Effect of electrolyte temperature on Faradaic effect in electrochemical microdrilling

M.A.H. Mithu*
Department of Industrial & Production Engineering,
Shahjalal University of Science & Technology,
Sylhet 3114, Bangladesh
Email: mithu-ipe@sust.edu
Email: mithuie@gmail.com
*Corresponding author

G. Fantoni and J. Ciampi
Department of Civil and Industrial Engineering,
University of Pisa,
Pisa 56126, Italy
Email: g.fantoni@ing.unipi.it
Email: jonathanciampi@gmail.com

Abstract: Electrochemical micromachining (ECµM) is an emerging non-
conventional manufacturing technology suitable for the fabrication of
micro-sized components on a wide range of electrically conductive materials.
This study emphasises on the effects of electrolyte temperature on the Faradaic
effect during electrochemical microdrilling on nickel plates by a cylindrical
microtool made of tungsten. A short cylindrical microtool of 43 µm in diameter
near to the tool tip and 53 µm mean diameter was selected, and allowed to
machine on nickel plate. During machining, only the electrolyte temperature
was varied keeping all the other parameters constant. The shape and size of the
fabricated microholes, machining time, actual material removal rate, non-
Faradaic non-transient effect and the number of short circuits are considered as
response factors. Experimental results confirm that the material removal rate
and machining time, respectively, increases and decreases with an increase in
the electrolyte temperature. It is also observed that both the side gap ratio and
the taper angle increase with the electrolyte temperature.

Keywords: electrochemical microdrilling; electrolyte temperature; Faradaic
effect; machining time; material removal rate; nickel plate.

Reference to this paper should be made as follows: Mithu, M.A.H., Fantoni, G.
and Ciampi, J. (2017) ‘Effect of electrolyte temperature on Faradaic effect in
electrochemical microdrilling’, Int. J. Precision Technology, Vol. 7, No. 1,

Biographical notes: M.A.H Mithu is a Professor of Manufacturing
Engineering in the Department of Industrial & Production Engineering,
Shahjalal University of Science and Technology (SUST), Sylhet, Bangladesh.
He received M. Engg. in Manufacturing Engineering from Bangladesh
University of Engineering and Technology, Bangladesh in 2006, and PhD from
the Department of Mechanical, Nuclear and Production Engineering (DIMNP),
University of Pisa, Italy. At present, he is working in the field of
Electrochemical Micromachining (ECµM) and his research has been focused on design, development and fabrication of ECµM workcell, design and fabrication of microtools and its applications in practical fields. He has published numerous international journals.

G. Fantoni is an Associate Professor in the Department of Civil and Industrial Engineering, University of Pisa, Italy. He received his Master’s in Mechanical Engineering in 1999, and PhD in Robotics, Automation and Bioengineering in 2005. His main interests are in the fields of microfabrication, micromanipulation, assembly and design methods. During his carrier, he led several regional, national and international research projects and industrial collaborations on different fields of the manufacturing technologies especially on advanced manufacturing methods. His publications include more than 50 peer-reviewed papers, and co-inventor of more than 10 patents.

J. Ciampi received his Master’s in Mechanical Engineering from Pisa University in 2010 with a thesis. His main interests are in the field of manufacturing processes both at macro-and micro-level. He was a tenure track Project Engineer at Ansaldo Breda, a specialised rolling-stock manufacturing company for railways and subways; currently, he is working in Piaggio Group, a well-known Italian motor bike company as a Process Engineer in the Manufacturing Technologies Department.

1 Introduction

Recent innovations in the area of microfabrication have created a distinctive opportunity for manufacturing structures in the micrometre range. For fabricating these microstructures, i.e. microproducts, several conventional and non-conventional machining processes have been developed. The electrochemical micromachining (ECµM) is one of the promising candidates among them (Fan and Hourng, 2009). This process engrosses selective metal dissolution from unprotected surfaces of an electrically conductive workpiece that is made an anode in the electrolytic cell. Dissolution of anode is performed in electrolytes when a DC and/or pulsed DC current are applied between the electrodes. The workpiece and/or the electrode tool must be moved relatively to each other in order to maintain a predefined gap, and electrolyte flows between the electrodes within the gap. The process does not need any contact between the tool and the workpiece, and neither a thermal or mechanical stress nor a heat affected zone is generated offering a nice quality machined surface. Therefore, it finds wide applications for the processing of advanced micro-patterns (Debnath et al., 2014), microfluidic devices (Jain et al., 2012a), microelectronic components, medical and biomedical products, in the field of aviation (Bhattacharyya et al., 2007), automobile and fabricating microholes to be drilled with high aspect ratio in extremely hard and brittle materials (Ahn et al., 2004).

The utilisation of short-pulsed power supply in mask-free ECµM process has been proved to be a necessary technology for the localised material dissolution (Schuster et al., 2000; Kock et al., 2003; Burkert et al., 2009; Ryu, 2009). Hence, for the pulsed ECµM process, the effects of process parameters such as voltage, electrolyte concentration, pulse duty cycle and feed rate on the machined hole diameter have been studied, and different
mathematical models are developed. Later, the effects of electrolyte and temperature on precision finishing of microproducts by pulsed electrochemical micromachining are well studied (Misra et al., 2012; Singh and Jain, 2015; Sahoo and Jain, 2016). These articles successfully evaluated the effects of electrolyte concentration and composition. It is observed that in pulsed ECµM process, the useful values of the on- and off-pulse times are limited by the rate of charging and discharging, respectively, of the electrical double layer, which is defined as the structure of charged ions or oriented dipoles that always forms at the interface of an electrode when it is immersed into an electrolyte solution (Wang, 2006). On the application of a potential difference between two electrodes, the potential profile of the electrical double layer becomes similar to that of an equivalent circuit of capacitors and resistors (Burkert et al., 2009). However, all the current flow through an electrochemical cell is not caused by electrochemical reactions. There is reaction current called Faradaic current and transient current called non-Faradaic current (Bard and Faulkner, 2001). Faradaic current determines the material dissolution rate and non-Faradaic current results from current flow that charges and discharges only the double layer capacitance (Park et al., 2006). The growths in the functionality of highly sophisticated electrical and electronic components offer the opportunity to visualise the effect of different machining parameters such as current and applied potential, applied frequency and its duty cycle, interelectrode gap (IEG), machining time, electrolytic flow and its composition, concentration, etc. that can influence the rate of a chemical reaction during electrochemical micromachining (Mithu et al., 2011a, 2011b; Jain et al., 2013; Mithu et al., 2014).

It is, therefore, clear that the electrochemical reactions during ECµM are strongly dependent on the electrolyte used, and external forcing mediums (Jain et al., 2012b; Misra et al., 2012; Helmenstine, 2016; Sahoo and Jain, 2016). The conductivity of the solution depends on the concentrations of the ionic species and behaves differently for strong and weak electrolytes. It has also been stated that better accuracy can be achieved using lower electrolyte concentrations (Davydov et al., 2004), as the lower concentrations generate comparatively less sludge by not only giving lower amounts of precipitates, but also minimises the machining allowance (Luo, 2006). However, a lower concentration of reactants leads to a lower reaction rate, which tends to be associated with a higher machining time. Besides, an increase in temperature is accompanied by an increase in the reaction rate as the temperature is a measure of the kinetic energy of a system. So higher temperature implies higher average kinetic energy of molecules and more collisions per unit time. Although the behaviour is not linear, a general rule of thumb for most chemical reactions is that the rate at which the reaction proceeds will approximately double for each 10°C increase in temperature (Helmenstine, 2016). The rate of a chemical reaction also depends on the medium in which the reaction occurs, and the quantity of hydrogen ions (pH value) can alter a reaction rate since they are the carrier of the electrochemical process itself.

In ECµM, the tool electrode advances towards the workpiece at a constant feed rate where the IEG is lowered to several microns, and machining voltage and the electrolyte concentrations are kept lower for better resolution (Rajurkar et al., 2006). The pH value of the electrolyte solution is chosen to ensure good dissolution of the workpiece without the tool being attacked. Therefore, acidic electrolytes are advantageous due to the formation of soluble reaction products, which can be completely swept clean from the narrow IEG during micromachining (Bhattacharyya et al., 2005). In addition, lower duty
cycle and short pulse-on time increase the machining time, and machining at high electrolyte temperature generates hydrogen gas much higher than at room temperature. It also evaporates the water in the small IEG due to the fact that heating increases the electrolyte concentration, and viscosity making the process inconvenient. The resulted high concentrated viscous electrolyte is not able to remove all the reaction products from the narrow machining zone. These by-products remain in that narrow IEG retard the machining rate. However, there is a possibility of microspark or short circuit in between the microtool tip and the workpiece that ultimately increases the machining time. Therefore, with the decrease in the electrolyte concentration, heating of electrolyte is preferred to achieve better dimensional accuracy and improved micromachining efficiency (Davydov et al., 2004).

From the afore-stated literatures, it emerges that ECµM is one of the promising candidates for fabricating microparts, where the reaction rate increases with the increase in electrolyte concentration, temperature or the decrease in pH value. This article is, therefore, devoted to investigate the effect of electrolyte temperature under pulsed potential during electrochemical microdrilling on the nickel plate. Moreover, the waveforms generated during machining are compared to the results obtained. The material removal rate (MRR), machining time and the dimensions of fabricated microholes are considered as response factors, and compared to the waveforms generated and the amount of Faradaic effect is estimated during machining.

2 Experimental

2.1 Experimental setup

The self-developed electrochemical micromachining workcell is shown in Figure 1. It consists of an electrical function generator, an oscilloscope, a computer-controlled motion system for feeding the tool and the workpiece. The motion system was controlled by a three-axis microstep controller system that was interfaced with a desktop computer. The controller was controlled by customised software. The specifications of the testing equipment are given in Table 1. To avoid the physical contact between the tool (tungsten) and the workpiece (nickel plate), a tailored electronic circuit was used that automatically stops and retracts the tool. After a set time (0.5 s plus retracting time), the circuit automatically restarts feeding the tool maintaining the predefined gap between the workpiece and tool. Moreover, the function generator, the oscilloscope and the tailored circuit were used as signal source, signal analyser and tool feed controller, respectively, for in-process monitoring and controlling systems. A thick leather part was placed below the set-up and four mechanical dampers were located on the legs of the micromachining cell in order to reduce the vibration during machining. The electrolytic basin was a specially designed sink that ensured the requirements of high signal-to-noise ratio, low dead volume, well-defined hydrodynamics, small ohmic drop, and ease of fabrication and maintenance. The material of the basin was so selected that it became electrically non-conductive and became a good thermal insulator. Therefore, the best choice of the material was Plexiglas due to its low cost, transparency, chemical inertness and impermeability. An electrical wire-wounded circuit was placed into the electrolytic basin
Effect of electrolyte temperature on Faradaic effect

No electrolyte circulation system was integrated during experimentation as the circulation of electrolyte reduces the consigned electrolytic temperature.

Table 1  Specifications of testing equipment used for electrochemical machining workcell

<table>
<thead>
<tr>
<th>Test equipment</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function generator</td>
<td>Keithley 3390 50 MHz; frequency resolution, 1 µHz; amplitude, 10 mVpp – 10 Vpp; 4 digits resolution; phase range, −360° to +360°; accuracy, 8 ns</td>
</tr>
<tr>
<td>Oscilloscope</td>
<td>Rigol DS1000E, 1 GHz, 2 channel, digital storage, 64 K colour display</td>
</tr>
<tr>
<td>Linear travel guide</td>
<td>PLS-85, X- and Y-axes, maximum travel 155 mm, resolution of 0.1 µm, uni-directional repeatability 0.05 µm, maximum 100 mm/s, and ML 40, Z-axis, maximum travel 40 mm, resolution 0.1 µm, maximum 5 mm/s</td>
</tr>
<tr>
<td>Microcontroller</td>
<td>SMC corvus eco, three-axis closed-loop control, velocity &lt;0.1 µm/s, 15–25 rev/s, linear interpolation, miCos, GmbH</td>
</tr>
</tbody>
</table>

Figure 1  The experimental electrochemical micromachining workcell (see online version for colours)

2.2 Fabrication of microtools and microdrilled holes

The ECµM needs a tool electrode on micron scale. Tungsten is widely used as tool material because of its high electric and thermal conductivity, good wear resistance, high rigidity, toughness and capability to withstand the pressure of electrolyte. Therefore, straight tungsten wire of 0.38 mm in diameter and 0.5 m in length was used to fabricate microtools. The required tungsten pieces were cut from the supplied long wire and the ends of the specimen were ground, polished and cleaned. During microtool fabrication, tool specimens were fixed to a holder unit, immersed vertically at a constant depth into the electrolytes basin containing caustic solution of specific concentration. On the application of a potential difference between electrodes, where the tungsten specimens

to maintain the selected temperature during machining. No electrolyte circulation system was integrated during experimentation as the circulation of electrolyte reduces the consigned electrolytic temperature.
were considered as workpiece, dissolution process proceeded and a certain etching time resulted in a straight microshaft with a certain diameter. Each of the tools was rinsed in the hot water to remove foreign particles and formed oxides. The uniformity in the variation of diameter of the microtool was monitored by measuring the diameters at different locations in between the points slightly away from the tool tip and shank. Image analysis application software, easy analysis, integrated with the optical microscope (Nikon SMZ800) was used to measure the diameter, length and tip angle of the tool produced by ECµM. The scanning electron microscope (SEM) image of microtool fabricated by this reverse electrochemical process is illustrated in Figure 2.

Figure 2  SEM image of a fabricated microtool

The selection of workpiece material was based on the properties of corrosion and heat resistance. Nickel being inert against most chemicals, an uncoated nickel plate of 50 × 50 × 0.075 mm in dimension was selected as work material. The prefabricated microtool was fixed with the tool holder unit, and tool was fed towards the nickel workpiece. Microtool feeding was controlled by the servo-controlled feed mechanism of Z stage, while the workpiece was positioned horizontally by X-Y axes travel guides, if required. It is practical to use the acidic electrolytes rather than the common salt electrolytes as the acidic electrolytes usually produce by-product much less and they easily allow the refreshing of electrolyte in the machining area. Moreover, the difficulty is that salts crystallise out of the solution at higher concentration and clog the machining areas in the machine enclosure. But a concentrated electrolyte offers low resistance to flow of machining current. Again, dilute acidic electrolytes are preferable for electrochemical micromachining process because they do not create any insoluble reaction products when the surface finish is most important machining criterion (Anh et al., 2004; Bhattacharyya et al., 2004; Kim et al., 2005). Therefore, less toxic and dilute acidic electrolyte, 0.2M HCl was selected during microholes fabrication. Fresh and clean electrolytes were used in order to reduce the effects associated with the precipitation. The physical properties of electrode materials and the machining conditions applied in microdrilling process are summarised in Table 2. The dimension of fabricated microholes, material removal rate, machining time and the frequencies of short circuits were recorded and taken into account as response factors.
Effect of electrolyte temperature on Faradaic effect

Table 2  Machining conditions for microhole fabrication

<table>
<thead>
<tr>
<th>Factors</th>
<th>Parameters/Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working materials</td>
<td>Electrode materials Microtool Workpiece</td>
</tr>
<tr>
<td></td>
<td>Tungsten microshaft Nickel plate</td>
</tr>
<tr>
<td>Dimensions</td>
<td>φ 0.38 mm, L = 0.5 m</td>
</tr>
<tr>
<td>Purity (%)</td>
<td>99.9 99.0</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.28 0.312</td>
</tr>
<tr>
<td>Yield strength (MPa)</td>
<td>550 660</td>
</tr>
<tr>
<td>Tensile modulus (GPa)</td>
<td>411 199.5</td>
</tr>
<tr>
<td>Electrical resistivity at 0–20°C (µΩ cm⁻¹)</td>
<td>5.4 6.9</td>
</tr>
<tr>
<td>Coefficient of thermal expansion at 0–100°C (K⁻¹)</td>
<td>4.5 × 10⁻⁶ 13.3 × 10⁻⁶</td>
</tr>
<tr>
<td>Thermal conductivity at 0–100°C (Wm⁻¹ K⁻¹)</td>
<td>173 90.9</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Goodfellow Goodfellow Ltd., UK</td>
</tr>
<tr>
<td>Electrolyte conc. (M/L)</td>
<td>0.2M HCl solution (without circulation)</td>
</tr>
<tr>
<td>Electrical parameters</td>
<td>Applied frequency: 1 MHz</td>
</tr>
<tr>
<td></td>
<td>Duty cycle: 30%</td>
</tr>
<tr>
<td></td>
<td>$V_{pp}$: 16 V</td>
</tr>
<tr>
<td></td>
<td>$V_{max}$: 10.6 V</td>
</tr>
<tr>
<td></td>
<td>$V_b$: −5.0 V</td>
</tr>
<tr>
<td>Tool feed rate</td>
<td>0.1–0.5 µm s⁻¹, computer controlled</td>
</tr>
</tbody>
</table>

Entrance and exit diameters of each fabricated microholes were measured by image analysis application software, Easy Analysis™, integrated with the optical microscope (Nikon SMZ800). The tool electrodes were cylindrical, but the entrance and exit diameter of the machined microhole were not the same due to etching process in case of non-insulated tool, and corner etch of the hole entrance in addition with the linear etching resulted tapering the side wall. Therefore, to evaluate the total material removed during machining, it can be calculated from the truncated cone equation:

$$V_m = \frac{\pi h}{12} \left( \phi_{ent}^2 + \phi_{exit}^2 + \phi_{ent} \phi_{exit} \right)$$

where $\phi_{ent}$, $\phi_{exit}$, $h$ are hole entrance diameter, hole exit diameter and thickness of the metal plate, respectively. Again, referring to Figure 3, the actual material removal rate (MRRact) is calculated as the total volume of material removed from the workpiece over the total machining time which is expressed as cubic millimetre per second, and $g_{ent}$, $g_{exit}$, $\phi$ are entrance side gap, exit side gap and microtool diameter, respectively.
3 Experimental results

A cylindrical microtool of 43 µm in diameter near to the tip, 53 µm mean diameter and 860 µm in length was selected, and allowed to machine on the nickel plate. During machining, only the electrolyte temperature was varied keeping all other parameters constant. In pulsed electrochemical process, the current resulting from a change in oxidation state of the electro-active species is termed the Faradaic current because it obeys the Faraday’s law. The shape and magnitude of the potential profile represents the amount of Faradaic and non-Faradaic current generated that practically governed material dissolution process. As the Faradaic effect, the product of voltage value acquired by oscilloscope (\(V_{top}\)) and the time for remaining the voltage value at this level determined how much material was dissolved for a single pulse. The total Faradaic effect was calculated from the product of Faradaic current and the total time required for that particular machining determined the total amount of material dissolved during machining (Mithu et al., 2011b). Tool electrode baseline potential also plays an important role in pulsed ECµM. When it is observed that the Faradaic current is approximately similar, the baseline potential profile plays an important role in the material removal process (Ryu, 2009). Then, the non-transient current is leading the material removal rate in the electrochemical micromachining process. Therefore, to establish the relationship between the input and the outputs, the shapes of the waveforms that formed during microdrilling were captured and stored. These stored waveforms were analysed to see how the shape of the waveform and different values of the corresponding waveshape influenced the material removal rate and so on.

Table 3 and Figure 4 show the relationship between the MRR\(_{act}\), machining time, non-Faradaic non-transient effect and the fabricated microholes diameter for varying the electrolyte temperature. From Figure 4, it is observed that the MRR\(_{act}\) and machining time, respectively, increase and decrease with the increase in the electrolyte temperature. The side gap ratio, the ratio between the side gap at the entrance and exit of the microhole, and taper angle also increase with the electrolyte temperature. However, for the same parameters, both the entrance and the exit diameters of the fabricated microholes decrease with the increase in electrolyte temperature, as illustrated in Figure 5. The number of short circuits also decreases with the increase in the electrolyte temperature. These phenomena are due to the concentration of ions present into the electrolyte and the movement of ions within the solution, are stated in Section 4.
Table 3  Input variables for each experiment and corresponding experimental results

<table>
<thead>
<tr>
<th>Electrolyte temperature (°C)</th>
<th>Tool feed (µm/s)</th>
<th>Number of short circuits</th>
<th>Machining time (min)</th>
<th>MRR (mm³/s)</th>
<th>Taper angle (°)</th>
<th>Side gap ratio (gexit/gin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>0.1–0.2</td>
<td>6</td>
<td>20</td>
<td>1.42 × 10⁻⁶</td>
<td>12</td>
<td>1.13</td>
</tr>
<tr>
<td>28</td>
<td>0.2–0.4</td>
<td>2</td>
<td>14</td>
<td>1.72 × 10⁻⁶</td>
<td>10</td>
<td>1.12</td>
</tr>
<tr>
<td>56</td>
<td>0.5</td>
<td>0</td>
<td>7</td>
<td>2.37 × 10⁻⁶</td>
<td>14</td>
<td>1.23</td>
</tr>
</tbody>
</table>

Figure 4  Effect of electrolyte temperature on non-transient current, material removal rate, machining time and the diameter of fabricated microholes on nickel plate

Figure 5  Microscopic image of fabricated microholes for electrolyte temperature at (a) 14, (b) 28 and (c) 56°C
4 Discussion

The electrolytes are the solutions containing free ions which not only complete the electric circuit between the microtool and work piece, but also offer an environment for machining to occur. The conductivity of an electrolyte solution depends on the concentration of the ionic species and behaves differently for strong and weak electrolytes. The charges are generally considered to be evenly distributed over the entire surface of the electrolyte and these small charged ions have a strong polarising power because of the intense field around them, and have a very strong effect in producing induced dipoles or aligning permanent dipoles in the solution. These ions get together in an alignment to form an array of particles and/or dipoles in every material interface when the material is dipped in the electrolyte solution, which is termed as electrical double layer. This layer has a complex structure of several distinct parts shown in Figure 6. The inner layer, which is the closest to the electrode, is known as the inner Helmholtz plane, contains solvent molecules and specifically adsorbed ions that are not hydrated in the aqueous solutions. The next layer, the outer Helmholtz plane (OHP), reflects the imaginary plane passing through the centre of solvated ions that are remained non-adsorbed and are attracted to the surface by long-range coulomb forces. Both Helmholtz layers represent the compact layer (CL) of charges is strongly held by the electrode and can survive even when the electrode is pulled out of the solution. The outer layer, beyond the compact layer, is loosely associated with the object because it is made of free ions which move in the fluid under the influence of electric attraction and thermal motion rather than being firmly anchored. It is called the diffuse layer, or Gouy layer. This is a three-dimensional region of scattered ions distributed in the bulk solution, which extends from the OHP into the bulk solution where the total charge of the compact and diffuse layers equals (and is opposite in sign) to the net charge on the electrode side.

Figure 6 Schematic representation of the electrical double layer (see online version for colours)
In ECPµM system, the electrodes are separated on the micron scale, the voltage pulsing of the tool in an electrolyte leads to the charging and discharging of electrical double layers at both the tool and workpiece. For voltage pulses, this electrical double layer resembles an ordinary parallel-plate capacitor, and the capacitance of the double layer consists of a combination of the capacitance of the compact layer in series with the diffuse layer of the electrolyte (Davydov et al., 2004). The capacitance of the compact layer increases with decreasing separation between the electrode surface and the counter-ionic layer, and the value of diffusion layer capacitance is strongly affected by the electrolyte concentration, where the compact layer is largely independent of the concentration. As the rate of electrochemical reactions is exponentially dependent on the voltage drop in the double layer, the reaction at the workpiece is strongly confined to the charged region (Luo, 2006; Park et al., 2006).

Minimum pulse-on time needed to overcome the effects associated with double layer capacitor is found to be in the range of 10–30 ns for the electrodes with the diameter ranging 40–80 µm in diameter (Park et al., 2006). In this work, the applied pulse-on time is fixed to 300 ns (30% duty cycle) which is much higher than the required ultra-short voltage pulses. In the ECµM process, the material dissolution is affected by the conductivity of electrolyte, which is primarily determined by the concentration of ions, and mobility of ions in a given electric field (Kenney et al., 2004). In ultra-short pulses, the material removal decreases due to highly confined electron motion. The electrical migration becomes dominant when the pulse duration is extremely short, such as <100 ns since there is no significant product build-up. As the temperature raises the movement of ions inside the solution, the rate of reaction increases with the increase in the electrolyte temperature during electrochemical machining. The reason is that the increase in electrolyte temperature decreases the molecular bond strength, increases the ion movement and speeds up the reaction rate. Again, in ECµM, the reactions involve in mass transport of the electro-active species to the electrode surface can be occurred by three different modes, such as diffusion, convection and migration. The raise in the electrolyte temperature also accelerates the mass transfer modes of all kinds. The viscosity of electrolyte also decreases progressively with increasing temperature. This decrease in viscosity facilitates easy migration of the ions within the bulk solution, and helps to reduce the effect of double layer. But generally at a high temperature, the viscosity reduced to a level where machining is sometimes impossible. Hydrodynamic disturbance due to change in viscosity affects the distribution for diffusion layer thickness on the micromachining zone, which influence the electrochemical dissolution process to a great extent.

It is well established that the Faradaic current is a direct measure of the rate of the chemical reaction, which determines the amount of material dissolved during that particular machining process. The resulting potential profile, potential signal (vertical axis) and time (horizontal axis) for each pulse period, represents the amount of Faradaic and non-Faradaic current generated that practically governs material dissolution process. Referring to Figure 7, it can be observed that the amounts of Faradaic effects are the same for the increase in electrolyte temperature, then the non-transient effects are dominating on MRR and machining time as the baseline potentials, the median voltage value of the waveform’s flat base are decreasing with the temperature; hence, the MRR increases and machining time decreases, as illustrated in Figure 7b–d. This phenomenon can be explained in accordance with the experience of baseline potential. However, when the baseline potential is strongly negative, sludge is observed near the tool electrode.
surface. The floating sludge lump disturbs uniform electrochemical dissolution. Also, the dissolved metal is deposited on the tool electrode surface. Therefore, tool electrode baseline potential was kept with negative value for preventing metal deposition on the tip.

Figure 7  Waveform generated for electrolytic temperatures at (a) prior to machining, (b) 14, (c) 28 and (d) 56°C (see online version for colours)

From the experimental results according to tool electrode baseline potential variation, the proper voltage is acquired in the range of $-1.5$ to $-2.0$ V. When the baseline potential was in the specified range, machining rate was quite high (Löwe et al., 2002; Ryu, 2009). But machining was possible for the baseline potential up to $-2.5$ V. After this limit, the amount of Faradaic current decreased rapidly and the resulting MRR was very low because the amount of non-transient current increases with the increase in baseline potential. The exact shape and magnitude of the time versus voltage response is governed by the processes involved in the electrochemical process; and the total current is the summation of the Faradaic currents for the sample and bulk solutions, as well as the non-Faradaic charging background current, this phenomenon can be greatly simplified by the calculation of non-Faradaic non-transient state of the waveforms generated during machining.

Again, the conductance of an electrolyte is dependent on the ability of the electrolyte to carry a current and this, in turn, is dependent on the degree of dissociation of the electrolyte. The greater the dissociation, the better the conductance. The conductivity of a solution increases with the increase in temperature because of a combination of the increased dissociation and increased speeds of the ions. Since the ion mobility increases with temperature, the resistance of electrolytes generally falls with increasing
Effect of electrolyte temperature on Faradaic effect

In this work, the effect of electrolyte temperature on actual material removal rate, machining time and the dimensions of fabricated microholes under pulsed potential electrochemical microdrilling on the nickel plate is studied. The waveforms generated during machining are also analysed and compared to the results obtained. As a result of the analysis and experiments conducted, important conclusions are as follows:

- The MRR and machining time increase and decrease, respectively, with the increase in electrolyte temperature for a particular combination of micromachining parameters.
- The entrance and exit diameters of the fabricated microholes on the nickel plate decrease with the increase in electrolyte temperature. Both the side gap ratio and the taper angle formed also increase with the electrolyte temperature.
- The amounts of Faradaic effects are found approximately same for the increase in electrolyte temperature, and non-transient effects are dominating on MRR, machining time, number of short circuits and the size of the microhole.
- The number of short circuits also decreases with the electrolyte temperature and no short circuit occurs for higher electrolyte temperature due to higher MRR.
- The shape of the waveform and its corresponding values are in good agreement with the MRR, machining time and on the dimension of fabricated microholes.

5 Conclusion

In the light of this behaviour and the results of other work, it is concluded that the Faradaic effect becomes negligible and the non-transient current dominates the material dissolution process. It is also observed that the number of short circuits and the amount of overcuts decrease with the rise in temperature of electrolyte. This is due to the fact that at a lower temperature, the MRR was low, the tool electrode fails to maintain a constant gap and remained longer time during machining for the same feed rate which results in increased number of short circuits with more overcut. In this case, the feed rate needs to be adjusted (slowed down) with MRR, which ultimately increases the machining time. However, the side gap ratio that occurs during machining resulting in the difference between the entrance and exit of microhole diameters, which is also found increased for increase in temperature.
Acknowledgements

This research work was funded by Ministero dell’Istruzione dell’Università e della ricerca, Programmi di ricerca cofinanziati (COFIN), and carried out in the Department of Mechanical, Nuclear and Production Engineering, University of Pisa, Italy. Authors are sincerely indebted to Prof. M. Santochi and Prof. G. Tantussi for cordial supervision and valuable advices.

References


Effect of electrolyte temperature on Faradaic effect


