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# Analysis and evaluation of heat affected zones (HAZ) of the work piece surface machined using different electrode by Die-sinking EDM of EN-31 die steel

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**ABSTRACT**
*This paper presents the analysis and evaluation of heat affected zones (HAZ) of the workpiece surfaces machined using different tool electrodes by Die-Sinking 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.*

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

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## I. INTRODUCTION

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 .

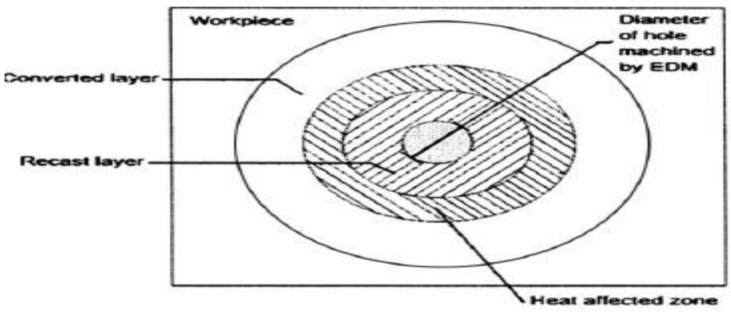



Fig. 1— Schematic diagram of three kinds of layers on an EDMed Component.

Figure1 shows these three kinds of layers developed on electro-discharged machined components. If molten material from the work piece 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 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, work piece 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 .

## II. EXPERIMENTAL PROCEDURE

A schematic diagram of an experimental set-up for electrical discharge machining is shown in Fig. 1.2.


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 1.1.

| Parameters | Range |
|---|---|
| Sparking voltage | 38 V, 40 V, 50 V and 60 V |
| Discharge current in steps | 4, 6.8, 10, 12 and 14 A |
| Pulse-on | 100-400 μs |
| Servo system | Electro hydraulic |
| Electrode polarity | Positive |
| Dielectric used | Commercial grade EDM oil |
| Dielectric flushing | Side flushing with impulsive |
| Work material polarity | Negative |
| Workpiece hardness | Hardened and tempered to 58HRC |

Table 1. 1— Process parameters and their range

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 1.2 and 1.3 respectively.

**Table 1.2— Chemical composition (wt. %) of EN-31 die steel**

| Elements | Composition (wt.%) |
|---|---|
| C | 1.07 |
| Si | 0.32 |
| Mn | 0.58 |
| P | 0.04 |
| S | 0.03 |
| Cr | 1.12 |
| V | -- |
| Fe | Balance |

**Table 1. 3—–Major properties of EN-31 die steel**

| MATERIAL | THERMAL CONDUCTIVITY (W/M-K) | DENSITY (G/CC) | ELECTRICAL RESISTIVITY (OHM –CM) | SPECIFIC HEAT CAPACITY (J/G-$^0$C) |
|---|---|---|---|---|
| EN31 STEEL | 46.6 | 7.81 | 0.0000218 | 0.475 |

Copper, 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 1.4.

**Table 9.4— Major properties of electrode materials**

| **MATERIAL** | **THERMAL CONDUCTIVITY (W/M-K)** | **MELTING POINT ($^0$C)** | **ELECTRICAL RESISTIVITY (OHM –CM)** | **SPECIFIC HEAT CAPACITY (J/G-$^0$C)** |
|---|---|---|---|---|
| COPPER (99%PURE ) | 391 | 1.083 | 1.69 | 0.385 |
| BRASS (60%CU,40%ZN) | 159 | 990 | 4.7 | 0.38 |

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 $mm^3$ /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.

## II RESULT AND DISCUSSION

The surface obtained by the electrode discharge machining of EN-31 die steel using different electrode material under various working conditions in fig 1.3

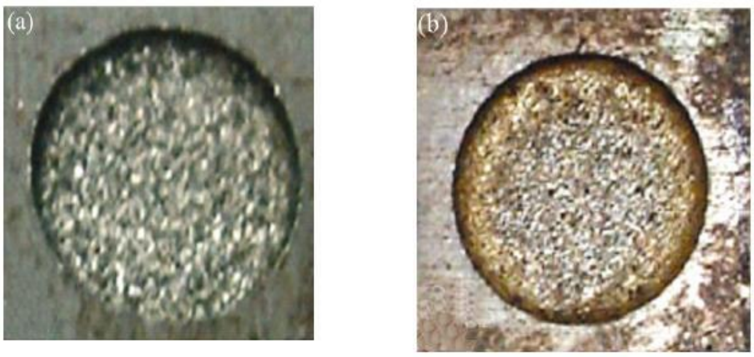



Fig 1.3 -EN-31 Work material after EDM at 14A with (a) copper tool elctrode (b) brass tool elctrode

## III. EFFECT OF DIFFERENT ELCTRODE MATERIALS ON MRR

The effect of gap current on the MRR of EN-31 tool steel machined by different electrode materials. MRR increases with increase in discharge current for all the two electrodes. However, in case of copper and brass , 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 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 .

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 work piece 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. Afterwards the effect of arcing dominates the removal of material from work piece 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 . 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 mm3 /min (copper electrode)

(ii) 38 V (gap voltage), 8 A, MRR = 13.9 mm3 /min (brass electrode)

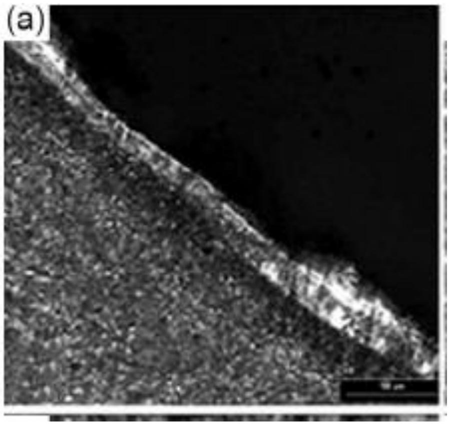
## IV. EFFECT OF DIFFERENT ELECTRODE MATERIALS ON SURFACE ROUGHNESS

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. Minimum SR values for EN-31 steel were noticed corresponding to discharge current of 4 A and 10 µs pulse on-time.

Surface roughness increases with increase in discharge duration . At 10 µs pulse on-time, the value for SR for different electrode materials is minimum as compared to 400 µs pulse on-time. The best value of SR has been attained by using brass electrode, which is recommended for high surface finish of work piece 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 work piece with reduced size of craters. 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 .

## V. ANALYSIS OF HAZ 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 work piece is in service. It is therefore essential to analyze the surface beneath the machined area. 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 1.6 and 1.7



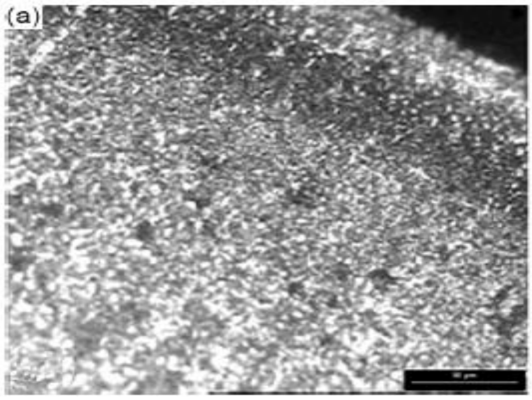


Fig1.6 SEM photographs of transverse surface machined by brass electrode HAZ AND Copper electrode banded structure .

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. 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.1.6 a . 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. 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. 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 in the area around the machined surface but it acquires the bigger shape from the area away from the machined surface . The overall examination of structural features indicates that the surface is modified differently because of the application of different electrodes materials on the work piece and effect of various machining parameters. 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 work piece 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 work piece and quenching mode existing within the system.

## VI. CONCLUSION

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 brass electrodes.

**(ii)** Among the two 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 work piece, causing unwanted discharges that damages both the electrode surfaces.

**(iv)** All two work pieces 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.

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