquid consisting in 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 analyze this phenomenon in strictly connection to wear tool.

Mohri et al. [4] reveal an interesting occurrence, studying on-line the wear of frontal plate zone of electrode. The total wear on this region is lower at the beginning of machining and grows 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 dielectric liquid with hydrocarbons content during EDM because of high local temperature. Plasma channel developed along discharge has temperature of around 10,000°C.

Experimentally, at finishing/superfinishing modes with low machining time 10-15min, we noticed a very low volumetric wear $\vartheta$, even negative [3]. 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.

More over, at carbon steel machining, carbon adheres very well on electrode surface in some cases and in other cases, it is very easy removable. X rays 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 with equivalent carbon content from workpiece material and hence with electrode wear. But at machining of materials with relative high content of Ni or Cr, the electrode wear is very low even their carbon content is reduced. It is considered that elements like Ni, Cr, Fe have a catalyzing role in carbon precipitation [5].

Through X rays analysis too, it was noticed that proportionality dependence exists between pulse time and deposited carbon quantity, and implicitly wear $\vartheta$, also experimentally confirmed as mentioned [3]. We also consider a strict connection between temperature during 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, hypothesis in accord with our experimental results.

5. EDM+US PHENOMENA INFLUENCING ELECTRODE WEAR

An oscillation period $T_{US}$ at EDM aided by longitudinal vibrations (normal on machined surface) of electrode-tool comprises two semiperiods with distinctive cavitational phenomena, influencing electrode wear, synthesized in fig.3. The graph values are calculated with relations (6) and (7), experimentally confirmed [3].

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

![Fig. 3. Cavitational phenomena ultrasonically induced at EDM+US](image-url)
Thus, gas bubbles resulted from previous electric discharges are dissolved when elongation $y$ is positive, due to acoustic pressure ($p_{ac}$) created within frontal gap, determined with formula [6]:

$$p_{ac} = 2\pi \cdot f_{US} \cdot A \cdot \rho \cdot c_s \quad [\text{Pa}]$$  

(6)

where: $f_{US}$ is ultrasonic oscillations frequency on normal direction [Hz];  
$\rho$ - dielectric liquid density [kg/m$^3$];  
$A$ – ultrasonic oscillation amplitude [m];  
$c_s$ – sound velocity in dielectric [m/s].

To produce cavitation, $p_{ac}$ must be greater than cavitation threshold that depends on existent conditions [7]. In our experimental researches, cavitation was obtained using $f_{US} = 20$ kHz, $A = 1…2$ μm in dielectric liquid with density $\rho = 840$ kg/m$^3$.

During compression, inertial forces of dielectric hydraulic are great and they restrict development of plasma channel. Hence discharges occurred within first semiperiod are characterized through great current density ($J$) in plasma channel. When working with positive polarity, density $J$ determines high electrode wear. However, the volumetric relative wear defined with relation (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 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 dielectric liquid from frontal working gap, explained by relation (7). Total hydrostatic pressure ($p_{hb}$) is equal with pressure from gas bubble exterior ($p_{eb}$), surrounding plasma channel and determined with:

$$p_{eb} = p_{ac} \sin \omega t + p_h \quad [\text{MPa}]$$  

(7)

where: $\omega = 2\pi f_{US} \quad [\text{s}^{-1}]$;  
$p_h$ is local hydrostatic pressure [MPa].

Thus, dielectric pressure from working gap becomes negative and volume of gas bubble resulted from an electric discharge previously occurred grows up to a value corresponding to high dielectric pressure at final of an oscillation period. At this moment, cumulative microjets are produced, resulting from implosion of gas bubbles from working gap. This phase is characterized by pressures of 100 MPa order, much higher than those from phase (d) at classic EDM, producing low values of relative wear $\vartheta$ due to great material volume removed by additional ultrasonic aiding.

During the stretching semiperiod, discharges could be produced mainly in 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 temperature of around 10,000 $^\circ$C. These secondary phenomena intensify cracking reactions in dielectric liquid, increasing carbon depositing on tool surface and consequently, tool wear decreasing [1].

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

6. OPTIMISATION OF WORKING PARAMETERS

From analyses previously presented, some optimisation conditions concerning the input technological parameters are elaborated, aiming maximisation of dimensional precision at EDM+US through decreasing of volumetric relative wear $\vartheta$. The optimisation conditions of working parameters are:

1) minimisation of flushing pressure and pause time $t_o$ still avoiding
degeneration of EDM process; this parameter is related to maximisation of discharge number within an oscillation period for efficiently exploiting the cumulative microjets phase;  

2) short time pulses must be used when using negative polarity and relaxation pulses; this option is advantageous in EDM finishing by producing flat craters, i.e low roughness ($R_a$); in order to not damage the craters margins that are very sensitive to cavitation shock waves, the power supply of ultrasonic chain has to be 30% lower than that used for commanded pulses, which produce more deeper craters [2].  

3) when using positive polarity, long time commanded pulses must be used; they must be located within stretching semiperiod; on the contrary, when negative polarity is used, short commanded pulses must be used inside compressing semiperiod;  

4) carbon depositing layer is favoured by long time pulses and intensification of cavitation effect through increasing power supply of acoustic chain ($P_{CUS}$); this is contradiction with condition (2); therefore an optimum must experimentally be found, depending on real working conditions; $P_{CUS} = 70W$ was appropriate in our experimental researches when using relaxation pulses, and $100W$ for commanded pulses;  

5) machining high carbon steels alloyed with Ni, Cr assures tool protection by carbon depositing; high $P_{CUS}$ values could remove C layer, increasing electrode wear. Some possible technological solutions are:  

□ synchronization of commanded pulses with tool oscillation semiperiods;  

□ working with frontal flat surfaces of standard electrodes and 3D CNC.  

7. CONCLUSION  

The analysis of removal mechanism at EDM+US emphasizes some technological solutions in order to increase precision of machined surface through relative electrode wear. The solutions are based on optimisation of key-parameters as: acoustic pressure, power supply of acoustic chain, polarity and pulse time duration strongly correlated with tool ultrasonic oscillations.  

8. REFERENCES  


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