Experimental Measurements and Theoretical Estimation of Temperature in ECDM Process

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Abstract. Electrochemical discharge can be effectively and economically used for machining of a wide range of conducting and non-conducting materials, ceramics, and composites. This can be also used for selective deposition of metals and micro welding. Its potentials for rapid prototyping of small metallic parts have been vindicated. All these processes require generation of temperatures above the melting temperature of the metal under consideration. In the present work, experimentally measured and theoretically estimated temperature results are presented for electro chemical discharge machining (ECDM) process. In situ temperature measurements are performed for the first time in ECDM, especially, in the machining zone with various temperature sensing schemes.

The temperatures at different radii of the workpiece are calculated by considering the spark as a constant, circular heat source on the surface of the workpiece and considering the heat balance of each discretised element of the workpiece. Experimentally measured and theoretically estimated temperature results are comparable.

Keywords: ECDM, discharge, workpiece temperature, transient temperature, pyrometer

INTRODUCTION

Producing discharge in electrolytes is comparatively easier than producing it in dielectrics [1]. The discharges produced in the dielectrics are used only for machining of metals hard to cut. The discharges in electrolyte can be effectively used for machining as well as for deposition of metals [2]. They can be used for machining of non conducting materials as well. Electro chemical discharge machining (ECDM) is a novel combination of electro chemical machining (ECM) and electro discharge machining (EDM) processes. In situ temperature measurements have been performed for the first time in ECDM. Present work shows the verification of the theoretical temperature estimation with the experimentally measured temperature on the workpiece surface.

ECDM cell consists essentially of an anode and a cathode much smaller in size than that of anode, dipped in an electrolyte. The workpiece to be machined is also placed in the electrolyte bath. Electrolysis takes place when the voltage is applied between anode and cathode. Discharge is generated at the tool tip when the voltage crosses a critical value which depends on various factors such as the electrolyte, concentration of the electrolyte, depth of cathode in the electrolyte etc. At the time of the discharge, large ionic current gets generated. These ions get bombarded on the surface of the work piece. This bombardment results in heating of the heated zone of the workpiece rises up to or beyond the melting point [3]. Hence machining takes place due to intense heating of workpiece. It is found that the machining rate is faster in ECDM as compared to that in ECM [1].

The supply voltage and experimentally measured average current are used to calculate the heat input and hence to theoretically estimate the work piece temperature. Both experimental and theoretical results are presented and compared. They show a good agreement.

DIFFICULTIES IN MEASUREMENTS

Following are the major difficulties while performing in situ temperature measurements:

1. Transient and localized nature of temperature where discharge strikes on the workpiece
2. Presence of electrolyte,
3. Noise due to the electrical discharge.
4. Wide temperature ranges involved on workpiece (few thousands of °K locally where the discharge strikes, to a few hundreds of °K away from discharge affected zone.)

To overcome these problems proper selection of sensors is done as discussed in the following section.

SENSOR SELECTION

Different types of temperature sensors are used to sense temperature at different positions. Their selection is based on the temperature range, sensitivity, response time and durability.

1. **Pyrometer**: Pyrometer is used to detect the workpiece surface temperature where discharge strikes. It is a non-contact type temperature sensor. The pyrometer has been suitably modified to sense the transient temperature at the workpiece surface. It is mounted on an x-y table placed outside the ECDM cell with fine adjustments for focusing purposes. It gives the temperature of the target area of around 1 mm². It uses a sensor working at 900 nm wavelength. The temperature sensing range is 1088-1973 °K. Digital storage oscilloscope is used to store the temperature transients.

2. **Small K type thermocouples**: To measure the temperature on workpiece surface at two places near discharge affected zone, two K type thermocouples fabricated with chromel_alumel wires of 24 gages have been used.

THEORETICAL MODEL FOR EROSION

The steady state temperature distribution in the copper workpiece is found out by discretising the same in small ring shaped elements and writing a heat balance for each element. Though the actual workpiece is a square of 2.5cm side, for all the calculation purposes, it is considered to be circular having radius 1.25cm as the temperature is assumed to be varying radially. The thickness of the work piece is 0.6mm. The discretisation of the work piece in circular elements is shown in Figure 1.

![Figure 1: Discretisation of work piece for theoretical analysis.](image-url)

A set of equations, for average temperatures at the centre of each element, forms a tri diagonal matrix which is solved by writing a computer program in ‘C’.

Assumptions:

1. A single spark takes place at a time.
2. The spark is a uniform circular heat source of radius (ri) 5 micrometer.
3. The heat lost to the electrodes is negligible.
4. The thermo physical properties of the material do not change with the temperature.
5. Temperature of the electrolyte is 294 °K.
6. After each spark, the work piece attains the temperature of the electrolyte.

The heat equations:

Each element in the work piece has three surfaces for the transfer of heat. The first element at the center of the work piece is a disc shaped element having radius same as the spark radius. One of its plane surfaces is receiving heat from the heat source and the opposite one is loosing heat to the electrolyte by convection. The annular surface is in contact with annular surface of the adjacent element and is conducting heat out to the same. The radial increment for the discretisation of the workpiece is also taken to be equal to spark radius. The last element has four surfaces, out of which three are in contact with the electrolyte and the annular surface is receiving heat from the annular surface of the previous element.

- Equation for the 1st element at the center:
  
  Heat input = heat entering the work piece due to the spark at the circular area on the top surface;  
  Heat going out = heat convected out to the electrolyte through the circular area at the bottom surface + heat conducted out to the next element through the annular area.
For all other elements:
Heat input = heat conducted in through the annular surface in contact with previous element
Heat going out = heat conducted out through the annular area in contact with the next element + heat convected out to the electrolyte through the surfaces in contact with the same.

Boundary Conditions:

\[-k \frac{\partial \theta}{\partial r} = q \text{ for } 0 < r < r_i \text{ (radius of the spark)} \]
\[q = vi \text{ (v = voltage, } i \text{ = average current)} \]
at \( r = 1.25 \text{ cm}, \theta = \text{ temperature of electrolyte} \]

Properties of copper used:

\[ k = 401 \text{ W/m K} \]
\[ \rho = 8920 \text{ Kg/m}^3 \]
\[ c = 385 \text{ J/Kg K} \]
\[ h = (\text{electrolyte}) 200\text{W/ m}^2 \]

Experimental parameters such as supply voltage and the resulting average process current are used to calculate the heat source.

EXPERIMENTAL

In the present work, graphite anode and copper cathode tool (diameter 2 mm) are used to machine workpiece with hydrochloric acid of different concentrations as the electrolyte. DC voltage is applied between cathode and anode. Workpiece to be machined is kept near the cathode. Workpiece is made of copper in a square form of 25mm side and 0.6 mm thickness. Figure 2 shows the temperature sensing scheme with details of positions of the temperature sensors on the workpiece. Pyrometer is placed outside the ECDM cell and focused on the workpiece surface where discharge strikes. Temperature sensing is done on two other locations as seen in the figure on workpiece in a line with the discharge location using small K type thermocouples, placed at T1 and T2. A proper fixture arrangement is designed for strategic placements of the sensors at various locations [4] on the workpiece. Fixture also holds the workpiece at the center of the electrolyte cell together with cathode at a distance of about 500 µm away from workpiece. The arrangement is made in such a way that discharge strikes the workpiece surface at its center and the overall symmetry of the cell is maintained. The depth of cathode inside the electrolyte is around 1 mm. Use of HCl as the electrolyte was chosen on the basis of its lower absorption at 900 nm wavelength [4]. This property makes it suitable for measuring the surface temperature of the workpiece by the pyrometer. Experiments are performed using the fractional method scheme [5] with supply voltage ranging from 130V - 180V and the HCl electrolyte concentration from 1% - 5% in volume. Average current is measured during each experiment.

RESULTS AND DISCUSSION

Typical Transient Temperature at the Discharge Affected Zone

Pyrometer records the transient temperature of the workpiece surface when it is 1088°K or above. It shows a sudden drop in temperature when the temperature becomes lower than 1088°C.

Figure 3 shows a typical transient temperature pulse (second waveform in the photograph) captured by the pyrometer. It is a snap shot of the oscilloscope’s display by a digital camera. The peak of the waveform corresponds to 1138°K. After a time period of around 2.8 ms it reduces below 1088°C and the pyrometer shows an abrupt zero reading for this temperature. The upper waveform in the figure represents the transient current due to the discharge and gives the evidence for the occurrence of the discharge as well [6].
Figure 3: Transient temperature at workpiece where discharge strikes (lower waveform)

Temperature Distribution on the Workpiece

The small localized discharge affected area on the copper work piece attains the maximum temperature. This temperature is experimentally measured by the pyrometer and it is calculated theoretically as well. The temperature in the discharge affected zone depends mainly on the discharge conditions; that is the voltage and the current during the discharge. The theoretically calculated temperature depends, also on the radius of the spark chosen for temperature calculations and the boundary conditions used.

The plots in Figures 4 and 5 compare the theoretical and experimental results. The Figure 4 shows the comparison between results obtained for the treatment of the work piece at 180V with electrolyte concentration of 3% v/v. The temperature of the discharge affected zone at the center of the work piece is 1297.27K theoretically where as experimentally; it is measured to be 1088K. At a distance of 4mm from the discharge affected zone the theoretical and experimental temperatures are 434.37 and 343K respectively. Similarly at a distance of 10mm away from the discharge affected zone the theoretical and experimental temperatures are 312.88 and 328 K respectively. It attains the temperature of the electrolyte at its boundary, 12.5 mm away from the discharge-affected zone. Similarly the plot in the figure 5 compares the theoretical and experimental values of the temperatures at different points on the work piece. In general it has been observed that the pyrometer has not recorded temperature which is above the melting temperature of the work piece in spite of the erosion of the work piece. The eroded part of the work piece must have been much above the melting temperature of the work piece. The shock wave which accompanies the electrochemical discharge is responsible for the instant evacuation of the metal above melting temperature and the temperature recorded by the pyrometer is normally below the melting isotherm on the work piece. This fact has been verified with work pieces of other materials such as tantalum, silicon and brass the results of which are not presented in the present paper. The temperatures at 4mm and 10mm distance away from the discharge affected zone depend mainly on the boundary conditions assumed. Experimentally measured temperature values at these points on the work piece depend on the type of contact between the thermocouple and the work piece. The embedded thermocouples might give more accurate results.
CONCLUSIONS

- In situ temperature measurements are carried out successfully for the first time in ECDM.
- In the machining zone, the temperature is of the order of melting temperature of the workpiece due to the bombardment of the ions generated locally by the discharge phenomenon.
- Sometimes the pyrometer misses the temperature pulses from recording due to occlusion of the workpiece surface from the pyrometer due to the shifting of location of discharge from the focused area.
- The heat equations at various points in the workpiece are purely geometrical and deduced from the first principles by writing the heat balance for each element. The material properties are input to the heat equations. The most important time dimension is not considered which makes the analysis preliminary. In spite of the simplified approach the results obtained are fairly close to the experimental observations. By changing the boundary conditions at the periphery of the work piece it may be possible to get the temperature distribution in the ECDM cell itself.

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