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Study of Workpiece Thermal Profile in Electrical Discharge Machining Process

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Abstract

The effectiveness of the EDM process is evaluated in terms of the material removal rate, relative wear ratio and the surface roughness of the work piece. The input discharge energy during this process is distributed to various components of the process, which further influences the material removal rate and other machining characteristics like surface roughness. The theoretical modeling of the process is based upon the heat transfer equations and fraction of energy transferred to the work piece is one of the important parameters. The accurate prediction of the fraction of energy effectively transferred to the work piece will help to reduce the errors of the thermal models. The analysis is based on certain assumptions to predict the shape of crater cavity, the material removal rate.

1. Introduction

Electrical Discharge Machining (EDM) is an electro-thermal non-traditional machining process, where electrical energy is used to generate electrical spark and material removal mainly occurs due to thermal energy of the spark. It gives high accuracy of the order of ± 0.025 to ± 0.127 mm. Volumetric material removal rate achieved is quite low (0.1 to 10 mm^3/min).

The input discharge energy during this process is distributed to various components of the process, which further influences the material removal rate and other machining characteristics like surface roughness. Since during this process the electrical energy is converted into heat energy, hence the theoretical modeling of this process is based upon the heat transfer equations. This heat energy is distributed between the various components of the system (workpiece, tool electrode and dielectric fluid) and is shared by large number of physical processes occurring during the main stages (ignition, main discharge, melting, evaporation, and expulsion) of EDM process.

The erosion by an electric discharge involves phenomena such as heat conduction, energy distribution, melting, evaporation, ionization, formation and collapse of gas bubbles in the discharge channel.

In general, the material removal rate and machining characteristics during the EDM process depend on the distribution of the energy supplied to the gap by the electrical current, shape and size of the discharge channel and also on the properties of the dielectric fluid and electrode material, such as melting point, density, specific heat, thermal conductivity, yield strength, etc. Hence, different materials even when they are machined under the same machining conditions would result in different machining characteristics, results in less accurate thermal models.

2. Literature Review

Earlier, most of the researches have worked on models based on the assumptions such as cylindrical plasma channel, uniform heat source, point heat source and constant or expanding heat flux radius. The thermal load in EDM workpiece mainly consists of heat flux and convection between workpiece and dielectric fluid. Literature survey has been carried to out understand the present status of the work in this area. Brief summary on literature is presented.

2.1. Heat source model

The thermal analysis of the EDM process considered the conduction as the primary mode of heat transfer between the ions of plasma and the molecules of the electrode [1]. A number of simplified thermo-mathematical models of the EDM process based on the equations of heat conduction into solids are available. However, a generally accepted theory does not yet exist because of the complicated nature of metal removal mechanism accompanying the electric discharge in the dielectric medium.

The type of heat flux applied onto the model as a heat source is one of the most important factors in the simulation process as it directly affects the accuracy of the results. Most of the previous researchers assumed two types of heat fluxes for their models: point heat source [2] and uniformly distributed heat flux [3,4], but none of them can be true since the energy density of the sparks is not uniform in different radii of the plasma channel during discharge.

The primary mechanism of material removal in EDM process is the thermal heating of work surface due to intense heat generated by the plasma, which raises the temperature of the electrodes (tool, work) beyond their melting point, sometimes even the boiling point. For the thermal analysis of the process, conduction is thus considered as the primary mode of heat transfer between the ions of plasma and the molecules of work/tool [5,6].

During the EDM process, material is removed predominantly by melting than evaporation. Latent heat of melting is thus, an important factor in the thermal modeling as it signifies the consumption of a considerable amount of supplied heat (generated in the spark plasma) for the phase change of the work/tool material during melting [3,7]. The DiBitonto's model has ignored the effect of latent heat of melting in their analysis.

The predictions of the models proposed recently by Izquierdo et al. [8] and Joshi et al. [1] are more accurate using Gaussian distribution of heat flux. In this work, the Gaussian distribution of heat flux input has been used to approximate the heat from the plasma. The heat q entering the workpiece due to EDM spark is given by,

$$q(r) = q_o \exp\left\{-4.5\left(\frac{r}{R_{pc}}\right)^2\right\}$$

where q_0 is the maximum heat flux, R_{pc} is spark radius at the work surface and r is radial coordinate of workpiece.

Spark radius is an important factor in the thermal modeling of EDM process. In practice, it is extremely difficult to experimentally measure spark radius due to very short pulse duration of the order of few microseconds. Different approaches have been proposed by researchers in the literature. The spark radius equations proposed by the earlier researchers were not realistic in nature as the EDM spark is controlled both by discharge energy and discharge on-time. Ikai and Hashiguchi [9] have derived a semi-empirical equation of spark radius termed as “equivalent heat input radius" which is a function of discharge current, I and discharge on-time, T_{on}. It is more realistic when compared with the other approaches.

$$R = (2.04e\text{-}3)\, I^{0.43}\, T_{on}^{\;0.44} \qquad (1)$$

where I (A) is the pulse current and Ton (s) is pulse on-time.

The thermal modeling and finite element simulation of EDM has to be done taking into account several important aspects such as temperature-dependent material properties, shape and size of the heated zone, plasma flushing efficiency and phase change to predict the thermal behaviour and material removal mechanism in EDM process.

3. Methodology

The methodology adopted for the present work is shown in figure 1. The component to be machined is selected first and 3D modelling of the workpiece is done in ANSYS 12.0. The finite element thermal analysis of the EDM workpiece is done using ANSYS software package.

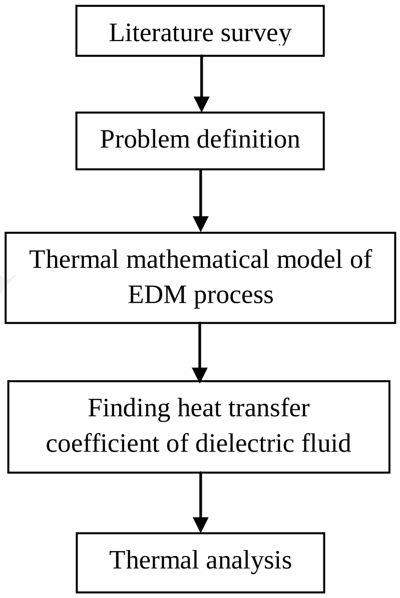

Figure 1. Methodology for the work

4. Problem definition

Incorporating factors such as plasma flushing efficiency, latent heat of melting, and Gaussian distribution of heat flux, considering material properties as a function of temperature, we can determine the theoretical MRR model of the EDM process for a particular electrode.

5. Heat source model

Important factors which contribute to the accurate calculation of the MRR in single spark EDM model include the amount of heat input, radius of plasma spark and the thermo-physical properties of material. Researchers have assumed two forms of heat input models viz., point source model with hemispherical crater cavity or uniformly distributed heat flux model. Both these models are simplistic as in actual practice neither is there a point heat source (like laser beam) nor is there any uniform (constant) application of heat on the work piece. A spark radius exists at the cathode electrode. Consideration of average thermo-physical material properties and constant EDM spark radius make the reported models simplistic and less accurate in predictions.

In this present work, the Gaussian distribution of heat flux input has been used to approximate the heat from the plasma. The Gaussian curve mathematically becomes zero at infinity so a 6σ range (-3σ to 3σ) that covers 99.73% of the total area under the curve was used in the present case. σ represents the standard deviation of the process. By rotating the Gaussian curve about its vertical axis (*z*-axis) a three-dimensional Gaussian heat source was achieved.

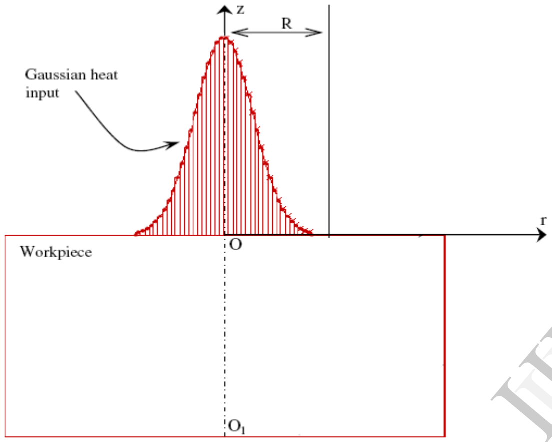

Figure 2. Gaussian heat source model

5.1. Heat distribution

The probability density function of Gaussian distribution for a random variable r is given by:

$$P(r) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{r^2}{2\sigma^2}} \qquad (2)$$

where σ is the standard deviation

So, if we replace σ by $\frac{R}{3}$, we have:

$$P(r) = \frac{3}{R\sqrt{2\pi}} e^{-4.5\left(\frac{r^2}{R^2}\right)} \qquad (3)$$

Assuming P(r) = Q(r) and $Q_0 = \frac{3}{R\sqrt{2\pi}}$

$$Q(r) = Q_0\, e^{-4.5\left(\frac{r^2}{R^2}\right)} \qquad (4)$$

Where ,Q_0 is the maximum intensity of heat applied at the centre of the work piece, R is the spark radius, r is the radius of the workpiece.

Since the heat flux is distributed on the surface, the energy incident on the work piece is:

$$\oint Q(r)dA = \int_0^R Q(r)2\pi r\,dr = 0.2191\pi\, Q_0 R^2 \qquad (5)$$

The equation that was governed for heat flux should be equal with the power applied on the workpiece, so we can write:

$$F_c\, VI = 0.2191\pi\, Q_0 R^2 \qquad (6)$$

Substituting we get,

$$Q(r) = \frac{4.57 F_c VI}{\pi R^2} e^{-4.5\left(\frac{r^2}{R^2}\right)} \qquad (7)$$

6. Workpiece material properties

AISI H13 tool steel (0.40% C, 1.00% Si, 5.30% Cr, 1.40% Mo, 1.00% V) is taken as the workpiece material during the present study. The properties of the workpiece material used for the simulation study are listed in Table 1.

Table 1. Properties of AISI H13 tool steel

Temp (K)	Thermal conductivity (W/m.K)	Specific heat (J/kg.K)	Density (kg/m^3)
293	24.3	460	7800
773	27.7	550	7640
873	27.5	590	7600

Melt temperature 1727 K

Latent heat of fusion 2.8 x 10^5 J/kg

7. Transient thermal analysis

The problem of determining the temperature distribution in the EDM workpiece is considered as a three-dimensional transient heat transfer problem. One half of the entire workpiece is considered for the analysis with the assumption of symmetric loading condition.

The workpiece crater shape and size is obtained by finite element method using ANSYS. To begin with, cross-sectional area pertaining to workpiece is created. The created areas are revolved about axis to create the volume of the generated areas. Then the material properties are assigned to the model.

7.1. Element type for transient thermal analysis

The element selected for the transient thermal analysis is four noded, axi-symmetric, thermal solid element (PLANE 55).

Since the model is axi-symmetric, two-dimensional 0.6x0.6mm geometry was defined. Discretization of the domain has been done by providing finer mesh on the area which is affected by the heat flux (top left corner) and coarse mesh on remaining area.

7.2. Assumptions

The assumptions made for carrying out the transient thermal analysis are as follows.

1. Work piece and tool materials are homogeneous and isotropic in nature.
2. The material properties of the workpiece and tool are temperature dependent.
3. Conduction is considered as the mode of heat transfer to the electrodes.
4. EDM spark channel is considered as a cylindrical column and the spark radius is assumed to be a function of discharge current and time.
5. Heat flux is assumed to be Gaussian distributed. The zone of influence of the spark is assumed to be axi-symmetric in nature.
6. Only a fraction of total spark energy is dissipated as heat into the work piece, the rest is lost into the dielectric convection and radiation.
7. PFE is a function of pulse current and pulse on-time

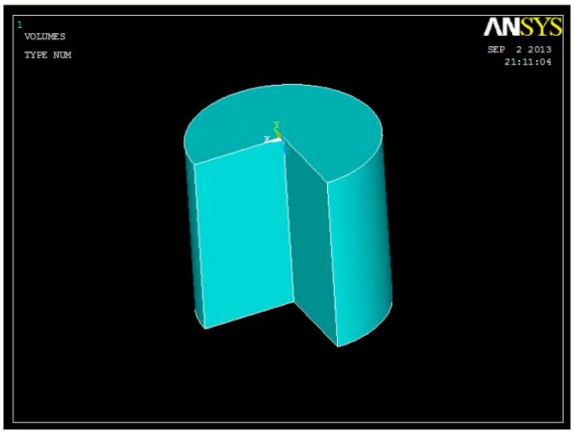

Figure 3. 3D model of workpiece

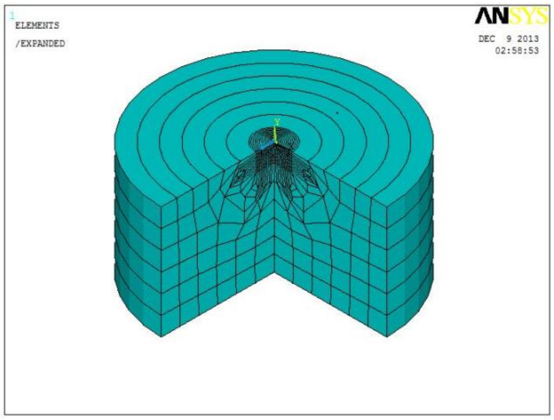

Figure 4. Finite element model of workpiece

7.3. Boundary conditions and initial conditions

Figure 5 illustrates the assumed boundary conditions for the model. On the top surface, the heat transferred to the workpiece during the spark on-time is represented by a Gaussian heat flux distribution. Heat loss to the dielectric is modeled using convective boundary conditions on surface BD. No heat transfer occurs across surfaces OO_1, DE, and O_1E as they are either symmetry line or boundary in the far distance, and the initial temperature is equal to dielectric temperature.

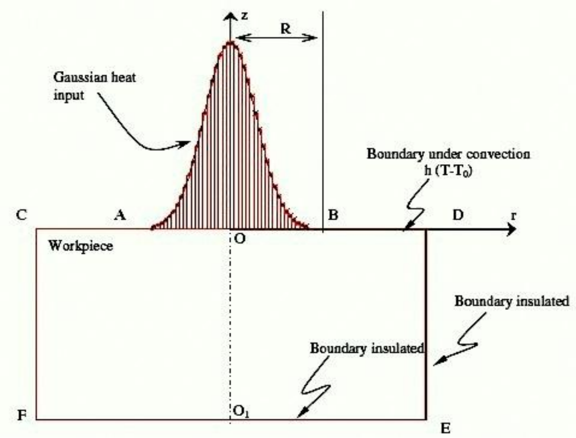

Figure 5. Boundary conditions adopted for the thermal analysis of EDM process

The In mathematical terms, the applied boundary conditions are represented by:

$k\frac{\partial T}{\partial z} = Q(r)$ if $0 \leq r \leq R$ on OD

$k\frac{\partial T}{\partial z} = h(T-T_0)$ if $r > R$ on OD

$T(t=0) = T_0$

Where,Q(r) is the heat flux applied to the work piece, h is the heat transfer coefficient for the dielectric fluid. K is thermal conductivity constant, T_0 is the dielectric temperature at the beginning of the EDM process, R is the spark radius.

Using these variables in Table 2 and Eq. (7), the heat flux values were calculated for different process settings. These calculated heat fluxes were used in transient thermal analysis as a thermal loading.

Table 2. Process parameters used for simulation study

Parameters	Values, unit
Discharge voltage, V	80 V
Current, I	10 A
Pulse on time, T_{on}	100 μs
Dielectric medium	Daphne oil
Film coefficient between dielectric oil and work piece, h	100000 W/m^2 K
Reference temperature, T_0	293 K
Spark radius, R	95.418 μm
Maximum heat flux to work piece, Q_0	23.39 GW/m^2

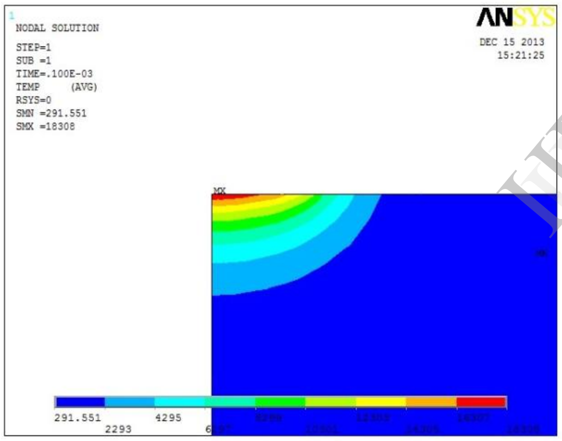

Figure 6. Temperature distribution on the workpiece (I_p = 10A & T_{on} = 100μs)

A shallow shape crater has been formed due to single spark, which is a cavity with a concave shape on the workpiece surface. The volume of the crater equals that of the removed material by the spark. The height and radius of a crater created by a single spark are 51 µm and 81 µm, respectively. It could be observed that the radius of the crater hemisphere formed in the radial direction is more than that of depth resulting in elliptical shape craters.

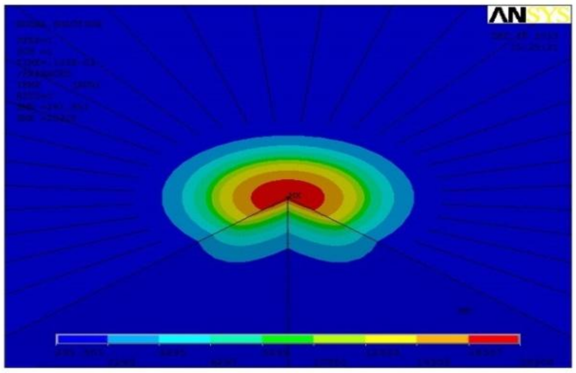

Figure 7. Schematic of temperature distribution of workpiece

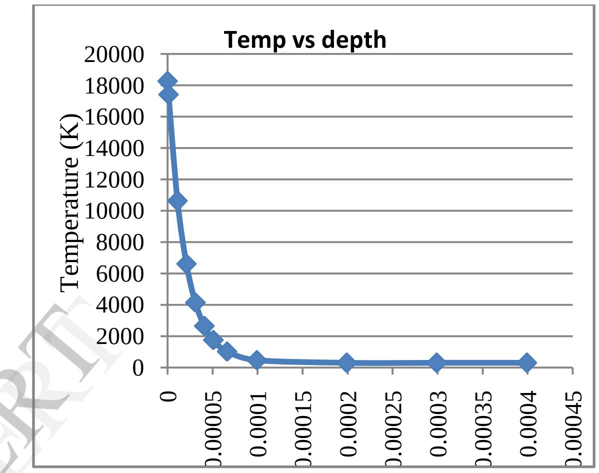

Figure 8. Temperature vs depth of the workpiece at I_p= 10A & T_{on} = 100μs

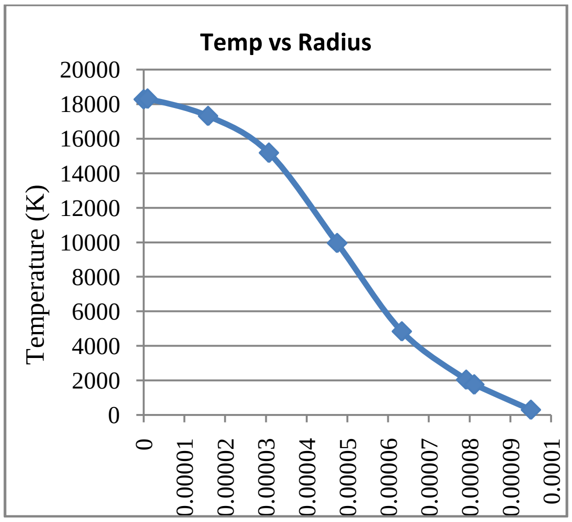

Figure 9. Temperature vs radius of the workpiece at I_p= 10A & T_{on} = 100μs

8. Conclusions

An axisymmetric model for AISI H13 tool steel was developed using ANSYS software to predict the temperature distribution. Finite element simulation and modeling were carried out for a single spark with temperature dependent material properties. The height and radius of a crater created by a single spark are 51 μm and 81 μm, respectively which results in elliptical shape crater. Our model has gone a step further than DiBitonto's model [2] due to real life conditions in the analysis. DiBitonto's model, in comparison, has approximated the spark as a point heat source on cathode which created hemispherical crater cavity.

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