Modelling Of Micro Electric Discharge Machining Using FEM

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Abstract

Micro EDM, a nonconventional machining process is widely used in the field of high aspect ratio machining in micro scale. It is an electro-thermal material removal process, in which there is no physical contact between tool and workpiece. In micro-EDM, crater formation is due to intense heat generated between the workpiece and tool electrode. Modeling of micro EDM will give the idea of material removal and temperature distribution. In previous work, finite element modelling of micro EDM was done using ANSYS. Temperature distribution and crater formation was studied. In this work, thermal modeling of micro EDM is carried out using FEM. A numerical simulation of single spark in micro EDM process has been carried out considering the 2D axi-symmetric process continuum and analysis is based on Gaussian distribution of heat flux. Themodel was developed using MATLAB and with this developed code the temperature distribution of micro EDM was studied. The developed single discharge model makes use of several important aspects such as properties of specific heat, thermal conductivity, percentage distribution of heat among tool, workpiece and dielectric fluid, and the material ejection efficiency, etc. Ti-6Al-4V was considered as the workpiece. It is wellknown for its high strength to weight ratio, which has tremendous application in automobile, nuclear, biomedical and aerospace. In the developed code, the process parameters have been considered based on the available machine. The model is compared with previous ANSYS work. Finally, for further validation, single discharge experiment with RC pulse generator was performed using titanium alloy and tungsten carbide as the workpiece and tool respectively.

Keywords: micro EDM, Ti-6Al-4V, modeling, MATLAB

1 Introduction

Micro EDM is a non-contact technique used to machine geometrically complex workpieces, which are hard and difficult to machine, by conventional machining process. Micro EDM derived from conventional EDM where material is removed due to vaporizing and melting through intense heat generation by plasma channel in an electric spark and ejection of molten material due to the collapse of the plasma channel. Micro EDM having same principle characteristics of conventional EDM, but difference is of low specific energy of material removal at low discharge levels, which improves the machining accuracy. The only criterion to fulfill for machining is that the workpiece material should be electrically conductive. Since the workpiece hardness won’t affect the machining, any material which is electrically conductive can be machined easily. These give a big advantage for the machining of high aspect ratio structures with high precision. Because of this micro EDM found many applications in the field of aerospace, marine, military, surgical, and space.

Ti-6Al-4V is a light weightalloy, which has extraordinary corrosion resistance and the ability to withstand extreme temperatures. Ti-6Al-4V is an electrically conductive and difficult to machine material, which has wide applications due to its high strength to weight ratio. Among its many advantages, it is heat treatable. This grade is an excellent combination of strength, corrosion resistance, weld and fabric ability. The low thermal conductivity of titanium alloys hinders quick dissipation of heat caused by machining. This leads to increase in wear rate of tool, which is not advisable for economic machining. In addition, titanium alloys shows significant spring back after deformation under cutting load. Due to these difficulties conventional machining of titanium alloys are not preferred. Ti-6Al-4V is widely used for aircraft structures, wings, turbine blades, etc.

Eventhough micro EDM has been used for machining of electrically conductive materials for many years, the material removal mechanism is not fully understood. Many researchers explained the
theory behind the electro spark process in their own manner. Modeling of micro EDM process will help in understanding of its material removal process. Finite element method is such a powerful, unique tool to model any complex shapes with boundary conditions.

In modeling and simulation of micro EDM process Rajurkar et al. [2003] developed a mathematical model of contouring edm process considering the profile of workpiece, actual tool path and machined surface profile. Joshi and Pande [2009] proposed an intelligent model for the electric discharge machining process using finite element method and artificial neural network. They consider Gaussian distribution of heat flux, time and energy-dependent spark radius, etc. to predict the shape of crater cavity, material removal rate, and tool wear rate. Three dimensional FEM modeling of micro EDM was developed by Jose Mathew et al. [2012] and analysed the effect of Gaussian heat flux on inconel 718 while machining. Allen and Chen [2007] found that tensile residual stress build up near the crater for single discharge, which may develop into micro craters for multiple discharges. The formation of recast layer on the work piece causes difference in the crater dimensions between the measured and the simulated values. Marafona and Chousal [2006] investigated the effect of Joule heating factor in the electro discharge machining which causes increase in the discharge region temperature and presented an integrated model incorporating both anode and cathode. Shabgard et al. [2011] studied the surface characteristics produced by EDM on tool steel using the FEM approach considering the crater to have circular parabolic geometry. The white layer thickness, depth of heat-affected zone increased with the pulse on time. Finite difference method to model the EDM-ed surfaces were applied by Izquierdo [2009].

Kansal et al. [2008] have developed numerical simulation of Electrical discharge machining using finite element. The model considered important aspects such as temperature sensitive material properties, type and nature of suspended powder, shape and size of heat source, percentage distribution of heat between tool, work piece and dielectric fluid, pulse on/ off time and material ejection efficiency. Min and Jeong [2007] developed a geometric simulation model of EDM drilling. The off line compensation for considering the tool wear rate was also achieved for micro EDM. Someshkar et al. [2012] presented a model for micro EDM based on electro thermal theory approach and obtained the diameter to depth ratio as 2.92. Dhanik et al. [2005] reported a comprehensive review of modeling efforts in the field of EDM processes and proposed the future directions for modeling of micro EDM process.

The material removal process of micro EDM is complex in nature. So it is reliable to make a numerical model. The modelling of micro EDM will shows the overall picture of workpiece temperature range and the temperature distribution along the workpiece surface gives an idea about the single spark effect. FEM is unique and accurate tool to model this process. Since Ti-6Al-4V is workhorse alloy, which is widely used in aerospace industries, during modelling its properties, are considered. Using FEM, the governing equations and boundary conditions are solved and coded in MATLAB. The model considered the important aspects such as material properties, shape and size of heat source, the percentage distribution of heat between work piece, tool and dielectric fluid. In previous work, using same conditions and parameters a model was developed in ANSYS. That is compared with the MATLAB results for validation.

2 Thermal Modelling

The process of material removal in micro EDM is complex and not yet fully understood at the microscopic level. Simulation of micro EDM process gives some idea about the mechanism of material removal. In this work transient non-linear thermal analysis of the single spark erosion has been performed. Only an axi symmetric model of workpiece domain is considered because of symmetry. The axisymmetric model with boundary condition and heat distribution is shown in Fig.1.

![Figure 1: Axisymmetric heat transfer model for micro EDM with boundary conditions](image-url)

2.1 Assumptions

Following assumptions were considered to simplify the model.
1. Tool and workpiece are considered homogenous and isotropic.
2. Heat transfer to electrode surface is dissipated only by conduction.
3. Fraction of discharge energy going to anode and cathode is constant.
4. Heat flux is assumed to follow Gaussian distribution. The zone of influence of the spark is assumed axisymmetric in nature.
5. Temperature analysis is considered to be of transient type.
6. There is no deposition of recast layer on the machined surface. I.e. flushing efficiency is considered to be 100%.
7. Capacitor is fully charged and discharged during the process.
8. Workpiece is free from any type of stress before micro-EDM.
9. A fraction of total spark energy is dissipated as heat into the workpiece. The rest is lost into the dielectric by convection.
10. The material properties of the workpiece and tool are temperature independent.
11. Model is developed for a single spark.

2.2 Governing Equations

The differential equation governing the three-dimensional heat conduction in Cartesian coordinate is given by

$$C_{\rho} \frac{dT}{dt} = K \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right]$$

Where $C$ is the specific heat, $\rho$ is the density and $K$ is the thermal conductivity of the work material, $t$ is the time, $T$ is the temperature.

2.3 Initial Conditions

The initial temperature of the workpiece is equivalent to the ambient temperature $T_0$ of the dielectric fluid supplied to the workpiece

$$T(x,y,z,t=0) = T_0$$

2.4 Boundary Conditions

The boundary conditions is as shown in fig 1

$$K \frac{\partial T}{\partial y} = \begin{cases} h(T - T_0), & r > R_z, \\ q_r, & r \leq R_z \end{cases}$$

For others boundaries

$$\frac{\partial T}{\partial n} = 0$$

2.5 Energy Calculation

The micro EDM used for experimental study is having RC circuit. So the discharge energy is given by

$$E = \frac{1}{2}CV^2$$

Where $C$ is the capacitance, and $V$ is the gap voltage. If the spark on time is known, i.e. $t_{on}$, then the total heat flow rate is given by

$$Q = \frac{E}{t_{on}}$$

In micro EDM process the heat developed is distributed among cathode, anode and dielectric medium. As compared to heat dissipated to dielectric supplied only small amount is absorbed by anode. So heat flow rate at anode is given by

$$Q_a = \eta Q$$

Assuming the value of $\eta$ to be 0.08 [9]

$$Q_a = 0.08Q$$

Now, the spatial distribution of heat flux density rate is given by

$$q = \frac{Q_a}{\pi R_z^2}$$

2.6 Heat Flux

The flux distribution in micro EDM have no specific model. Many researches have considered uniformly distributed heat source. However, when compared to the experimental results this distribution was not valid. So here Gaussian heat flux distribution is considered, which is given by

$$q_r = q_{max} e^{-4.5 (r/R_z)^2}$$

Where $q_{max}$ is maximum flux density rate when $r=0$ [10]

$$q_{max} = 4.5 q$$

$q$: Uniform heat flux density rate as given in equation number (9).

2.7 Material and dielectric properties

The work piece, tool electrode and dielectric fluid used in this study were titanium alloy (Ti-6Al-4V), tungsten carbide, and EDM3 oil respectively. EDM3 oil is having relatively high flash point, high ignition temperature and high dielectric strength.
Modelling Of Micro Electric Discharge Machining Using FEM

Fluid is a clear mineral oil exhibiting good resistance to oxidation: contains very low aromatic contents, low volatility and low pour point creating possibility of outside storage and low viscosity which ensures that metal chips are evacuated easily. Important properties of work piece and dielectric fluid are listed in Table 1-2 respectively.

Table 1: Workpiece material properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-6Al-4V material properties</td>
<td></td>
</tr>
<tr>
<td>Specific heat</td>
<td>526.3 J/kg°C</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>6.7 W/m-K</td>
</tr>
<tr>
<td>Melting point</td>
<td>1604-1660 °C</td>
</tr>
<tr>
<td>Density</td>
<td>4430 kg/m³</td>
</tr>
</tbody>
</table>

Table 2: Properties of dielectric fluid

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>EDM oil 3</td>
</tr>
<tr>
<td>Volumetric mass at 15 °C (kg/m³)</td>
<td>813</td>
</tr>
<tr>
<td>Viscosity at 20 °C (mm²/s)</td>
<td>7</td>
</tr>
<tr>
<td>Flash point Pensky-Martens</td>
<td>134/259</td>
</tr>
<tr>
<td>Auto-ignition temperature (°F)</td>
<td>470</td>
</tr>
<tr>
<td>Aromatics content (Wt%)</td>
<td>0.01</td>
</tr>
<tr>
<td>Distillation range, IBP/FBP (°C)</td>
<td>277/322</td>
</tr>
</tbody>
</table>

3FEM simulation

For modelling the micro EDM process, finite element approach is adopted. In this the given domain is divide into finite elements which are connected by nodes. All the relations connected to the model should be written for a finite element. Global equations for the domain can be assembled from finite element equations using connectivity information.

![Figure 2Workpiece domain to finite elements](image)

3FEM simulation

For simplicity in this work, square domain is considered and it is divided into finite number of elements as shown in Figure 2. The governing equations, boundary and initial conditions are solved using FEM in MATLAB. The output of MATLAB code gives the temperature distribution. The governing equation can be written in the form of residual as

\[
\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} - \frac{1}{\alpha} \frac{\partial T}{\partial t} = R
\]  

By using Galerkin method

\[
\int N_i R dA = 0
\]

\[
\int N_i \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} - \frac{1}{\alpha} \frac{\partial T}{\partial t} \right] = 0
\]

We can write

\[
\frac{\partial T}{\partial t} = N_i T_i + N_i T_i^2 + N_i T_i^3 + N_i T_i^4
\]  

Integrating and rearranging equation (14) we get,

\[
\int \frac{\partial N_i}{\partial t} \frac{\partial n_i}{\partial x} + \frac{\partial n_i}{\partial y} \frac{\partial T}{\partial x} + \frac{1}{\alpha} \int n_i \frac{\partial T}{\partial x} dx = \int n_i \frac{\partial T}{\partial x} dx +
\]

\[
\int n_i \frac{\partial T}{\partial y} n_y dy
\]

Equation (16) can be simplified as

\[ [M] [T] + [K] [T] = [F](17) \]

[K]-Global conductivity matrix, [M]-Global capacitance matrix, [F]-Global flux matrix, [T]–nodal temperature matrix and [T]–Time derivative of temperature. Furthermore the (17) can be modified

Using FDM method and can be written as

\[ M \frac{T_{i+1} - T_i}{\Delta t} + K T_i = F_i(18) \]

\[ [M]T_{i+1} = [M - K \Delta t] T_i + [F] \Delta t \]  

In matrix form we can write final solution for temperature after \( \Delta t \) seconds, which is solved in MATLAB

\[ T_{i+1} = \frac{[M] - K \Delta t}[T_i + [F] \Delta t]}{[M]} \]  

4 Result and Discussion

The temperature distribution for particular parameters (\( V=110V \) and \( C=0.1 \mu F \)) is as shown in the figure 3. The distribution shows the temperature along the length of the workpiece. Since the heat flux distribution selected was Gaussian distribution, the temperature distribution also follows the same. The highest temperature for specified parameters is around 12000 K.

![Figure 3 Temperature distribution along length for parameters V=110V & C=0.1μF](image)

For different parameters, the distribution is as shown in figures 4. This shows that the temperature distribution varies as the machining parameters changes. These variations are due to changes in
specific energy. As the voltage increases the specific energy increase and which results in high temperature. Likewise as capacitance value increases the specific energy increases, which in turn result in temperature rise and increased material removal rate.

![Graph of temperature distribution for different parameters](image1)

**Figure 4** Temperature distribution for different parameters

The variation of temperature distribution for various voltage values and capacitance values is as shown in figure 5. As discussed above, the specific energy is directly proportional to capacitance and square of voltage, the temperature increases as both these parameters increases.

![Graph of temperature distribution at constant capacitance (0.1µF) and different voltage](image2)

**Figure 5** Temperature distribution at constant capacitance (0.1µF) and different voltage

![Graph of temperature distribution at constant voltage (110V) and different capacitance (µF)](image3)

**Figure 6** Temperature distribution at constant voltage (110V) and different capacitance (µF)

5. **Experimental validation**

For validation, experiments were carried out on the multipurpose micro machining center, DT110, Mikrotools Pvt. Ltd. Since the experiments are to be carried out for single spark, separate attachment is required. Experiment parameters are selected same as that used for simulation so that the results can be compared. After doing the experiment using parameters as shown in table 3, the workpiece crater surface was analysed in SEM and AFM. The SEM images shows the crater radius and it is measured. SEM image of the crater formed is as shown in the Figure 8.

![Comparison of temperature distribution at capacitance 0.1µF and voltage 110V](image4)

**Figure 7** Comparison of temperature distribution at capacitance 0.1µF and voltage 110V

<table>
<thead>
<tr>
<th>Table 3: Experiment process parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap voltage</td>
</tr>
<tr>
<td>Capacitance</td>
</tr>
<tr>
<td>Feed Rate</td>
</tr>
<tr>
<td>Tungsten carbide electrode</td>
</tr>
<tr>
<td>Work piece</td>
</tr>
<tr>
<td>Dielectric</td>
</tr>
</tbody>
</table>

6. **Conclusion**

The FEM model calculates the temperature distribution, which will help us to study the crater radius. The material above melting point is assumed to be removed and crater radius is calculated based on the temperature values. This temperature distribution is compared with the results obtained from ANSYS simulation. Both the distribution shows same characteristics. The distribution follows normal curve since heat flux was assumed Gaussian distribution. The temperature variation is almost same for both models. The small variation is there because in ANSYS 3D model was considered and for coding 2D axisymmetric model was considered.
Using the Scanning electron microscope, images of surface of workpiece where crater formed due to single spark was taken and is as shown in figure 8. The results obtained from the numerical model is in good agreement with the experimental results. The spark diameter to depth ratio calculated experimentally is 4.623. The simulated crater diameter to depth ratio is 4.92. The error in the results are due to the solidification of the melted material. That is due to the formation of recast layer. It was assumed that the ejection efficiency is 100% and recast layer formation was not considered.

ANSYS simulated crater diameter to depth ratio is 5.1. The maximum temperature for particular parameters (capacitance 0.1µF and voltage 110V) is 12322 K. In case of MATLAB simulation, this is 10821 K. The difference is due to the mesh size, which changes the accuracy of the result. Also in ANSYS 3 dimensional analysis is done but in case of coding in MATLAB only 2D is considered.

7. References