Analysis and evaluation of heat affected zones in electric discharge machining of EN-31 die steel

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In this paper investigations are conducted on the machining of EN-31 die steel with different electrode materials (copper, brass and graphite) with electrical discharge machining (EDM) process. This study presents the analysis and evaluation of heat affected zones (HAZ) of the workpiece surfaces machined using different tool electrodes by EDM. The kerosene oil of commercial grade has been used as dielectric fluid. The effect of various important EDM parameters such as pulse duration, peak current and discharge gap voltage has been investigated to yield the responses in terms of material removal rate (MRR) and surface roughness (SR). Further the detailed analysis of heat affected regions has been carried out by using scanning electron microscopy (SEM) and optical microscopy (OM). Experimental results indicate that copper as a tool electrode shows a good response towards MRR, whereas brass gives superior surface finish as compared to other tool electrodes. From the microstructural analysis study it has been observed that heat affected zone is much deeper in the specimen machined by graphite electrode as compared to other tool electrodes.

Keywords: Electrical discharge machining; Surface integrity; Metal removal rate; Surface roughness; Heat affected zone

The basis of electrical discharge machining (EDM) can be traced as far back as 1770, when English scientist Joseph Priestly discovered the erosive effect of electrical discharges or sparks\textsuperscript{1}. Later, Lazarenko and Lazarenko\textsuperscript{2} exploited the destructive properties of electrical discharges for constructive use. They developed a controlled process of machining difficult-to-machine metals by vaporizing material from the surface of metal. The Lazarenko’s EDM system, later served as the model for successive development in EDM\textsuperscript{3}. The literature survey related to EDM reveals that surface characteristics of components machined by EDM mostly depends upon the selected electrical parameters. The importance of surface integrity of EDMed components has been recognized by the industry and it is still continues to be the major concern among the researchers. Surface integrity deals basically with two issues, i.e., surface topography and surface metallurgy. It deals with the possible alterations in the surface layers after machining. Surface integrity greatly affects the performance, life and reliability of the components. Microscopic study of EDMed components reveals the presence of three kinds of layers, e.g., recast layer, heat affected zone (HAZ) and converted layer\textsuperscript{4}. Figure 1 shows these three kinds of layers developed on electro-discharged machined components. If molten material from the workpiece is not flushed out quickly, it will resolidify and harden due to the cooling effect of the dielectric and gets adhered to the machined surface. This thin layer of about 2.5-50 µm is formed and is called re-cast layer. It is extremely hard, brittle and porous and may contain micro cracks. Such surface layers should be removed before

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Fig. 1—Schematic diagram of three kinds of layers on an EDMed component
using these products. Beneath the recast layer, a HAZ is formed due to rapid heating and quenching cycles during EDM. This layer is approximately 25 µm thick. The heating-cooling cycle and diffused material during machining are the responsible reasons for the presence of this zone. Thermal residual stresses, grain boundary weaknesses, and grain boundary cracks are some of the characteristics of this zone. Conversion zone (or converted layer) is identified below the HAZ and is characterized by a change in grain structure from the original structure.

There are many process variables that affect the surface integrity such as pulse duration, peak current, gap voltage, electrode polarity, material properties of tool electrode, workpiece dielectric liquid, debris concentration and even size of the electrode. These effects have tremendous effect on mechanical properties of the material such as fatigue, hardness, corrosion and wear resistance.

The texture of eroded surface has been analyzed by Kahng and Rajurkar. It is observed that the application of higher discharge energy results in deeper HAZ and subsequently deeper cracks. Spark eroded surfaces have been examined by Barash to study after-machining characteristics.

Zang et al. developed a theoretical model to estimate the surface roughness of the finished surface. Experiments which have been carried out using AISI 1045 steel as workpiece material and copper as tool electrode indicated that the roughness of finished surface increases with an increase in discharge voltage, discharge current and pulse duration.

Khan investigated the electrode wear and MRR during EDM of aluminum and mild steel using copper and brass electrode. During machining of mild steel, it was observed that electrode undergone more wear than during machining of aluminum. This is due to the fact that the thermal conductivity of aluminum is higher than that of mild steel which causes comparatively more heat energy to dissipate into the electrode during machining of mild steel.

Amorim et al. studied the behaviour of graphite and copper electrodes on the die sinking electrical discharge machining of AISI P20 tool steel. According to the study graphite and copper presented similar trends of MRR at positive polarity. Investigation further reveals that with larger gap width EDM performance is more stable. It means that higher MRR and lower electrode wear would be reached. The best surface roughness $R_s$ was obtained for copper electrode under negative polarity.

Khanra et al. reported the debris formation at different EDM conditions and concluded that EDM debris consist of two types of particles. A combined analysis of shape and EDS indicates spherical particles consist of mainly WP material and nano spherical particles generated from tool material. The average particle size seems to increase with energy input.

A study on fine finish die sinking micro EDM of tungsten carbide was conducted using tungsten (W), copper tungsten (CuW) and silver tungsten (AgW) electrodes by Jahan et al. The performance of the electrodes for the finishing micro EDM was based on the achieved surface roughness and surface characteristics with respect to MRR and electrode wear rate (EWR). It was found that the surface characteristics are dependent mostly on discharge energy during machining. AgW electrode produces smoother and defect free nano surface and CuW electrodes archived the highest MRR followed by AgW electrodes. In case of electrode wear the W electrode has the lowest wear followed by CuW and AgW electrodes.

In this paper, work on machining by EDM for EN-31 grade tool and die steel has been presented. Although some literature on EDM of low carbon steels, carbides and die steels is available but all have emphasized on machining parameters. Not more has been mentioned on heat affected regions to understand the mode of heat transfer which alternatively affects the microstructure of machined workpiece. The present investigation aims to establish correlations between spark energy, electrode material and HAZ during electrical discharge machining. An analysis has also been performed on the comparative performance of copper, brass and graphite electrodes.

**Experimental Procedure**

A schematic diagram of an experimental set-up for electrical discharge machining is shown in Fig. 2. The experiments were performed on CNC electric discharge machine (die sinking type) of model Sparkonix-25A having maximum capacity of 25 A working current generator producing rectangular pulses. The series of experiments have been conducted to study the effect of various machining parameters on EDM process. Various input parameters selected to investigate the surface characteristics and metal removal rates of tool steel for different electrode materials. The selected parameters for experimentation are shown in Table 1.
The experiments are conducted on EN-31 die steel material. The work materials (25 mm×25 mm×20 mm) were machined on shaper machine. Each piece was hardened and tempered to obtain hardness of 58HRc. The chemical composition and various properties of EN-31 die steel are shown in Tables 2 and 3 respectively. Copper, graphite and brass are used as tool electrode material. The diameter of the selected electrode is 10 mm. The different properties of various electrode materials are mentioned in Table 4. The kerosene oil of commercial grade is used as the dielectric fluid. A depth of cut of 10 mm was set for the machinability of all the work samples. Volumetric MRR has been calculated. The time of machining was noted from the machine generator-setting monitor; hence the MRR is calculated in mm³/min. The average surface roughness (Rₐ) is measured using Perthometer, which is a compact independent roughness measuring instrument. It is portable type, M4Pi make having evaluation length of 12 mm and cut off length is 2.5 mm.

Results and Discussion

The surfaces obtained by the electric discharge machining of EN-31 die steel using different electrode materials under various working conditions are shown in Fig. 3.

Effect of different electrode materials on MRR

Figure 4 show the effect of gap current on the MRR of EN-31 tool steel machined by different electrode materials. It has been found from this figure that MRR increases with increase in discharge current for all the three electrodes. However, in case of brass and graphite, it decreases after some limit. The enhancement in MRR may be attributed due to increase in pulse energy as the current increases. At a low current, a small quantity of heat is generated and substantial portion of it is absorbed by the

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### Table 1— Process parameters and their range

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sparking voltage</td>
<td>38 V, 40 V, 50 V and 60 V</td>
</tr>
<tr>
<td>Discharge current in steps</td>
<td>4, 6.8, 10, 12 and 14 A</td>
</tr>
<tr>
<td>Pulse-on</td>
<td>100-400 µs</td>
</tr>
<tr>
<td>Servo system</td>
<td>Electro hydraulic</td>
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<tr>
<td>Electrode polarity</td>
<td>Positive</td>
</tr>
<tr>
<td>Dielectric used</td>
<td>Commercial grade EDM oil</td>
</tr>
<tr>
<td>Dielectric flushing</td>
<td>Side flushing with impulsive pressure</td>
</tr>
<tr>
<td>Work material polarity</td>
<td>Negative</td>
</tr>
<tr>
<td>Workpiece hardness</td>
<td>Hardened and tempered to 58 HRC</td>
</tr>
</tbody>
</table>

### Table 2— Chemical composition (wt. %) of EN-31 die steel

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition (wt. %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>1.07</td>
</tr>
<tr>
<td>Si</td>
<td>0.32</td>
</tr>
<tr>
<td>Mn</td>
<td>0.58</td>
</tr>
<tr>
<td>P</td>
<td>0.04</td>
</tr>
<tr>
<td>S</td>
<td>0.03</td>
</tr>
<tr>
<td>Cr</td>
<td>1.12</td>
</tr>
<tr>
<td>V</td>
<td>–</td>
</tr>
<tr>
<td>Fe</td>
<td>Balance</td>
</tr>
</tbody>
</table>

### Table 3— Major properties of EN-31 die steel

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity (W/m·K)</th>
<th>Density (g/cc)</th>
<th>Electrical resistivity (ohm·cm)</th>
<th>Specific heat capacity (J/g·°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN31 Steel</td>
<td>46.6</td>
<td>7.81</td>
<td>0.0000218</td>
<td>0.475</td>
</tr>
</tbody>
</table>

### Table 4— Major properties of electrode materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity (W/m-K)</th>
<th>Melting point (°C)</th>
<th>Electrical resistivity (ohm·cm)</th>
<th>Specific heat capacity (J/g·°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper (99% pure)</td>
<td>391</td>
<td>1,083</td>
<td>1.69</td>
<td>0.385</td>
</tr>
<tr>
<td>Brass (60%Cu,40%Zn)</td>
<td>159</td>
<td>990</td>
<td>4.7</td>
<td>0.38</td>
</tr>
<tr>
<td>Graphite (15 µm Average grain size)</td>
<td>80</td>
<td>4800</td>
<td>3.5x10⁻³</td>
<td>7.10</td>
</tr>
</tbody>
</table>

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surrounding dielectric fluid and mechanical components and therefore lesser amount of heat left for melting and vaporizing the work material. But as the current increases, dense spark with higher energy is produced. Therefore, more heat is generated and substantial quantity of heat is utilized for material removal. MRR does not observe linearity with pulse energy and that may be due to the possible losses of thermal energy by conduction to surrounding material and dielectric fluid. Except for the copper electrode, an increase in current beyond certain limit for a given electrode area and material has adverse effect on MRR (Fig. 4). In all these experiments, maximum current limit is limited to 14 A. The electrical conductivity and thermal conductivity of EN-31 material is found to decrease with dispersed loading.

At higher levels of current, wear rate of graphite increases and causes some machining problems which further reduces MRR. This may be due to the arcing produced at high current densities. Copper shows good response in metal removal rate toward high values of discharge current. This may be because of the increase in thermal and electrical conductivity. As EDM is an electro-thermal process. The electrical and thermal conductivity and the melting point of the electrodes and workpiece materials play an important role in EDM performance. The high electrical conductivity (391 W/m-K) of copper facilitates the sparking process and increases effective pulses which increase MRR. Thermal conductivity of graphite (80 W/m-K) is lower as compared to brass (159 W/m-K) and copper (391 W/m-K) which creates substantial amount of heat in the inter electrode gap, due to which MRR of graphite is higher upto 10 A.
gap current. Afterwards the effect of arcing dominates the removal of material from workpiece due to insufficient spark interval. At higher discharge current, the work particles which erode during the EDM process did not get effective expulsion due to the lack of turbulence. Therefore, these particles remained in crater and hindered pace of erosion\(^ {14}\). Moreover, the excessive energy provided by plasma channel associated with characteristics, excessive pulse on-time duration melts the material but is unable to produce exploding pressure of the dielectric which can remove the molten metal away from EDM surface.

The effect of current on MRR using different electrodes can be easily visualized from the following summary:

(i) 50 V (gap voltage), 14 A, MRR = 26.5 \( \text{mm}^3/\text{min} \) (copper electrode)
(ii) 38 V (gap voltage), 8 A, MRR = 13.9 \( \text{mm}^3/\text{min} \) (brass electrode)
(iii) 40 V (gap voltage), 10 A, MRR = 18.2 \( \text{mm}^3/\text{min} \) (graphite electrode)

**Effect of different electrode materials on surface roughness**

The surface produced by EDM process at high current is found to be rough. During the experimentation an average surface roughness of EDM machined surface has been measured. As shown in Fig. 5 the SR is found to increase with the increase in discharge current. Minimum SR values for EN-31 steel were noticed corresponding to discharge current of 4 A and 10 \( \mu \text{s} \) pulse on-time. Surface roughness increases with increase in discharge duration\(^ {15}\). At 10 \( \mu \text{s} \) pulse on-time, the value for SR for different electrode materials is minimum as compared to 400 \( \mu \text{s} \) pulse on-time. A comparison graph as shown in Fig. 5 shows general trend of increasing surface roughness with current. It can be observed from this figure that graphite tool electrode promoted higher roughness than copper and brass electrode for all the discharge current and discharge durations. The higher SR obtained with graphite is due to the higher MRR reached for that material. This means that larger and deeper craters were made in the workpiece surface using graphite electrode. The best value of SR has been attained by using brass electrode, which is recommended for high surface finish of workpiece material after machining. However, the MRR of the brass electrode for all the discharge current and duration is minimum, which shows the lesser removal of material from workpiece with reduced size of craters. It is found that SR values of graphite are more as compared to copper, followed by brass. It is further observed that the surface of specimen machined by EDM is affected by alloying element of tool electrode material. So it was considered that the alloying effect could be used to enhance surface quality such as reducing residual stresses by a suitable source of alloying element\(^ {16}\).

It has been further concluded from the experimental results that if the graphite electrode assigned as cathode and operated under appropriate pulse duration, the removal rate of workpiece have a superior approach in reality.

**Analysis of heat affected zones of machined surfaces**

The alloy EN-31 die steel consists of different alloying elements. In order to have higher tool life, it is essential to avoid crack formation if any even, while workpiece is in service. It is therefore essential to analyze the surface beneath the machined area\(^ {17}\). Figure 3 shows the surfaces of specimens machined with different electrodes materials. The SR is observed to be uniform in the cavity machined by copper electrode along with minimum wear at corner edge (Fig.3a). Figure 3b shows cavity machined by brass electrode with minimum surface roughness as compared to copper and graphite electrode. This may be attributed due to the transfer of copper and zinc on the surface of workpiece during machining due to intense heat. During machining it was observed that, at higher voltage high, corner wear of the graphite electrode and erosion of work material take place. Thus the sparks are concentrated in the middle of machined area, thereby causing short circuiting and arcing at the middle of this area. Due to the arcing spattering of the electrode material take place over the entire cavity. Further, from the Fig. 3c it could be observed that accumulation of resolidified layer of work material and graphite take place on the workpiece surfaces. In the present research work, the structure features of such areas have been analyzed critically. In order to analyze such surfaces, the pieces are cut from the center in transverse direction. The samples are mechanically polished. The polishing is done first on belt grinder followed by emery and silver cloth. In order to make glossy and mirror finish surfaces, diamond paste is used. After achieving the mirror finish the surface was etched with nital itchant. The surface topography of EDM was investigated by JEOL 5600 JSM scanning electron microscope. The SEM photographs taken from
different surfaces machined by various electrode materials are shown in Figs 6-8. The photographs reveal that structures with martensite and spherical to ellipsoidal carbides are present and their concentration depends upon the available amount of heat in the inter electrode gap with different electrode materials. Figure 6 represents the structural features of such transverse section of the surfaces where brass electrode is used.

Figure 6a is a low magnification micrograph taken from the edge of machined area of the sample where machining was performed by brass electrode. In this figure, different structural features are visible. A banded line corresponding to heat effected zone is clearly visible in this micrograph. The structural feature comprises of spherical carbides in the banded zones and also away from banded zone can be seen in Fig. 6b. Tempered martensite structure is also visible in this micrograph, which is taken at higher magnification.

Further, it can be concluded that the overall structure is heterogeneous which consist of bigger spherical to ellipsoid features of the carbides followed by tempered martensite. Similar structural features are also observed in micrographs of copper electrode shown in Fig. 7. The basic difference from the case of
brass electrode is that the amount of tempered martensite is more and pronounced one. The size of the carbides varies from 1 µm to 3 µm, which are developed beneath the heat affected zone as shown in Fig. 7c. Moreover, structural variation in tempered martensite can also be seen in Fig. 7d. This type of variation is only possible, if heat transfer is not occurring uniformly.

The structural features observed for the graphite electrode, are shown in Fig. 8. In case of surface machined by graphite electrode, the formation of spherical shape carbides is much deeper. Though the sizes of these carbides are very small (Figs 8a and 8b) in the area around the machined surface but it acquires the bigger shape from the area away from the machined surface (Fig. 8c). The formation of tempered martensite along with carbides can also be evident in Fig. 8d. In case of graphite electrode the heat affected zone is much deeper as compare to other two electrodes.

The overall examination of structural features indicates that the surface is modified differently because of the application of different electrodes materials on the workpiece and effect of various machining parameters. In cases of graphite electrode, thick white layer on the surface is not observed because of the volcanic eruption, which has taken place during the course of machining of the surfaces. However, area which is being influenced by the heat is deeper and uniform as compare to other electrodes. The carbides which are in the form of needles are being converted to spherical shapes because of the thermal influence and surface tension. This spherical shape is obtained because of higher heat content. Moreover, rapid quenching may lead to formation of martensite structure in the material. Since the system is dynamic where a continuous flow of energy followed by quenching phenomenon occurs, so the structure obtained is not converted into martensite structure. Intervariate structure is normally obtained after the tempering of steel, which is called tempered martensite and is also visible in the specimen. Since workpiece always remain at higher temperature, so this phenomenon is quite obvious to occur. The overall analysis of structure features reveals that heat affected zone may vary depending upon the available amount of heat, its conduction through the workpiece and quenching mode existing within the system.
Conclusions
After analyzing the results of the experiment performed on EN-31 die steel with different electrode materials, following conclusions are arrived at:

(i) For the EN-31 work material, copper electrodes offer high MRR as compared to the machining performed by graphite and brass electrodes.

(ii) Among the three tested electrode materials, brass electrodes produce comparatively high surface finish for the tested work material at high values of discharge current, while graphite shows the poor surface finish.

(iii) It has been observed that with the increase of the discharge energy, the amount of debris particles in the gap becomes too large which form electrically conductive path between the tool electrode and the workpiece, causing unwanted discharges that damages both the electrode surfaces.

(iv) All three workpieces machined by different electrodes materials shows different pattern of heat affected zones.

(v) Heat affected zones for all the cases depends upon available amount of heat, its conduction and cooling action during the EDM process.

(vi) In case of graphite electrode heat affected zone is much deeper as compared to copper and brass electrode.

References