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Finite Element Modeling of Tool Wear Rate in Electrical Discharge Machining

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Abstract

Electrical Discharge Machining (EDM) is now a well-known non-conventional machining technique. It has wide area of application in the field of tool and die making, medical tools, dental instruments, oil field production, space applications etc. In the present investigation, tool wear rate (TWR) modeling has been carried out using an axisymmetric model of Cu based tool during electrical discharge machining (EDM). A finite element model of single spark EDM was developed to calculate the temperature distribution in the tool. Further, TWR has been calculated for multi-discharge by calculating the number of pulses. Validation of model has been done by comparing the experimental results obtained under the same process parameters with the analytical results. A good agreement was found between the experimental results and the theoretical value.

Keywords- Electrical Discharge Machining, FEA, Metal Matrix Composites, Tool Wear Rate, Multi-Discharge.

Introduction

Electrical Discharge Machining is now a well-known non-conventional machining technique. Its principle is to use the eroding effect on the electrodes (tool as cathode and work as anode) of successive electric spark discharges created in a dielectric liquid. During the spark-on time, the high energy plasma melts both electrodes (tool and workpiece). However, more heat generates at the anode causing melting and vaporization of anode (Dibitono *et al*., 1989). A major part of melt from anode is flushed out with remaining melt being re-solidified during pulse off time owing to reduced plasma pressure. The amount of material removal from the both electrodes mainly depends upon the thermal diffusivity and dielectric constant.

The investigations had been reported for modeling of EDM. Snoey, Van Dijk (1971; 1972) used an electron emission theory for calculating the power distribution between cathode and anode. It was concluded that theoretical model should include the possibility of accounting for the plasma channel widening in order to obtain acceptable agreement with experimental data. Di Bitonto *et al*., (1989 a) presented a cathode erosion model considering heat source as point source. This model was built using less detailed information about its boundary condition of the growth rate of the plasma bubble. In the continuation of theoretical series Di Bitonto *et al*., (1989 b) presented an erosion model for anode material. Unlike cathode erosion model, the anode erosion model was built using more information about its boundary condition of the growth rate of the plasma bubble. Pandey, Jilani (1982; 1986) developed a

2D conduction heat transfer model, assuming disc heat source. They studied the effect of different EDM input parameters on metal removal crater shape. Dhar *et al*., (2007) developed a second order, non-linear mathematical model for establishing the relationship among machining parameters. Kanagarajan *et al*., (2008) also developed a statistical models based on second order polynomial equations for the optimization of different process characteristics, using non-dominated sorting genetic algorithm (NSGA-II). Witold *et al*., (2011) presented a FEA model to predict the thermal stresses induced during the cooling of Cr-Al_2O_3 composite processed by sintering. Mandal *et al*., (2011) developed a mathematical model using regression analysis to predict the wear behavior of the MMCs. The wear of MMC is much lesser in comparison with hardened; tempered AISI 4340 steel. Tamer, (2008) observed that the tool wear was higher at higher SiC_P reinforcement in Al-SiC composite. Machining of MMCs includes high wear rate due to abrasive particles present in the reinforcement. During the machining of MMC, matrix material melts before the reinforcement liberating reinforced particles between the tool and workpiece. These freed particles and debris causes wear due to abrasion to the tool electrode.

Literature reports extensive studies on various aspects of EDM process, but very less attention has been given to FEA modelling of EDM process to calculate tool wear rate. In the present investigation a FEA model has been developed, for single discharge EDM. Different aspects of machining have been considered like pulse-on time, pulse-off time, number of pulses, heat input etc. Further, the predicted results obtained from the model have been compared with the experimental results and co-efficient of correlation has been found between predicted and experimental results.

Thermal Model of EDM

Following assumptions are made in the present analysis to make problem mathematically feasible:

Assumptions

The tool domain is considered to be axisymmetric

The composition of tool material is homogeneous

The heat transfer mode in the tool is conduction

Inertia and body force effects are negligible during stress development

The initial temperature was set to room temperature

Analysis is done considering 100% flushing efficiency

Governing Equation

The governing heat transfer differential equation without internal heat generation written in a cylindrical coordinates of an axis symmetric thermal model for calculating the heat flux is given by Eq. (1) (Kumar, 2000).

$$\rho Cp\left[\frac{\partial T}{\partial t}\right]=\left[\frac{1}{r}\frac{\partial}{\partial r}\left(K_r\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(K\frac{\partial T}{\partial z}\right)\right] \qquad \ldots(1)$$

Where, ρ is density, C_P is specific heat, K is thermal conductivity of the workpiece, T is temperature, t is the time and r& z are coordinates of the tool

Heat Distribution

Plasma channel incident on the workpiece surface causes the temperature to rise in the workpiece. The distribution of plasma channel can be assumed as uniform disk source (Kunieda *et al*., 1997; Luo, 1997; Furutani *et al*., 2001; Chen et al., 2003) or Gaussian heat distribution (Di bitono *et al*., 1989; Bhattacharya *et al.*, 1996; Yadav *et al.,* 2002), for EDM. Heat generated on the anode is grater then the heat generated at the cathode. Gaussian distribution of heat flux is more realistic and accurate than disc heat source. Fig. 1 shows the schematic diagram of thermal model with the applied boundary conditions.

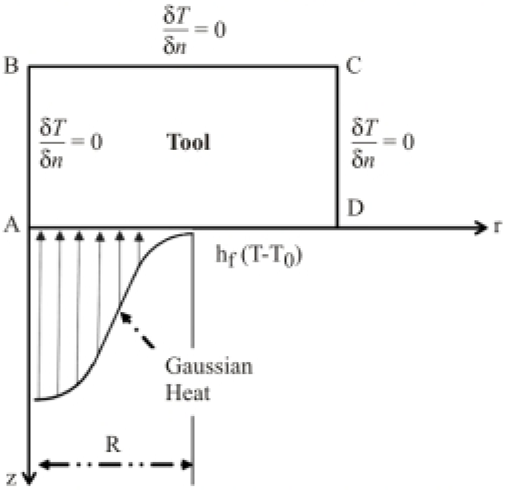

Figure : Axisymmetric model of tool in EDM process

Boundary Conditions

The tool domain is considered to be axisymmetric about z axis. It is clearly evident from the Fig. 1 that the maximum heat will generate at the point A.

On the bottom surface (AD), the heat transferred to the tool is consist of two part up to spark radius Gaussian heat flux will be applied and beyond that convection takes place between the tool and dielectric. There will be no heat transfer at surface AB, BC and CD.

In mathematical terms,

$$K \frac{\partial T}{\partial Z} = Q(r), \text{when R} < \text{r for boundary AD}$$

$$K \frac{\partial T}{\partial Z} = h_f (T - T_0), \text{ when R} \geq \text{r for boundary AD}$$

$$\frac{\partial T}{\partial n} = 0, \text{ at boundary AB, BC \& CD.}$$

where, h_f is heat transfer coefficient of dielectric fluid, Q(r) is heat flux due to the spark and T_0 is the initial temperature.

Material Properties

The tool material is copper of 6 mm diameter. Material properties are given in Table 1.

Table 1: Thermal Properties of Pure Copper	
Thermal Conductivity	367 W/mK
Specific Heat, C_p	438J/kgK
Density, ρ	8640 Kg/m^3
Melting Temperature	1356K

Heat Flux

A Gaussian distribution for heat flux (Yadav *et al*., 2002) is assumed in present analysis.

$$Q(r) = \frac{4.45\,PVI}{\pi R^2} exp\left\{-4.5\left(\frac{r}{R}\right)^2\right\} \quad \ldots(2)$$

where, P is the fraction of heat input to the tool, V is the discharge voltage, I is the current and R is the spark radius. Earlier many researchers have assumed that there is no heat loss between the tool and the workpiece. Dibitono *et al*., (1989) predicted that about 8% of the total heat supplied is absorbed by anode; about 18% is absorbed by cathode and the rest is discharged to the dielectric fluid. Yadav *et al*., (2002) have done experiment on conventional EDM and calculated the value of heat input to the workpiece to be 0.08. Shankar *et al*., (1997) calculated the value of P about 0.4-0.5 using water as dielectric.

Spark Radius

During the spark-on time the size of plasma does not remain constant but it grows with time (Dibitono and Eubank, 1989), mainly depends upon electrode material and polarity. Due to absorption of the electrons spark radius at the anode is much larger as compare to cathode, where electrons emission takes place. In present analysis cathode radius is taken a much smaller value of 5µm.

Tool Wear Rate Calculation

Tool wear rate prediction depends upon the crater morphology. The morphology of crater is assumed to be spherical shape. The volume of crater can be calculated by using Eq. (3).

$$C_v = \frac{2}{3}\pi r^3 \quad \ldots(3)$$

For multi-discharge the tool wear can be calculated using number of pulses (NOP), given by Eq. (4).

$$NOP = \frac{T_{mach}}{T_{on} + T_{off}} \quad \ldots(4)$$

Where, T_{mach} is the machining time, T_{on} is pulse-on time and T_{off} is pulse-off time. Knowing the C_v and NOP one can easily derive the TWR for multi-discharge by using Eq. (5).

$$MRR = \frac{C_v \times NOP}{T_{mach}} \quad \ldots(5)$$

Results and discussion

Results have been obtained for single spark and the temperature distribution is shown in Fig. 2. Fig. 2 shows only a part of the tool, where the temperature variation is actually visible. The dimension of the tool taken for modeling is 1mm × 3mm. It is clearly evident from Fig. 2 that the maximum temperature occurs at the center line. Table 2 shows the process parameter used for present model.

Table 2: Process Parameters Used to Simulate the Tool Wear in EDM Process (Dvivedi *et al*., 2009)

Properties	**Value**
Voltage (V)	60 V
Initial temperature (T0)	298 K
Co-efficient of heat transfer of dielectric fluid (hf)	10000 W/m2K
Spark radius (R)	5 µm

Fig 3 shows the FEA model after tool wear. Those elements were killed whose temperature rose above the melting point of the material. Fig. 4 shows 2D expanded model at the end of the pulse-on time.

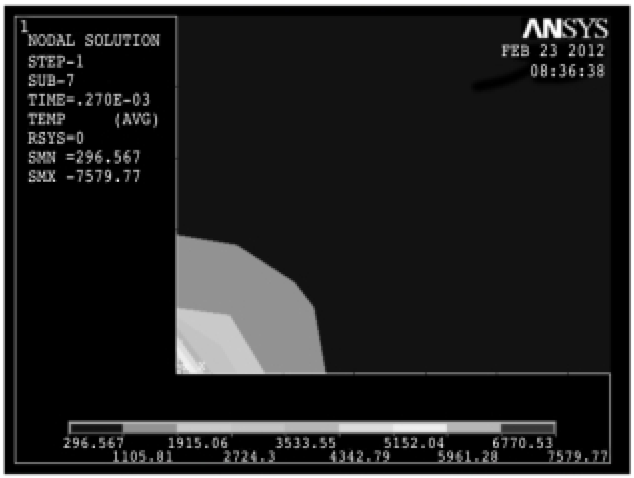

Figure 2 : Temperature distribution in copper tool at I = 27A, T_{on} =270μs.

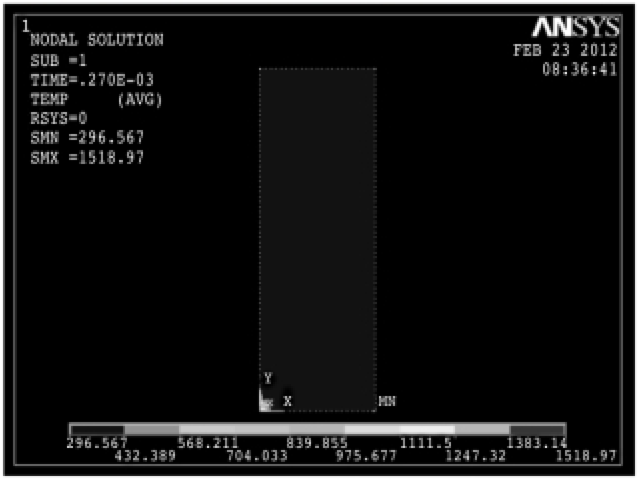

Figure 3 : FEA model after tool wear

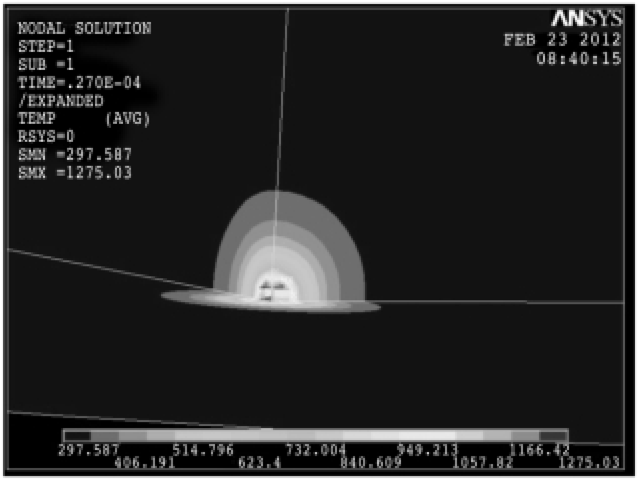

Figure 4 : 2D Expanded model at the end of the pulse-on time

Model validation

Model validation has been done by comparing the predicted TWR with the experimental results (Dvivedi *et al*., 2009). Fig. 5 shows the comparison between theoretical MRR and experimental values. The predicted TWR shows a coefficient of correlation of 86.61% with the experimental TWR. The predicted values are coming larger as compare to experimental value; this could possibly be due to some simplifying assumptions taken in the present FEA model like 100% flushing efficiency, no deposition of recast layer, etc. It is well known that the melted material is not fully flushed from the crater; a considerable amount of melted material again solidifies in the crater and forms the recast layer. Adhesive property of molten metal also caused problem in material removal. However, it is very difficult to model and incorporate all these effects in the analytical model. The results reported in present analysis shows that the trends of the predicted results and experimental results are almost same.

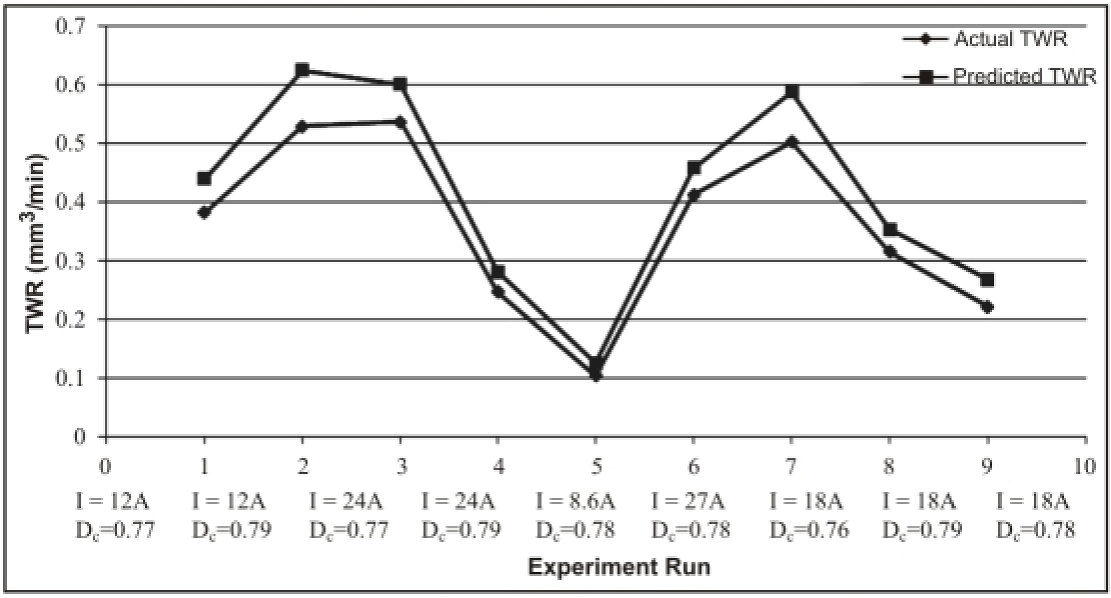

Figure 5 : Comparison of actual value and predicted value

Conclusion

In the present investigation an FEA model has been developed to predict tool wear. TWR will be less for the lower value of current. The effect of current is different for tool wear rate and material removal rate. Optimal value of pulse-on and pulse-off time can also leads to a lower TWR. The developed FEA model shows a good agreement between the experimental result and predicted values.

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