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Review Article

A COMPARISON STUDY OF MATERIAL REMOVAL RATE IN ELECTRICAL DISCHARGE MACHINING PROCESS BY USING FINITE ELEMENT ANALYSIS AND EXPERIMENT

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ARTICLE INFO **ABSTRACT**

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Generally the non-convectional machining processes use thermal source of energy for the material removal. Among them Electrical discharge machining (EDM) or spark erosion machining is most important one. The important process parameters in this technique are discharge pulse on time, discharge pulse off time current and gap voltage. The values of these parameters significantly affect such machining outputs as material removal rate. In the present research, an axisymmetric thermo-physical finite element model for the simulation of single sparks machining during electrical discharge machining (EDM) process is exhibited and the model has been solved by using ANSYS 11.0 software. A transient thermal analysis assuming a Gaussian distribution heat source with temperature-dependent material properties has been used to investigate the temperature distribution on the surface. Material removal rate was calculated for multi-discharge machining by taking into considerations the number of pulses. Comparison of the theoretical result and experimental result by considering the same process parameters has been done, and the result is highly agreed between the experimental and theoretical value.

INTRODUCTION

EDM is among the earliest and the most popular non-conventional machining process with extensively and effectively used in a wide range of industries such as die and mould-making, aerospace, automotive, medical, micromechanics, etc (Ho, 2003; Das *et al*., 2003). The high-density thermal energy discharge creates during machining causes the local temperature in the work piece gets close to the vaporization temperature of the work piece, leads to the thermal erosion. EDM is a very complex process (Schumacher, 2004), involving several disciplines of science and branches of engineering it combines several phenomena, but excluding very tiny discharges, it can be considered with small error that the thermal effect takes over (Hargrove and Ding, 2007), (Salah *et al*., 2006).

An ionised narrow path is created between two electrodes i.e., work piece (anode) and tool (cathode) when the potential difference is maintained. Resulting repetitive sparks which causes intense local heating of the work piece, thus melting and evaporation of material takes place. The theory is still under research for changes of material properties in micro levels and metallurgical transformation due to the high thermal energy. The thermal problem to be solved so as to model an EDM discharge is fundamentally a heat transmission problem in which the heat input is representing the electric spark. By solving this thermal problem yields the temperature distribution inside the workpiece, from which the shape of the generated craters can be estimated. (Bitonto *et al*., 1989; Patel *et al*., 1989).

For solving these numerical models finite-element method or the finite-differences method are normally used with single spark analysis (Erden *et al*., 1995; Yadav *et al*., 2008) investigated the thermal stress generated in EDM of Cr die steel. The influence of different process variables on temperature distribution and thermal stress distribution has been reported. The thermal stresses exceed the yield strength of the work piece mostly in an extremely thin zone near the spark. Salah and Ghanem *et al*. (Salah *et al*., 2006) presented temperature distribution in EDM process and from these thermal results, MRR and roughness are inferred and compared with experimental explanation. Using ANSYS software for this EDM process a Finite Element Model is developed in the present work.

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The mathematical model of EDM process is developed by taking thermal energy parameters as various heat transfer modes, latent heat associated with the material melting and evaporating, the discharge energy percentage that transfer to the material, the radius of plasma channel and thermal properties of En-19steel.

Basing upon discharge and duration of spark Gaussian distribution of heat flux are considered for calculation of MRR. The effect of machining parameters on temperature distribution, which is the deciding factor of MRR was investigated in the present study.

Thermal model of edm

Description of the Model

In this process, electrodes are submerged in dielectric and they are physically separated by a gap, called inter-electrode gap. It can be moulded as the heating of the work electrode by the incident plasma channel. Fig.1 shows the idealized case where work piece is being heated by a heat source with Gaussian distribution.

Due to axisymmetric nature of the heat transfer in the electrode and the work piece, a two-dimensional physical model is assumed. The various assumptions made to simplify the random and complex nature of EDM and as it simultaneously interact with the thermal, mechanical, chemical, electromagnetism phenomena.

Assumptions

a. The work piece domain is considered to be axisymmetric.
b. The work piece material is quasihomogeneous in composition.
c. Conduction is the mode of heat transfer to the work piece.
d. Effect of body force and inertia in the time of stress development is considered to be negligible.
e. The work piece material is perfectly plastic.
f. Flushing efficiency is considered to be 100%.
g. Before machining the work piece is assumed to be stress-free.
h. On the projected surface of the work piece, Gaussian distribution of heat flux is taken for the input heat source.

Governing Equation

Considering the axisymmetric model the differential equation in conduction mode of heat transfer neglecting internal heat generation for cylindrical co-ordinate system can be given by Eq. (1).

$$\rho C_p\left[\frac{\partial T}{\partial t}\right]=\left[\frac{1}{r}\frac{\partial}{\partial r}\left(K_r\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial Z}\left(K\frac{\partial T}{\partial Z}\right)\right] \tag{1}$$

Where ρ is density, Cp is specific heat, K is thermal conductivity of the work piece, T is temperature, t is the time and r& z are coordinates of the work piece.

Heat Distribution

The spark generated between the electrodes creates a plasma channel, which resulting the temperature rise on the work piece surface.

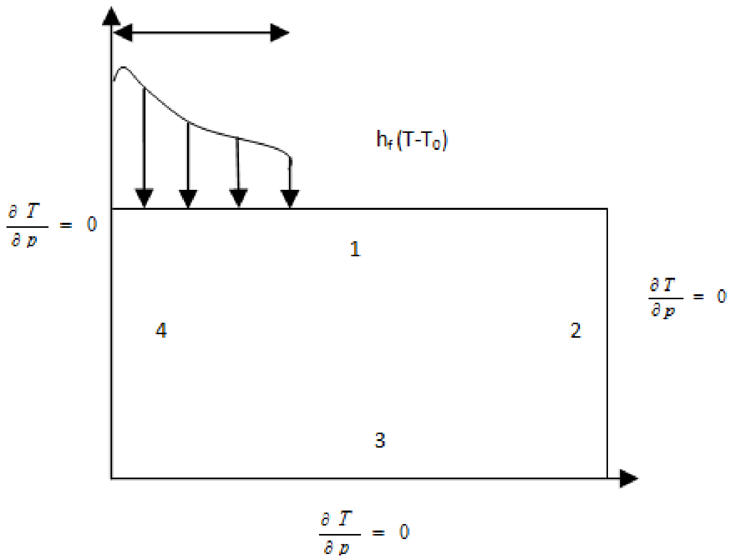

Fig. 1. Axisymmetric boundary conditions

For EDM process the plasma distribution on the work piece surface can be assumed either as uniform disk source (Kunieda and Yanatori, 1997)-(Tzeng and Fu-chen, 2003) or Gaussian heat distribution (Bitonto *et al*., 1989)-(Yadav *et al*., 2008), (Eubank and Patel, 1993), (Bhattacharya *et al*., 1996).

For the present analysis Gaussian distribution of heat flux is assumed on the work piece surface since it is more realistic and accurate than the uniform disc heat source (Eubank and Patel, 1993). A schematic diagram of thermal model with the boundary conditions is shown in the Fig. 1.

Boundary Conditions

Since the model is axisymmetric in nature therefore one half of the work piece is considered for analysis. The work piece domain along with applied boundary conditions is shown in Fig. 1. A Gaussian distribution of heat flux is applied on the work piece surface and the flux is applied on boundary 1 up to spark radius R same as of the electrode diameter.

A convection mode of heat transfer takes place due to dielectric fluids on the top surface beyond the distance R. The effect of heat transfer is considered to be negligible on the surfaces 2 & 3 since they are far from the spark location. For boundary 4, heat transfer is zero since an axis of symmetry model is assumed. Applied boundary conditions in mathematical term are given below:

$$K\frac{\partial T}{\partial Z} = Q(r), \text{ when } R< r \text{ for boundary 1} \quad (2)$$

$$K\frac{\partial T}{\partial Z} = h_f\left(T - T_0\right), \text{ when } R \geq r \text{ for boundary 1} \quad (3)$$

$$K\frac{\partial T}{\partial n} = 0, \text{ at boundary 2, 3 \& 4} \quad (4)$$

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.

Heat flux

A Gaussian distribution for heat flux (9) is assumed in present analysis.

$$Q(r) = \frac{4.45PVI}{\pi R^2}\exp\left\{-4.5\left(\frac{r}{R}\right)^2\right\} \quad (5)$$

Where P represents percentage of heat induced in the workpiece, V represents the gap voltage, I represent current and R represents the radius of the spark. Although earlier research based on assuming there is no heat loss between the tool and the workpiece but Yadav *et al*. (2008) calculated the value of heat input as 0.08 for conventional EDM and. Shankar *et al*. (Shankar *et al*., 1997) calculated the value of P about 0.4-0.5 when water is used as dielectric.

Experimental setup and results

The EDM Machine, model ELECTRONICA- EMS5535IPS50, specification: X-300*Y-200*Z-250, maximum capacity: 300 Kg and positive. The tool is taken as positive polarity (anode) and the workpiece is taken as negative (cathode) polarity. The dielectric used during the EDM process was paraffin.

The parameters those are considered to carry out the experiment are current, spark gap voltage, and pulse on time and electrode diameter. Sensitivity parameter was kept constant and this parameter is not used during the entire experiment. Fig.2 shows the EDM machine used for the experiment.

The electrode made up of copper was machined in cylindrical shape on a lathe machine and brazed with mild steel. Diameter of the electrode was 10 mm and thickness 40mm. The work piece material is En-19 side 15 x 15 mm^2 with thickness 10 mm. All surfaces were ground finished. The initial weight of the work piece material was measured. Fig.3 shows work piece material after the machining operation.

Table I . Chemical composition of en-19

Elements	Composition (wt. in %)
C	0.035 – 0.045
Si	0.1 – 0.35
Mn	0.5 – 0.8
Cr	0.9 – 1.5
Mo	0.2 – 0.4

Fig. 2. Experimental Setup

Fig. 3. Workpiece after machining

Table 2. Experimental data of mrr

Current in Amp	Gap Voltage in Volt	Pulse on time in μs	Electrode diameter in mm	MRR in m^3/min
6	6	500	14	0.0144
6	8	1000	16	0.0224
6	9	2000	18	0.08445
7	6	1000	18	0.0245
7	8	2000	14	0.0444
7	9	500	16	0.031
9	6	2000	16	0.0421
9	8	500	18	0.0413
9	9	1000	14	0.04351

Finite element simulation

Material Properties for FEA

Table 3. Material property of electrode and workpiece material at room temperature

Material Property	Copper (Cathode)	En- 19 (Anode)
Density (gm/mm^3)	8290 x 10^{-6}	7700 x 10^{-6}
Conductivity (W/mmK)	400 x 10^{-3}	222 x 10^{-12}
Resistivity (Ω-mm)	1.7 x 10^{-11}	22.2 x 10^{-11}
Specific heat (J/gK)	385 x 10^{-3}	473 x 10^{-3}

Solution of Thermal Model

For the solution of the model of the EDM process commercial ANSYS 11.0 software was used. An axisymmetric model was created. A non-uniformly quadrilateral distributed finite element mesh with elements mapped towards the heat-affected regions was meshed, with a total number of 2640 elements and 2734 nodes with the size of the smallest element is of the order of 0.0015 × 0.0015 cm. The approximate temperature-dependent material properties of En-19 tool steel, which are given to ANSYS modeller, are taken from (Rajan and Sharma, 2001). The governing equation with boundary conditions mentioned above is solved by finite element method to predict the temperature distribution and thermal stress with the heat flux at the spark location and the discharge duration as the total time step. First, the whole domain is considered to obtain the temperature profile during the heating cycle. The temperature profile just after the heating period is shown in Fig.3, which depicts four distinct regions signifying the state of the workpiece. Fig.4 and 5 shows typical temperature contour for En-19 steel under machining conditions.

Sample calculation for MRR from simulation result

The dome shaped crater formed on the workpiece after material removal is assumed to be spherical shape.
Where r is the radius of spherical dome and h is depth of dome.

From geometry:

h = 0.004 m
r = 0.008 m

The volume of material removal is calculated by calculating the volume of the dome (C_v).

$$C_v = \frac{1}{6}\pi h\left(3r^2 + h^2\right) = 0.000000435552 \text{ m}^3$$

For multi discharge machining process the number of Pulse (NOP) during machining is calculated by dividing the total time of machining of the workpiece to pulse duration time.

$$\text{NOP} = \frac{T_{mach}}{T_{on} + T_{off}} = \frac{20 \times 60}{1000 \times 10^{-3}} = 1200000$$

Where T_{mach} is the machining time, T_{on} is pulse-on time and T_{off} is pulse-off time.

For multi-discharge machining the MRR is calculated as:

$$\text{MRR} = \frac{C_v \times NOP}{T_{mach}}$$

$$= \frac{0.00000043\,5552 \times 1200000}{20} = 0.0261 \text{ m}^3/\text{min}$$

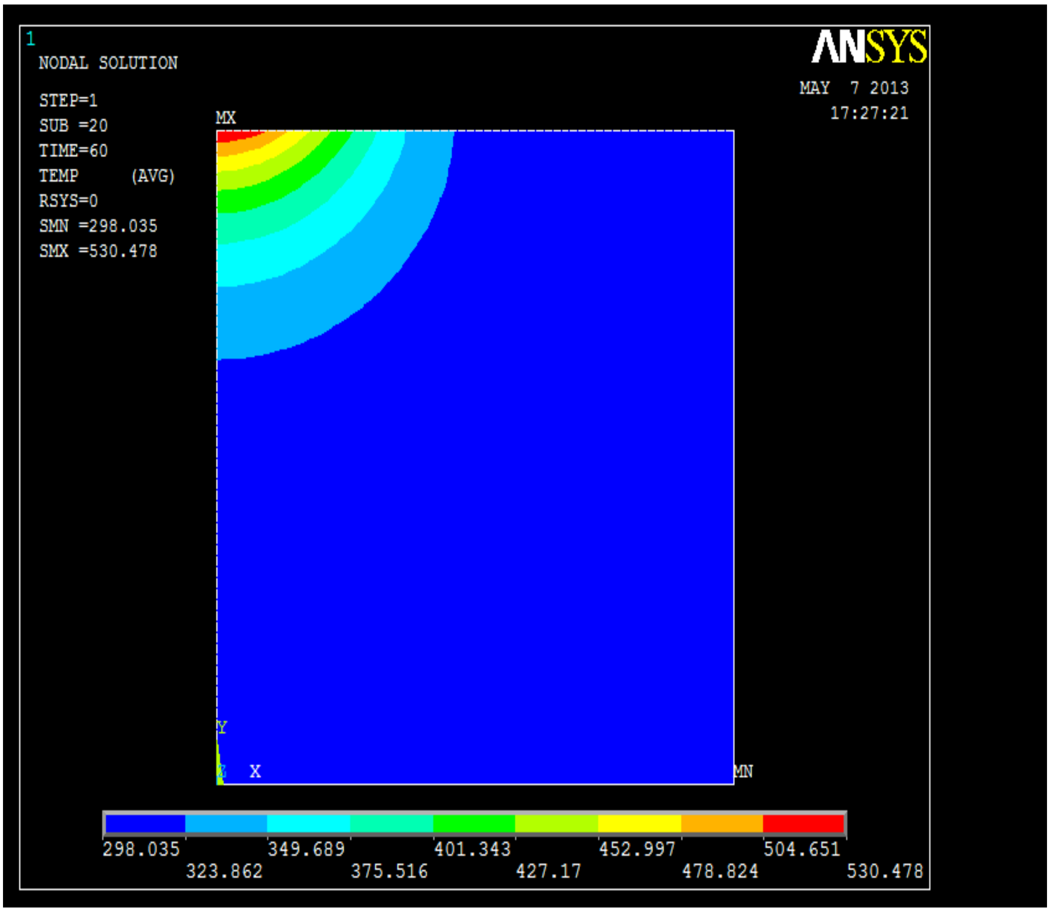

Fig.4. Temperature Profile

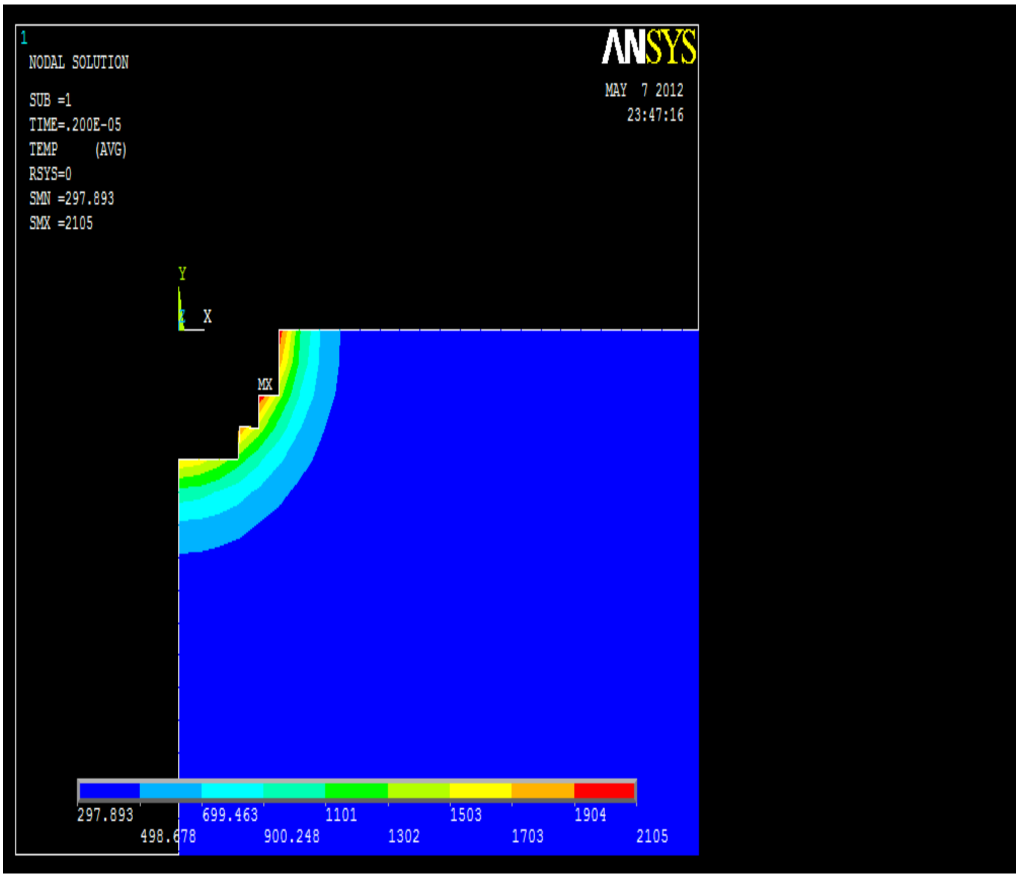

Fig.5. Profile after Melting of Material

Table 4. Experimental data of MRR

Current in Amp	Gap Voltage in Volt	Pulse on time in μs	Electrode diameter in mm	MRR in m^3/min (expt.)	MRR in m^3/min (FEM)
6	6	500	14	0.0145	0.01582
6	8	1000	16	0.022	0.0262
6	9	2000	18	0.0845	0.056
7	6	1000	18	0.0245	0.02745
7	8	2000	14	0.044	0.05069
7	9	500	16	0.03	0.02249
9	6	2000	16	0.042	0.049
9	8	500	18	0.0413	0.03569
9	9	1000	14	0.0435	0.0392

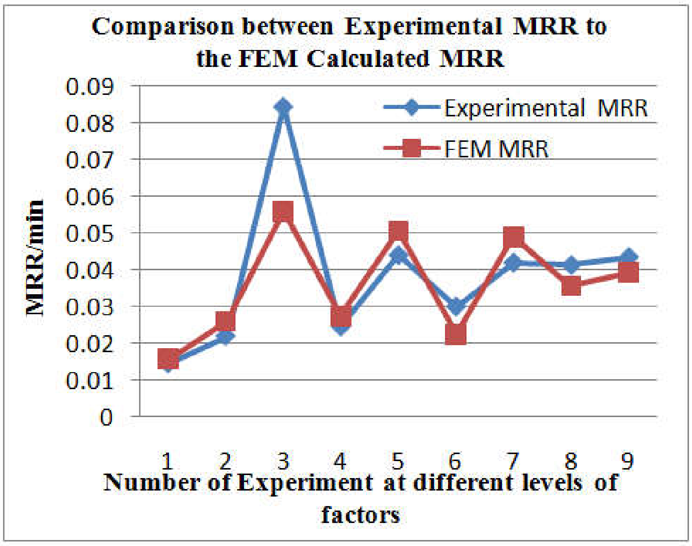

Fig.6. Comparisons between Experimental MRR to the FEM Calculated MRR

RESULTS AND DISCUSSION

Taking En-19 as workpiece material with single spark the results have been obtained. According to Gaussian distribution of heat flux, the heat flux is maximum at the center line, on the top surface of the workpiece. Temperature distribution in the workpiece has been shown in Fig. 4. From the simulation result it is clear evident that at the center line, on the top surface of the workpiece highest temperature generates. The high temperature rises during the spark on time can easily melt the material and formed a dome in the work piece. This is evident from the temperature distribution after material removal in FEA model as shown in Fig. 5. The volume of metal remove depends on amount of heat energy induced in the material. Therefore the MRR increase in both increase in current and voltage. Fig.6 shows the graphical representation of MRR obtained in FEM model and experimentally. Out of nine no of experiment eight experimental result are almost equal to the predicted MRR obtained by FEM model.

Conclusion

In the present work prediction of material removal(MRR) has been found out by developing an axisymmetric thermal model for spark machining process. For developing such model various important process parameters are taken into account such as pulse on/off time, material properties, shape and size of heat source and heat energy given as input to the work piece. The temperature distribution and its impact on Material removal rate has studied by developing by FEA based model. The model is highly validated as the MRR values obtained by FEA model are in good agreement with the experimental results. Further study can be carried out for finding the residual stress distribution, thermal stress distribution in reinforcement particle bursting phenomenon.

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