Thermal Model for Single Discharge EDM Process Using COMSOL Multiphysics

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Abstract: Electrical Discharge Machining (EDM) is a non-conventional process used for machining electrically conducting materials. In die sink-EDM, sparks are generated between tool and workpiece resulting in heating of both electrode surfaces and creating a melt pool of metal which leads to generation of new surfaces on cooling. The physical processes involved in electric discharge and material removal are not yet fully understood. So based on some simplifying assumptions an attempt has been made to study the temperature profiles and residual stresses prevailing in the electrodes during single discharge EDM. Heat Conduction and Residual Thermal Stress modules of COMSOL Multiphysics have been used to develop this model for the process. Predictions of temperature profiles and residual stresses obtained from this are then compared with experimental data and used further in determining the optimal operating conditions for the process.

Keywords: EDM, Temperature Profiles, Residual Stresses, COMSOL.

1. Introduction

Modeling of any process requires definition of geometry, physics involved in the process and assumptions involved in simplifying the model. Actual model of EDM consists of two cylindrical electrodes corresponding to workpiece and tool. But to reduce computational efforts, cylindrical geometry of electrodes has been reduced to a 2D-axisymmetric geometry which is shown in Figure 1. Physics involved in the process of EDM is mainly based on Heat Conduction and Joule Heating but as proposed by Van Dijck et al. [1] the changes observed in results due to the addition of Joule Heating are not so significant. Modeling of EDM process also requires a definition of heat source. Depending on heat source definition, the results can vary significantly. Definitions of heat source can include a point heat source, a disc heat source, or gaussian heat source. Simulation results were found to be much better when a gaussian heat flux profile was used for the cathode workpiece and equilibrium or disc profile for the anode tool.

Another factor important for defining the model is the expansion of plasma channel considered. Various empirical equations of the form:

$$\boldsymbol{R_p(t) = C_o * I^m * t^n}$$

have been proposed for the expansion of plasma channel where $\boldsymbol{R_p}$, $\boldsymbol{I}$ and $\boldsymbol{t}$ represent radius of plasma channel, current and time duration respectively. And $\boldsymbol{C_o}$ is a constant whose value is optimized to match the experimental results. Also as proposed by P.C. Pandey et al. [2], expansion of plasma channel can also be considered assuming that the cathode spot temperature remains constant (equal to the boiling temperature of electrode). Equation used for the expansion of plasma channel also has a significant effect on the temperature profiles. Generally the material properties are averaged over the temperature range and assumed to be constant. However in this work the temperature dependency of material properties is also taken into consideration. Equations used for modeling, boundary conditions provided to the model, computational methods involved in calculating crater depth and radius, and results obtained, are all discussed in detail further.

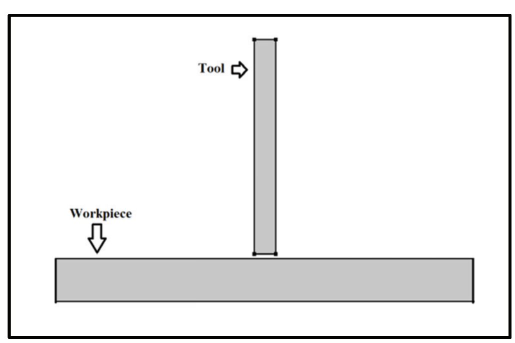

Figure 1. 2D model geometry

2. Governing Equations and Boundary Conditions

Governing equations for the model are based on the Heat Conduction and Joule Heating modules available with COMSOL Multiphysics. Also Residual Thermal Stress module has been used to evaluate the residual stresses prevailing in the electrodes. Each of the equations used in obtaining the results are discussed in the subsections below.

2.1 Heat Conduction Physics

Temperature distribution across the electrodes is governed mainly by the heat conduction phenomenon in electrodes. Equation below describes the basic heat diffusion equation used for heat conduction:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u}.\nabla \mathbf{T} = \nabla.(\mathbf{k}\nabla \mathbf{T}) + \mathbf{Q}$$

Here, **T** is the temperature, ***t*** is time, **Q** is the thermal energy generated per unit volume, **k** is thermal conductivity, ρ is density, C_p is specific heat and **u** is the velocity vector.

Above equation is simplified for 2D-axisymmetric case and then **Q** and **u** are set as zero in the simplified equation (**Q** is zero only if Joule Heating is ignored). In order to get the results for temperature distribution, it is necessary to provide appropriate boundary conditions. For this, a region of plasma channel must be defined on the respective boundaries of both the electrodes where heat flux is provided as boundary condition. This region varies with time according to the equation used for plasma expansion. And all other boundary regions are considered to be thermally insulated. Gaussian distribution used for the heat flux profile is governed by the equation shown below:

$$\mathbf{q} = \left(\frac{P}{\pi * r^2}\right) * \mathbf{exp}(-4.5 * \left(\frac{r^2}{R^2}\right))$$

Here, **q** is the heat flux (W/m^2), **P** is power (W) which is dependent on voltage and current used for the process, **r** is the distance from axis of symmetry and **R** is the radius of plasma channel at a given time.

Initially at t=0, the whole domain is considered to be at room temperature and finally the transient analysis is carried out considering the above boundary conditions, to obtain the profiles. Figure 2 below describes the boundary conditions specified for solving heat conduction part and the plasma region.

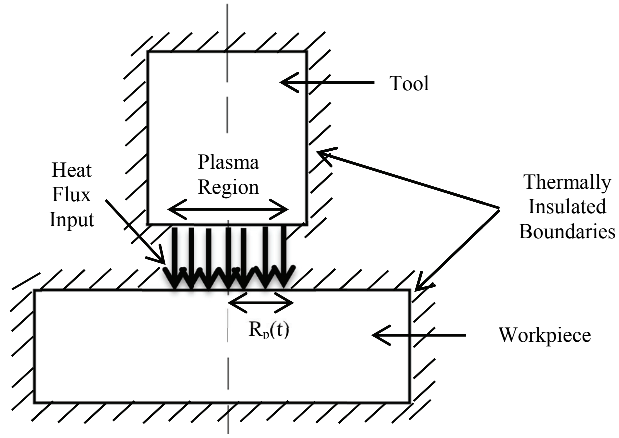

Figure 2. Boundary Conditions used for solving heat diffusion equation

2.2 Residual Thermal Stress

To obtain the residual stresses prevailing in the electrodes, Thermal Stress module of COMSOL Multiphysics has been used. Calculation of Von Mises stress is based on the equations shown below:

$$(-\nabla.\boldsymbol{\sigma} = \mathbf{F_v}), (\boldsymbol{\sigma} = \mathbf{s}) \qquad (1)$$

$$\left(\mathbf{s} - \mathbf{s_o} = \mathbf{C}: (\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon_o} - \boldsymbol{\alpha}(\mathbf{T} - \mathbf{T_{ref}}))\right) \qquad (2)$$

$$\boldsymbol{\varepsilon} = \frac{1}{2}(\nabla\mathbf{u} + (\nabla\mathbf{u})^{\mathbf{T}}) \qquad (3)$$

Equation (1) above corresponds to the equilibrium equation where $\boldsymbol{\sigma}$ is the stress tensor and $\mathbf{F_v}$ denotes the volume forces (body forces). Equation (2) relates the stress tensor **s** with strain tensor $\boldsymbol{\varepsilon}$ using Duhamel-Hooke's law. In equation (2), $\mathbf{s_0}$ and $\boldsymbol{\varepsilon_0}$ are initial stress and strain tensors respectively. **C** is fourth order elasticity tensor, $\boldsymbol{\alpha}$ is thermal expansion and '**:**' stands for the tensor double-dot product. And equation (3) relates strain tensor $\boldsymbol{\varepsilon}$ with the displacement gradient ($\nabla\mathbf{u}$).

For calculating residual stress in the electrodes, temperature distribution in electrodes is provided from the previous results obtained by solving the heat conduction part. And all boundaries are assumed to be perfectly rigid, i.e. their motion is completely restricted.

Thus, the temperature and stress distribution in electrodes is obtained using above given modules of COMSOL Multiphysics and are further processed in MATLAB to obtain the required results.

3. Use of Livelink with MATLAB™

Once the simulation is performed and required results are obtained, all the necessary data is transferred to MATLAB using Livelink feature of COMSOL. For this purpose a GUI (shown in Figure 3 below) is built which gives in a coordinate file to COMSOL. It extracts the results at those given coordinates and finally saves them in a file. Once these data is taken in a file, crater depth or radius is evaluated as follows: Firstly, the difference $\mathbf{(T(i,j)-T_{melt})}$ is calculated at all the data points (here $\mathbf{T(i,j)}$ is the temperature at point with coordinates $\mathbf{(i,j)}$ and $\mathbf{T_{melt}}$ is the melting temperature). After this a tolerance value $\boldsymbol{\varepsilon}$ is defined as per the requirement and all the points satisfying the conditions $\mathbf{(T(i,j)-T_{melt})<\varepsilon}$ are separated. This procedure is repeated for all the time steps used in performing simulation. Then for each time step, average of all separated points is taken. And then depending on those averaged values, the variation of crater radius or depth with time is obtained. Radius or depth for residual stress isocontours is obtained is a similar way.

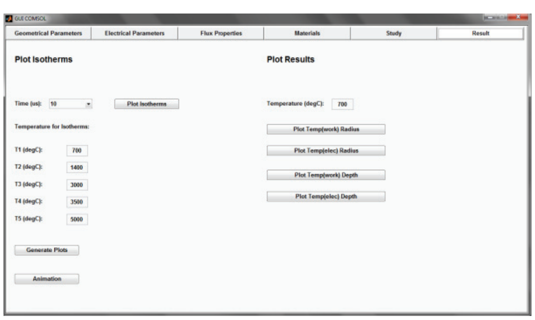

Figure 3. MATLAB GUI

Further some additional features were also added in GUI to perform multiple simulations varying the heat flux profile, plasma expansion equation and various other parameters and to compare the obtained results with experimental data.

4. Results and Discussion

Results shown below are obtained using steel as workpiece and graphite as tool material and are for single discharge process with pulse on duration of 150µs. Moreover, it is assumed that the energy received by workpiece is 20% of the total energy input while that received by tool is 8%. Considering above factors, results obtained for variation in temperature distribution and residual stresses have been discussed below. As it is relatively difficult to obtain experimental data for single discharge EDM process, the results obtained from this model have been validated using the experimental data provided in previous research papers on EDM.

4.1 Temperature distribution in electrodes:

Each of the six figures shown below corresponds to distribution of temperature in the electrodes at six different time intervals.

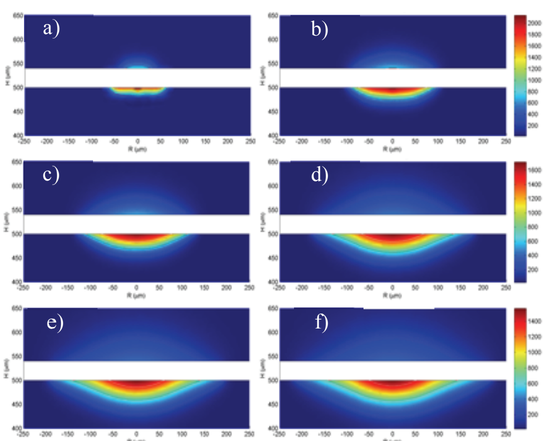

Figure 4. Temperature distributions at time: **a)** t=20µs **b)** t=40µs **c)** t=60µs **d)** t=100µs **e)** t=120µs **f)** t=140µs

As observed from the figure above, the crater geometry generated in the workpiece using time dependent gaussian heat source is almost bowl-shaped, i.e. width of the crater is higher as compared to the depth. Also, both width and depth of crater increases with time. Nature of increase in width and depth of crater with time is captured by plotting the numerical values of crater radius and depth obtained from MATLAB against time.

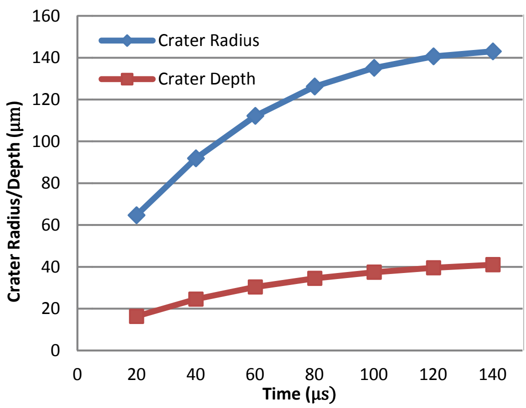

Figure 5. Variation in Crater dimensions with time

In comparison to point heat source where the crater geometry is almost semi-spherical, time dependent gaussian heat source provides a much flatter geometry with lesser depth.

4.2 Residual Stresses:

Once the heat conduction part is solved, the temperature distribution obtained is provided to the Thermal Stress module to simulate the residual stresses prevailing in the electrodes. Figure 6 below shows the distribution of Von Mises stress in electrodes at time t=150µs.

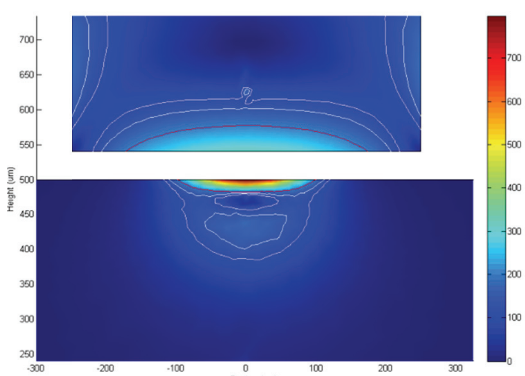

Figure 6. Residual Stress distribution

White isocontours in the picture above correspond to stress level of 120MPa. To observe the nature of stress variation along the depth of electrode, stress values are plotted against depth for time t=150µs in figure 7 below.

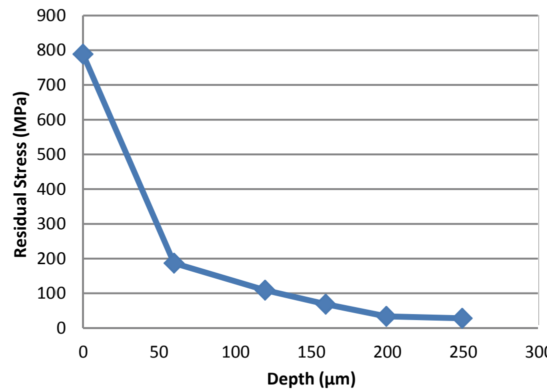

Figure 7. Residual stress variation along depth

As observed from the plot above, there is a sharp decrease in residual stresses as we move away from the electrode surface (shown in Figure 7). Near to the surface, these stresses are in the range of 200-800MPa but as we move away there is a drastic decrease in these stresses and they almost become negligible after a depth of about 150µm. Such high stresses near the surface can result in formation of micro-cracks. More often such stresses may not affect the workpiece instantaneously but they can prove to be harmful when the machined surface is used in applications.

5. Conclusions

Model proposed here provides good predictions for temperature distribution in electrodes. Moreover the crater geometry obtained using gaussian heat source and temperature dependent material properties was found to be in good agreement with the experimental data as compared to that obtained using point or disc heat source and constant material properties. Simulation results can further be improved by optimizing the constant C_0, and exponents **m** and **n** in the equation used for plasma expansion. Computed values for residual stresses were found to be very high near the surface of electrodes. However, a sudden decrease in these stresses was observed as we moved away from the surface. Future work includes improving upon the model so as to reach as close as possible to experimental values.

6. References

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