Finite Element Modeling and Thermal Stress Analysis of Copper and Graphite Electrode in EDM Machining

Balwan Singh¹ Dr. Sanjeev Kumar²
¹Master Scholar ²Associate Professor
¹,²Department of Mechanical Engineering
¹,²PEC University of Technology, Chandigarh

Abstract— EDM is a non-conventional method of machining in which material removal takes place due to strong electric field generated in the tool workpiece gap causing plasma arc to generate. High temperature zone is concentrated at spark zone radius due to which thermal stress is generated at tool electrode and workpiece. If this thermal stress increases to the yield stress value of material, it creates various problems like micro-cracks and catastrophic failure etc. In this study Graphite and copper electrodes are chosen for the analysis of temperature distribution and thermal stresses generated due to this high temperature zone. And analysis is done on ANSYS 15.0.

Key words: Wireless Sensor Network, Energy Conservation, LEACH, TEEN, APTEEN, PEGASIS, DEEC, DDEEC, HEED, BEENISH, cluster head etc

I. INTRODUCTION

With rapid development in the field of materials, it has become essential to develop cutting tool materials and processes which can safely and conveniently machine such new materials. Besides this industries face problems in manufacturing of components because of several reasons such as the complexity of the job profile or may be due to surface requirements with higher accuracy and surface finish. Consequently, non-traditional techniques of machining are providing effective solutions for the problems raised by the increasing demand for high strength temperature resistant alloys, parts with intricate and compacted shapes and materials so hard which are difficult to machine by conventional methods. As there is no direct contact between the tool and the work piece in the non-conventional machining; hence the tool need not be harder than the job. Today after the huge technical advancements, the conventional machining processes can’t produce complex geometrical shapes in the hard and temperature resistant alloys and die steels effectively.

Batish et al. [2012a] studied material transfer mechanism in die steels using PMEDM. They investigated the effect of process parameters and mechanism of material deposition in PMEDM on surface properties of EN31, H11, and High Carbon High Chromium (HCHCr) die steel materials.

Das et al. [2003] developed a finite element-based model for the sinking-EDM which uses process parameters such as power input, pulse duration, etc., to predict the transient temperature distribution, liquid- and solid-state material transformation, and residual stresses induced in the work piece as a result of a single-pulse discharge. This model was able to predict the shape of the crater that is formed as a result of the material removal.

Marafona and Chousal [2006] developed a thermal-electric model for spark generated by electric discharge machining in a liquid media. Shape used was cylindrical for the discharge channel between electrodes. It was certified that discharge channel being electrical conductor will dissipate heat, which can be explained by Joule heating effect.

Joshi and Pande [2010] carried out numerical analysis of the single spark operation of EDM process considering the two-dimensional axis-symmetric continuum. The analysis was based on Gaussian distribution of heat flux.

The heat equation entering the workpiece due to EDM spark was taken as

\[ q(r) = q_0 e^{-4.5(r/l)^2} \]

Further maximum heat flux was calculated as

\[ q_0 = \frac{4.57 F_{cw} V I}{\pi R^2} \]

B. Izquierdo et al (2008) In this paper a new contribution to the simulation and modeling of the EDM process is presented. Temperature fields within the work piece generated by the superposition of multiple discharges, as it happens during an actual EDM operation, are numerically calculated using a finite difference schema.

Panda (2008) developed a finite element model to estimate steep temperature gradient induces thermal stresses, which can cause a network of micro cracks, damaging the electro-discharge machined surface. In this context, review of different models reveals few limitations concerning too many assumptions and too simplified boundary conditions. Considering the limitations of the earlier models, the close form solution of three-dimensional heat conduction transient is used as forcing function to obtain the mathematical expression of thermal stresses.

C.H. Che Haron (2008) In this paper the machining characteristics were investigated when machining XW42 tool steel at two current settings (3 A and 6 A), three diameter sizes (10, 15 and 20 mm) and kerosene as the dielectric. The results show that the material removal rate is higher and the relative electrode wear ratio is lower with copper electrode than graphite electrode. The increase in the current and electrode diameter reduced tool wear rate as well as the material removal rate.

Harmander Singh (2012), the author experimentally calculated the distribution of input discharge energy during EDM, using heat transfer equations. The results obtained especially of fraction of energy transferred to the workpiece (Fw) for different machining parameters are in good concurrence with the results obtained by other authors for the effect of Fcw, i.e., MRR, for same combination of electrodes.

Vinod Yadav et al. [2002] developed a finite element model to estimate the temperature field and thermal stresses due to Gaussian distributed heat flux of a spark. Developed code calculated the temperature in the work...
piece and then the thermal stress field was estimated using this temperature field. The effects of various process variables (current and duty cycle) on temperature distribution and thermal stress distribution had been reported.

In this study, Gaussian distribution of heat flux is consider In the present work, a model, to represent thermal stress due to EDM, has been developed based on the finite element technique. The principal aim of developing this model is to predict the nature of thermal stresses occurring in electrode during EDM machining. The electrode taken for the study are graphite and copper electrodes. And analysis is done on ANSYS 15.0.

II. PROBLEM FORMULATION

A. Assumption:
- Model is developed using single spark study.
- Material is considered as homogeneous and isotropic.
- Gaussian distribution of heat flux is used as a heat source.
- Transient thermal analysis has been considered.
- Condition of zero initial stress is considered.
- Convection is taken beyond the spark radius ‘R’ on the top surface.

B. Mechanical and thermal properties of the Electrodes

<table>
<thead>
<tr>
<th>Properties</th>
<th>Copper</th>
<th>Graphite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>8930</td>
<td>1831</td>
</tr>
<tr>
<td>Modulus of elasticity (MPa)</td>
<td>110000</td>
<td>11032</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.364</td>
<td>0.195</td>
</tr>
<tr>
<td>Coefficient of thermal expansion per°C (X 10^{-5})</td>
<td>1.64 (20°C)</td>
<td>0.839</td>
</tr>
<tr>
<td>Thermal conductivity (W/m °C)</td>
<td>398 (27°C)</td>
<td>357 (727°C)</td>
</tr>
<tr>
<td>Specific heat (J/kg °C)</td>
<td>385</td>
<td>1600</td>
</tr>
<tr>
<td>Melting Point °C</td>
<td>1083</td>
<td>3500</td>
</tr>
</tbody>
</table>

Table 1: Mechanical and thermal properties of the Electrodes

C. Dimensions of Electrode:
The finite element model of electrode is generated with ANSYS Workbench 15.0 version. The 3D axisymmetric model is developed. As mention earlier Cubical shape of electrode is used in this research work of size 0.6×0.6×0.4 mm.

D. Spark Radius
As Size of plasma channel is not constant but grows with time. Theoretical and experimental efforts have been made by some researchers to predict the spark radius. In present work spark radius is taken as 0.125 mm. Spark radius is varying from 5 μm to 125 μm and heat flux is given to these segments in such a way that will leads to consideration of spark intensity vary with radius. This is done for all 25 different steps.

E. Heat transfer to the electrode:
Patel et al. [1998] and DiBitonto et al. [1989] have predicted that for EDM process out of the total heat supplied only a fraction of heat transfer to the workpiece. They predict that 8% of the total heat goes to anode (i.e. work piece) and 18% to cathode (i.e. electrode) and remaining heat is lost in dielectric medium.

Xia et al [1996] has taken 40% of heat goes to anode and 25% heat goes to cathode. So in the present study, 25% of heat transfer to electrode is consider. And heat flux equation is taken

\[ Q_w(r) = \frac{4.57 P V I}{\pi R^2} e^{-4.95 \frac{R^2}{R^2}} \text{ (by joshi and pande)} \]

F. Parameters used in simulation of Electrodes

<table>
<thead>
<tr>
<th>Current</th>
<th>2, 4, 6 and 8 (Amp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>35 volt</td>
</tr>
<tr>
<td>F</td>
<td>0.25</td>
</tr>
<tr>
<td>T_{on}</td>
<td>100 μs</td>
</tr>
<tr>
<td>Spark radius</td>
<td>0.125 mm</td>
</tr>
<tr>
<td>T_o</td>
<td>25 °C</td>
</tr>
<tr>
<td>Tm (melting temperature)</td>
<td>Copper=1083°C and Graphite =3500 °C</td>
</tr>
<tr>
<td>Dielectric Fluid</td>
<td>Kerosene (convective heat transfer Coefficient 12000 W/m²-K)</td>
</tr>
</tbody>
</table>

Table 2: Parameters used in simulation of Electrodes

III. RESULTS AND DISCUSSIONS

After simulation, the following outputs are extracted and analyzed further:
- Temperature distribution electrodes along radial and depth direction
- Stresses induced into the electrode due to elevated temperatures.
  - Equivalent stresses variation with radial direction
  - Equivalent stresses variation with Depth.
  - Radial stresses
  - Tangential stresses
- Axial stresses in direction perpendicular to top surface at different radii.
- Axial stresses in direction perpendicular to top surface at different depth.

A. Temperature distribution along the radial direction for Copper and Graphite electrodes

Temperature distribution has been predicted for the pulse on time T_{on} =100μs, discharge Voltage V = 35 V, heat transfer factor for electrode F= 0.25 (by Xia et. al), current I= 2, 4, 6, 8 amp. Taking F=0.25 and varying current at that fixed heat transfer factor (F) and at pulse on time 100μs. The temperature distribution of copper electrode is shown below.

Fig. 1.1: Temperature distribution along the radial direction generated during simulation using T_{on} = 100μs, V = 35 Volt, F=0.25 and current I= 2, 4, 6, 8 amp for Copper electrode
Temperature distribution has been predicted for the pulse on time $T_{on}=100\mu$s, discharge Voltage $V = 35$ V, heat transfer factor for electrode $F=0.25$ (by Xia et. al), current $I= 2, 4, 6, 8$ amp. Taking $F=0.25$ and varying current at that fixed heat transfer factor ($F$) and at pulse on time $100\mu$s. The temperature distribution of graphite electrode is shown below.

Fig. 1.2: Temperature distribution along the radial direction generated during simulation using $T_{on} = 100\mu$s, $V = 35$ Volt, $F=0.25$ and current $I= 2, 4, 6,$ and $8$ amp for graphite electrode

It can clearly visible from the above figures 1.1 and 1.2, for same input parameters $T_{on}=100\mu$s, $V = 35$ Volt, $F=0.25$ and current $I= 2, 4, 6,$ and $8$ amp, the copper subjects to low temperature as compare to graphite electrode. So the wear rate of graphite is more than copper electrode and thermal stresses are also more in graphite electrode as compared with copper electrode.

B. Temperature distribution along the depth of Copper and Graphite electrodes

Temperature distribution has been predicted for the pulse on time $T_{on}=100\mu$s, discharge Voltage $V = 35$ V, heat transfer factor for electrode $F=0.25$ (by Xia et. al), current $I= 2, 4, 6,$ and $8$ amp. Taking $F=0.25$ and varying current at that fixed heat transfer factor ($F$) and at pulse on time $100\mu$s. The temperature distribution of graphite electrode is shown below.

Fig. 1.3: Temperature distribution along the depth generated during simulation using $T_{on} = 100\mu$s, $V = 35$ Volt, $F=0.25$ and current $I= 2, 4, 6,$ and $8$ amp for copper electrode

Temperature distribution has been predicted for the pulse on time $T_{on}=100\mu$s, discharge Voltage $V = 35$ V, heat transfer factor for electrode $F=0.25$ (by Xia et. al), current $I= 2, 4, 6,$ and $8$ amp. Taking $F=0.25$ and varying current at that fixed heat transfer factor ($F$) and at pulse on time $100\mu$s. The temperature distribution of graphite electrode is shown below.

Fig. 1.4: Temperature distribution along the depth generated during simulation using $T_{on} = 100\mu$s, $V = 35$ Volt, $F=0.25$ and current $I= 2, 4, 6,$ and $8$ amp for graphite electrode

It can clearly visible from the above figures 1.3 and 1.4, for same input parameters $T_{on}=100\mu$s, $V = 35$ Volt, $F=0.25$ and current $I= 2, 4, 6,$ and $8$ amp, the copper subjects to low temperature as compare to graphite electrode. So the wear rate of graphite is more than copper electrode and thermal stresses are also more in graphite electrode as compared with copper electrode.

Temperature at the top surface is maximum and starts decreasing while moving downwards from center of spark along the depth. It is noticed that temperature rises by increasing $I$.

C. Stresses induced in copper and Graphite Electrode

It is seen that very high temperatures are generated at the spark location. Due to this, high temperature region under spark tries to expand which is restricted by surrounding material. Because of this restriction of expansion of region, sufficient amount of stresses are generated in the electrode material. These induce thermal stresses within the heat affected zone (HAZ), which is the most potential zone of initiation of micro cracks. Microscopic studies reveal multilayered heat-affected zone including a hardened layer that possesses high brittleness, and reduced fatigue strength of the work-material.

To understand the effect of thermal stresses on electrode of EDM machining different simulations are done with variable parameters. Radial, Tangential and Axial stresses of components in electrode material have been calculated in static structure module as explained in Chapter 3. Equivalent Von-Mises stresses are also calculated in radial and axial direction. In detail each type of stresses are explained below.

D. Radial Stresses

To predict the radial stresses setup into copper electrode material, simulations are done using input parameters $T_{on}=100\mu$s, $V = 35$ Volt, $I= 2, 4, 6,$ and $8$ Amp, $F = 0.25$. Figure 1.5 gives the radial stresses generated in copper electrode. Different views of the 3D generated radial stresses are shown in Figure 1.5(a). Radial stress distribution for $T_{on}=100\mu$s, $V = 35$ Volt, $I= 8$ Amp, $F = 0.25$ is shown in figure 1.5, peak stress is at the centre with compressive nature and its maximum value is 2439.8 MPa.
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Fig. 1.5: Radial stress distribution along the radial direction generated during simulation using $T_{on} = 100\mu$s, $V = 35$ Volt, $F=0.25$, $I= 2, 4, 6, 8$ Amp for copper

To predict the radial stresses setup into graphite electrode material, simulations are done using input parameters $T_{on} = 100\mu$s, $V = 35$ Volt, $I= 2, 4, 6$ and 8 Amp, $F = 0.25$. Figure 1.6 gives the radial stresses generated in copper electrode. Different views of the 3D generated radial stresses are shown in Figure 1.6. Radial stress distribution for $T_{on} = 100\mu$s, $V = 35$ Volt, $I= 8$ Amp, $F = 0.25$ is shown in figure 1.6, peak stress is at the centre with compressive nature and its maximum value is 228.71 MPa.

(b)

Fig. 1.6: Radial stress distribution along the radial direction generated during simulation using $T_{on} = 100\mu$s, $V = 35$ Volt, $F=0.25$, $I= 2, 4, 6, 8$ Amp for graphite

Tangential Stress

To predict the tangential stresses setup into copper electrode material, simulations are done using input parameters $T_{on} = 100\mu$s, $V = 35$ Volt, $I= 2, 4, 6$ and 8 Amp, $F = 0.25$. Figure 1.7 gives the tangential stresses generated in copper electrode. Tangential stress distribution for $T_{on} = 100\mu$s, $V = 35$ Volt, $I= 2, 4, 6$ and 8 Amp, $F = 0.25$ is shown in figure 1.7.

Fig. 1.7: Tangential stress distribution along the radial direction generated during simulation using $T_{on} = 100\mu$s, $V = 35$ Volt, $F=0.25$, $I= 2, 4, 6, 8$ Amp for copper

To predict the tangential stresses setup into graphite electrode material, simulations are done using input parameters $T_{on} = 100\mu$s, $V = 35$ Volt, $I= 2, 4, 6$ and 8 Amp, $F = 0.25$. Figure 1.8 gives the tangential stresses generated in graphite electrode. Tangential stress distribution for $T_{on} = 100\mu$s, $V = 35$ Volt, $I= 2, 4, 6$ and 8 Amp, $F = 0.25$ is shown in figure 1.8.

Fig. 1.8: Tangential stress distribution along the radial direction generated during simulation using $T_{on} = 100\mu$s, $V = 35$ Volt, $F=0.25$, $I= 2, 4, 6, 8$ Amp for graphite
E. Axial Stresses along the radial distance

To predict the Axial stresses setup into copper electrode material, simulations are done using input parameters \( T_{\text{on}} = 100 \mu s \), \( V = 35 \text{ Volt} \), \( I = 2, 4, 6 \) and \( 8 \text{ Amp} \), \( F = 0.25 \). Figure 1.9 gives the axial stresses generated in copper electrode. Axial stress distribution for \( T_{\text{on}} = 100 \mu s \), \( V = 35 \text{ Volt} \), \( I = 2, 4, 6 \) and \( 8 \text{ Amp} \), \( F = 0.25 \) is shown in figure 1.9.

![Fig. 1.9: axial stress distribution along the radial direction generated during simulation using \( T_{\text{on}} = 100 \mu s \), \( V = 35 \text{ Volt} \), \( F = 0.25 \), \( I = 2, 4, 6, 8 \text{ Amp} \) for copper](image)

To predict the axial stresses setup into graphite electrode material, simulations are done using input parameters \( T_{\text{on}} = 100 \mu s \), \( V = 35 \text{ Volt} \), \( I = 2, 4, 6 \) and \( 8 \text{ Amp} \), \( F = 0.25 \). Figure 1.10 gives the axial stresses generated in graphite electrode. Axial stress distribution for \( T_{\text{on}} = 100 \mu s \), \( V = 35 \text{ Volt} \), \( I = 2, 4, 6, 8 \text{ Amp} \), \( F = 0.25 \) is shown in figure 1.10.

![Fig. 1.10: Axial stress distribution along the radial direction generated during simulation using \( T_{\text{on}} = 100 \mu s \), \( V = 35 \text{ Volt} \), \( F = 0.25 \), \( I = 2, 4, 6, 8 \text{ Amp} \) for graphite](image)

F. Axial Stresses along the depth

To predict the Axial stresses setup into copper electrode material, simulations are done using input parameters \( T_{\text{on}} = 100 \mu s \), \( V = 35 \text{ Volt} \), \( I = 2, 4, 6 \) and \( 8 \text{ Amp} \), \( F = 0.25 \). Figure 1.11 gives the axial stresses generated in copper electrode. Axial stress distribution along the depth for \( T_{\text{on}} = 100 \mu s \), \( V = 35 \text{ Volt} \), \( I = 2, 4, 6, 8 \text{ Amp} \), \( F = 0.25 \) is shown in figure 1.11.

![Fig. 1.11: axial stress distribution along the depth generated during simulation using \( T_{\text{on}} = 100 \mu s \), \( V = 35 \text{ Volt} \), \( F = 0.25 \), \( I = 2, 4, 6, 8 \text{ Amp} \) for copper](image)

To predict the axial stresses setup into graphite electrode material, simulations are done using input parameters \( T_{\text{on}} = 100 \mu s \), \( V = 35 \text{ Volt} \), \( I = 2, 4, 6 \) and \( 8 \text{ Amp} \), \( F = 0.25 \). Figure 1.12 gives the axial stresses generated in graphite electrode. Axial stress distribution along the depth for \( T_{\text{on}} = 100 \mu s \), \( V = 35 \text{ Volt} \), \( I = 2, 4, 6, 8 \text{ Amp} \), \( F = 0.25 \) is shown in figure 1.12.

![Fig. 1.12: Axial stress distribution along the depth generated during simulation using \( T_{\text{on}} = 100 \mu s \), \( V = 35 \text{ Volt} \), \( F = 0.25 \), \( I = 2, 4, 6, 8 \text{ Amp} \) for graphite](image)

G. Equivalent Stresses along the radial direction

To predict the equivalent stresses setup along the radial direction into copper electrode different simulations are done using input parameters \( T_{\text{on}} = 100 \mu s \), \( V = 35 \text{ Volt} \), \( I = 2, 4, 6 \) and \( 8 \text{ Amp} \), \( F = 0.25 \). Figure 1.13 gives the equivalent stresses generated in electrode. Different views of the 3D generated equivalent stresses are shown in Figure 1.13, which show us the variation of stress on top surface and along the depth of electrode. Equivalent stresses distribution for \( T_{\text{on}} = 100 \mu s \), \( V = 35 \text{ Volt} \), \( I = 8 \text{ Amp} \), \( F = 0.25 \) is shown in figure 1.13.

![Fig. 1.13: Equivalent stresses set up on copper electrode using input \( T_{\text{on}} = 100 \mu s \), \( V = 35 \text{ Volt} \), \( I = \text{8 Amp and } F = 0.25 \)](image)

Equivalent stresses along the radial direction have been calculated using Input parameters \( V = 35 \text{ Volt} \), \( I = 2, 4, 6 \) and \( 8 \text{ Amp} \), \( F = 0.25 \), \( T_{\text{on}} = 100 \mu s \), stress variation is shown in figure 1.14. Equivalent stress variation in radial direction for copper electrode is shown with varied current in Figure 1.14.
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Fig. 1.14: Equivalent stress distribution along the radial direction generated during simulation using $T_{on} = 100\mu s$, $V = 35$ Volt, $F=0.25$, $I= 2, 4, 6,$ and $8$ Amp for copper electrode

It can be inferred from above figure the equivalent stress of copper electrode is less at low current i.e $I=2$A and equivalent stress of electrode increases as current increases the dark line shows the yield point of copper electrode .So with increase in current value the wear rate of electrode increases.

To predict the equivalent stresses setup along the radial direction into graphite electrode different simulations are done using input parameters $T_{on}=100\mu s$, $V = 35$ Volt, $I= 2, 4, 6$ and $8$ Amp, $F = 0.25$. Figure 1.15 gives the equivalent stresses generated in electrode. Different views of the 3D generated equivalent stresses are shown in Figure 1.15, which show us the variation of stress on top surface and along the depth of electrode. Equivalent stresses distribution for $T_{on}=100\mu s$, $V = 35$ Volt, $I= 8$ Amp, $F = 0.25$ is shown in figure 1.15.

Fig. 1.15: Equivalent stresses set up on graphite electrode using input $T_{on} =100\mu s$, $V = 35$ Volt, $I = 8$ Amp and $F = 0.25$

Equivalent stresses along the radial direction have been calculated using Input parameters $V = 35$ Volt, $I= 2, 4, 6$ and $8$ Amp, $F = 0.25$, $T_{on} = 100\mu s$, stress variation is shown in figure 1.16. Equivalent stress variation in radial direction for graphite electrode is shown with varied current in Figure 1.16.

Fig. 1.16: Equivalent stress distribution along the radial direction generated during simulation using $T_{on} = 100\mu s$, $V = 35$ Volt, $F=0.25$, $I= 2, 4, 6,$ and $8$ Amp for graphite electrode

It can be inferred from above figure the equivalent stress of graphite electrode is less at low current and equivalent stress of electrode increases as current increases the dark line shows the ultimate point of graphite electrode .So with increase in current value the wear rate of electrode increases.

IV. CONCLUSION

A. Temperature Distribution
- It is observed that temperature distribution in electrode material is maximum at center of the region under spark and it decreases towards radial as well as axial direction following Gaussian distribution.
- Temperature sharply decreases in depth direction as compared to radial direction so depth of crater is much less as compared to radius of crater.
- Temperature is directly proportional to discharge current, pulse on time and heat transfer factor F, temperature increases with increase in all of these parameters. It is also deduced that pulse on time and current are more influencing parameters as compared to F.
- Temperature of graphite electrode is more than copper electrode for the same input parameters. So the thermal shock of graphite electrode is more than copper electrode so wear rate of the graphite electrode is more than copper electrode.

B. Stresses induced in electrodes material
To calculate the effect of thermal stresses on electrode of EDM machining different simulations are done with variable parameters during the study. Radial, Tangential and Axial stresses of components in electrode material have been calculated in static structure module. It is observed that increasing current increases the stress values setup into the electrode material. Also for higher values of F stresses are high. High stresses near to centre surface leads to tendency of the material to fail. So it is concluded that that in order to avoid material failure, the value of current and F should be within specific limits. It is also predicted that with increase in pulse on time, stresses setup into the electrode material will increase and material will more prone to failure near the surface due to low strength caused by high stresses setup into the material near surface.
REFERENCES


