SELECTED PROBLEMS OF ELEKTRODISCHARGE DRILLING OF HIGH ASPECT RATIO HOLES

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ABSTRACT

In the paper characteristic of drilling process of high–aspect–ratio holes is presented. The drilling of difficult–to–machine materials (such as hardened steel, carbides, alloys of high strength, composite materials, ceramics) is ineffective with application of conventional methods. The conventional methods are used to machine of materials with a relative machinability. The nonconventional methods are applied to the machine of holes in difficult–to–machine materials, especially in microscale. In the article is described electrodischarge drilling with using of deionised water which is called as hybrid process – electrochemical discharge machining (ECDM). The hybrid process enables machining high aspect ratio holes by simultaneous interaction of anodic dissolution and electrical discharges. This paper also presents mathematical modelling of temperature increase during time of the impulse.

Key words: EDM drilling, micromachining, mathematical modelling

1. INTRODUCTION

Nowdays in different fields of industry micro–holes a wide range of application, such as electronics, aerospace, automotive and medical. The need for products containing micro–holes (diameter less than 1000 µm) significantly increases. The industry is focused on the production of smaller products with much better properties and made of advanced engineering materials which is very difficult to machine by using conventional methods. The microparts is generally defined as element with the range of dimension 1 – 999 µm [1]. Difficult–to–cut materials are more and more applied in modern industry due to high physical properties (such as hardness, compressive strength and chemical, abrasive, corrosion, creep, temperature resistance). In aerospace industry, turbine vanes and blades are required to operate at turbine in temperature higher than the melting point of the materials used in gas turbine engines. Advanced cooling holes are drilled in parts of gas turbine. The cooling technology has been introduced in gas turbine engines to convince the vanes and blades overheating resistance. Modern gas turbine rotor and sensor may have more than 20 000 cooling holes with small diameter [2]. Additionally, turbine blades are subjected to high loads and vibrations due to shape and quality of the cooling holes play an important role for mechanical integrity [3, 4].

In the first part of the article electrodischarge drilling and electrodischarge drilling with using of deionised water (it is called as hybrid process – electrochemical discharge machining – ECDM), are presented. The second part of the paper involves mathematical modelling of temperature increase during time of the impulse in ECDM. The temperature increase plays an important role in achieving of critical stage in the machining area, during hybrid process. The hybrid electrochemical discharge process enables to improve quality and accuracy of machined surface of the holes than EDM or ECM process and to achieve significant higher material removal rate [5].
2. CHARACTERISTIC OF EDM DRILLING

In electrodischarge machining (EDM) material is removed by electrical discharge machining due to changing the electrical energy to thermal energy. The electrical discharges or sparks remove the material by material melting, evaporation and disruption (Fig. 1). Electrical discharges are created between two electrodes (workpiece and tool electrode) which are connected to the pulse generator (the source of discharge voltage up to a few hundred volts and current ranges up to tens of ampers) [6, 7]. The interelectrode gap is filled with dielectric medium.

![Fig. 1. Scheme of EDM material removal mechanism [6]](image1)

In EDM drilling, the tool electrode as drill has rotary and feed motion. The shape of the electrode can be tubular shape (dielectric fluid is pumped through tubular hole of electrode, the dielectric fluid is flushed through the interior hole of the tube in order to remove machining debris) (Fig. 2) or solid rod (the dielectric is fed to the machining zone by either suction or injection through pre-drilled hole). During EDM drilling tool electrode wear occurs. Wear appears both at tip and on the side of the electrode (it is called carrot effect) [8]. The carrot effect appears in many EDM drilling application of electrode with single hole. Therefore, to overcome this effect electrodes with multiple channels are developed. High wear affects on accuracy and efficiency of the process. After drilling the side of the electrode wear contributes to conical shape of the hole. The phenomenon appears mainly during drilling of high–aspect–ratio holes. Tool electrode wear occurs at centric of the electrode what can cause deformation of the bottom of the hole[9, 10]. In the center of electrode tip the wear is most intensive due to the lack of dielectric flow (it is called dielectric stagnation zone).

![Fig. 2. Scheme of EDM drilling with application of a tubular tool electrode](image2)
Electrodicharge machining is a thermo–electric process, what causes that mechanical force between electrodes in the machining area are insignificant and material can be machined regardless of its hardness, density, toughness. For shaping difficult-to-machine and metallic materials (hardened steel, titanium alloy, steel alloy, carbides, composites, etc.), the process is alternative method. Machined surface has relative good quality (with roughness less than 0.1 μm). The process enables to drill holes with high accuracy (less than 5 μm). After drilling the holes characterize regular shape and high accuracy of burr–free surface. It is worth to underline that electrodischarge machining is high temperature process what in some cases cause poor surface layer with heat affected zone [5]. The drilling of high–aspect ratio holes is limited only by machining debris accumulation which can cause abnormal electrical discharges. Additionally, machining of the deep holes requires a correct dielectric flow into the discharge area what can be difficult by generated bubbles in the interelectrode gap [7]. In EDM drilling, applying of tubular shape electrode enables to machine holes with the range of diameter 0.2 – 3 mm and high–aspect–ratio up to 150:1 [11].

3. HYBRID PROCESS – EDM DRILLING WITH USING OF DEIONISED WATER

One can state that special place in group of microdrilling methods are connected with application of unconventional methods, such as electrodischarge (EDD) and electrochemical (ECD) drilling. Characteristics of both processes indicate a number of similarities in machining and essential complementary advantages, such as machining kinematics, tool shape and material, etc., which gives possibility to apply both of the processes into the hybrid process. The comparison of characteristics of EDD and ECD is presented in Table 1.

Table 1. The comparison of properties of EDD and ECD

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td><strong>Electrodischarge Drilling (EDD)</strong></td>
<td></td>
</tr>
<tr>
<td>- accurate (&lt; 5 μm), burr free and high aspect holes with thin walls can be drilled,</td>
<td>- not applicable for materials with a bad electric conductivity,</td>
</tr>
<tr>
<td>- applicable to machine the wide range of materials, irrespective of their hardness and toughness,</td>
<td>- significant tool wear,</td>
</tr>
<tr>
<td>- difficult-to-machine materials (harder than a tool) can be machined.</td>
<td>- heat affected and recast layer occurs,</td>
</tr>
<tr>
<td></td>
<td>- low material removal rate comparing to other methods,</td>
</tr>
<tr>
<td></td>
<td>- poor surface integrity.</td>
</tr>
<tr>
<td><strong>Electrochemical Drilling (ECD)</strong></td>
<td></td>
</tr>
<tr>
<td>- no tool wear</td>
<td>- only electrically conductive materials can be machined,</td>
</tr>
<tr>
<td>- high material removal rate,</td>
<td>- not environmental friendly process,</td>
</tr>
<tr>
<td>- no heat affected zone, good surface quality,</td>
<td>- electrolyte may cause corrosion of the machining equipment,</td>
</tr>
<tr>
<td>- difficult-to-machine materials (harder than a tool) can be machined,</td>
<td>- frequent failure of the tool insulation,</td>
</tr>
<tr>
<td>- machined surface has good quality, no residual stress and no burrs,</td>
<td>- stray removal which is an reason of machining delocalization, hole inaccuracy and pitting occurrence.</td>
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<tr>
<td>- possibility of simultaneous drilling of large number of deep holes of high aspect ratio.</td>
<td></td>
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</table>
The hybrid process gives possibility to minimize disadvantages and strength the advantages of electrochemical and electrodischarge machining. Depending on the machined material, type of the machining [5, 12, 13, 14]:
- ECAM – electrochemical arc machining,
- ECSM – electrochemical spark machining,
- ECDM – electrochemical discharge machining (also called as simultaneous electrodischarge and electrochemical machining).

In the article, ECDM process is presented. In the integration of electrochemical and electrodischarge machining, the allowance can be removed by simultaneous interaction of anodic dissolution and electrical discharges on the surfaces [15]. ECDM process is carried out in weak electrolyte solution. In the process the workpiece is the anode and the tool electrode is the cathode (Fig. 3). During the ECDM, the voltage between the cathode and anode increases rapidly, and if the voltage achieves the critical breakdown voltage ($\phi_2$), sparks will be produce and the voltage will drop to the value $\phi$. The arcing occurs till the end of the pulse time. During stage I the material is removed by electrochemical dissolution. On the contrary in stage II the sparks are produced and the allowance is removed in a typical way for the EDM process (Fig. 4) [15].

![Fig. 3. Scheme of ECDM drilling with application of a tubular tool electrode](image)

![Fig. 4. Scheme of typical ECDM voltage characteristic](image)

Depending on the machining parameters such as interelectrode gap thickness, voltage, current density, pulse on/off time, the material can be removed by anodic dissolution, electrical discharges or simultaneous electrochemical dissolution and electrical discharges. The performance of ECDM process can be more 5 times higher than electrochemical machining and 50 times higher than electrodischarge machining [5, 13], especially difficult-to-cut materials are machined.

The idea of hybrid electrochemical discharge drilling process includes two types:
- electrode discharge drilling with using of deionised water,
- tube electrode high-speed electrochemical discharge drilling (TSECDD).

The article is focused on the electrode discharge drilling with using of deionised water. The deionised water can be treated as dielectric fluid and also as electrolyte with low conductivity what contributes that material is removed by simultaneous interaction of electrochemical dissolution and electrical discharges. The results of research of electrode discharge drilling using of deionised water indicate that the process enable to achieve a smoothly machined surface with higher dimensional accuracy and quality surface than after electrochemical or electrode discharge drilling [16, 17]. The reaction of electrochemical dissolution provides decreased layer with heat affected zone and higher material removal rate.
The research of EDM drilling with using of deionised water and tube electrode has been carried on at Institute of Production Engineering at Cracow University of Technology. A machined materials the reaction bonded silicon-infiltrated silicon carbide (SiSiC) [18] and X5CrNi18–10 stainless steel [19] are selected.

4. MATHEMATICAL MODELLING OF TEMPERATURE INCREASE DURING TIME OF THE IMPULSE

In electrodischarge machining with using of deionised water the parameter such as time of the impulse \(t_i\) plays an important role. An adequate long time of the impulse provides conditions which enable to appear electrical discharge [20]. In case when discharge voltage achieves high values, up to critical value (Fig. 4), the water begins to boil and to evaporate. The gas bubble is generated on the tool electrode surface and at the critical conditions the electrode surface is fully covered with bubbles. The result is a decrease in the interelectrode gap thickness and to produce electrical discharge. The electrical discharge occurs till the end of the pulse time. The critical conditions are caused by an excessive temperature increase in the machining area. The temperature increase can be result of Joule’s heat generation by flow electric current in working fluid and heat transfer through the electrode surfaces. The main of reason of the temperature increase is Joule’s heat generation by flow electric current by working fluid in the machining area.

The simulation of mathematical modelling of temperature increase during time of the impulse is created by using of the Matlab (Statistic Toolbox) software. The aim of the mathematical model is:

– characteristic of the process for its different variants during time of the impulse,

– critical pulse time causing deionised water boil – the selecting of the parameters and time of the impulse which will be provided deionised water boiling. In the case in the machining area (between electrodes), electrical discharges are produced.

The temperature increase \(\theta\) during time of the impulse \(t_i\) in the mathematical model is expressed as [21, 22]

\[
\theta = \frac{\kappa U^2}{\rho_e C_p S^2} t_i
\]

where: \(\kappa\) – working fluid conductivity [A/Vm], \(U\) – discharge voltage [V], \(\rho_e\) – working fluid density [kg/m\(^3\)], \(C_p\) – working fluid specific heat [J/kgK], \(S\) – gap size [m].

By using equation (1), the temperature of working fluid involving previous the temperature increase \(T_{wz_n}\) is obtained

\[
T_{wz_n} = T_{wz_{n-1}} + \frac{\kappa \cdot U^2}{\rho_e (T_{wz_{n-1}}) \cdot C_p (T_{wz_{n-1}}) \cdot S^2} \cdot \Delta t_i
\]

where: \(T_{wz_n}\) – the temperature of working fluid involving previous temperature increase \((n = 2, ..., p)\), \(T_{wz_{n-1}}\) – previous temperature of working fluid, \(\Delta t_i\) – time step.

In the simulation the constant of parameters are working fluid conductivity, discharge voltage, gap size and time step. The dielectric fluid density and dielectric fluid specific heat are changed according to the temperature increase. In mathematical model the time of the impulse is treated as time step \(\Delta t_i\). Then the time steps are summed till the point of intersection \(T(t_i)\) with the temperature of boiling \(T_{boil} = 373,15\ K\). The summed time steps determine of critical pulse time \(t_i^*\). Fig. 5 presents the results of the simulation.
The temperature boil is achieved the fastest for the amplitude voltage $U = 50 \, V$. High amplitude voltage enables faster heating of deionised water in the machining area. The shortest critical pulse times $t_i^*$ providing of the temperature boil during time of the impulse, are reached for small gap thickness $S = 10 \, \mu m$ (Fig. 6). Small gap thickness involves lower volume of working fluid which can be heated. In results the temperature of boiling is achieved faster. The defined critical pulse times for given the amplitude voltage and various gap thickness, are presented in Table 2.

Fig. 5. Changing of the temperature of working fluid during pulse on time

![Graph showing temperature change](image)

**Fig. 6.** The change of the critical time of the impulse $t_i$ at varies the gap size $S$, for given the amplitude voltage $U$

**Tab. 2.** The effect of the gap size on the critical time of the impulse, for given the amplitude voltage

<table>
<thead>
<tr>
<th>No.</th>
<th>$U , [V]$</th>
<th>$S=10 , [\mu m]$</th>
<th>$S=20 , [\mu m]$</th>
<th>$S=30 , [\mu m]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>0,04</td>
<td>0,18</td>
<td>0,365</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>0,018</td>
<td>0,072</td>
<td>0,162</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>0,0101</td>
<td>0,04</td>
<td>0,092</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>0,0065</td>
<td>0,025</td>
<td>0,058</td>
</tr>
</tbody>
</table>
5. CONCLUSION

Actually, effective techniques of drilling high-aspect-ratio micro-holes are required, especially in the machining of difficult-to-cut materials. Disadvantages of EDM and ECM process and not yet completely understood the mechanism of ECDM cause difficulties in machining of holes with high accuracy and high surface quality. One of the development trends today’s drilling technology is the integration EDM and ECM in hybrid process which is called electrochemical discharge machining. ECDM enables to achieve higher dimensional accuracy and quality surface and a decrease conical shape of the hole than after ECD or EDD. Effective drilling of high-aspect-ratio holes can be achieved by EDM drilling with using of deiosed water (one of the type ECDM process), which gives possibilities to achieve higher machining speed and higher accuracy of micro-holes. The determining of critical pulse time by using of mathematical modelling of temperature increase during time of the impulse, can broaden the knowledge of the phenomena which occur in machining area in ECDM process.

6. REFERENCES