Surface modification of tool steel by using EDM green powder metallurgy electrodes

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Abstract. Electro-discharge machining (EDM) is mostly used for machining difficult-to-cut materials which are difficult to machine by conventional machining processes. In recent years, EDM is also used for surface modification. This work aims to investigate the phenomenon of surface modification of tool steel Calmax (Uddeholm) by EDM process using Cu-ZrO2 powder metallurgy green compact electrode. Results show that the higher Material Transfer Rate of 46.5 mg/min is achieved on the combination of $I_p=9$A and $T_{on}=25$ $\mu$s. The effect of peak current and pulse duration on the material transfer rate and surface roughness (Ra and Rz) was investigated. Machined surfaces were characterized by scanning electron microscopy (SEM).

1. Introduction

Tool steels used in applications that require improved surface properties such as high hardness at high temperature, wear resistance, and corrosion resistance. Hence, the surface modification process is necessary. Conventional methods such us chromium plating, carburizing, nitriding, chemical vapor deposition (CVD)/ physical vapor deposition (PVD), plasma arc spraying and ion implantation are used for surface modification to improve the performance and life of the material [1]. Nevertheless, the high cost of equipment and the special surface preparation makes these processes complicated and time consuming. These issues with conventional methods lead to the use of an alternative surface modification process, such as the electrical discharge machining [2,3]. Electrical discharge machining is one of the most commonly used thermo-electrical non-conventional machining processes, used for machining of difficult-to-cut materials. It is based on the principle of removing material using electric discharge that occurs between an electrode and a workpiece in the presence of a dielectric fluid. In this process, there is no contact between the tool and the workpiece, so, no tool forces are applied [4]. EDM is used in a lot of industries such as aerospace, automotive, micro-electronics, biomedical, die and mould production. Additionally, EDM is used for machining hard materials, and complex shapes with high precision [5].

Two conductive electrodes, a cathode and an anode are immersed in a dielectric fluid (oil or deionised water). A voltage difference is applied between the electrode and the workpiece, separated by a dielectric fluid, causing the ionization of the dielectric fluid. When the applied voltage overcomes the dielectric strength of the fluid, a plasma channel (electric discharge phase) is formed in between the electrode and the workpiece. The electric discharge generates high temperatures (6,000–12,000 °C) and causes melting and evaporation of the material at the point of discharge, leading to material removal from both...
the electrodes. As a result, a small crater is created both on the tool electrode and workpiece surfaces [5, 6]. A part of the molten and all of the evaporated material is flushed away by the dielectric fluid, while another part of the molten material from the tool and the constituents of the dielectric get re-solidified on the machined surface, generating the white layer (WL) or recast layer. The formation of recast layer is attributed to material transfer and is useful in surface modification of the base material by EDM process.

Surface modification has been observed in the EDM process for over five decades. It can be done in different ways which includes conventional electrode materials, powder metallurgy electrodes and powder-mixed dielectric fluid [7]. The P/M electrodes can be classified into two types, green compact type and sintered type. Samuel and Philip compared conventional solid electrodes with P/M electrodes. The P/M electrodes were found to be more sensitive to changes in peak current and pulse duration [8]. Compaction and sintering parameters conditions play an important role in the electrode performance and hence the EDM process performance [9]. The machined surface with P/M electrode improved the hardness, wear, fatigue, corrosion, oxidation resistance.

A lot of research works for EDM surface modification using PM electrodes have been carried out. Patowari et al. [10] studied the surface integrity of C-40 steel in EDM. WC-Cu powder metallurgy (P/M) green compact tools were used. MTR, TWR and SR were considered as the output responses. It was found that WC was transferred over the work surface in the form of a hard and uniformly deposited layer. T_{on} and I_{p} and settings have significant influence over the process. Gill and Kumar [2] machined hot die steel (H11) using Cu-Mn powder metallurgy electrode. Taguchi method was used to design the experiment. The formation of cementite, ferrite and manganese carbide phases were responsible for increase in MH. Gülcan et al. [11] investigated the effect of Cu–Cr and Cu-Mo powder metal tool electrodes on electrical discharge machining performance outputs. SAE 1040 steel workpiece was used as a workpiece material. They revealed that electrode material was deposited as a layer over the work surface which yields high surface hardness, corrosion resistance and strong abrasion. Gill and Kumar [3] investigated and compared the surface micro-hardness of H11 die steel using composite tool electrode (Cu–Cr–Ni) manufactured by powder metallurgy and conventional copper tool. Taguchi method was used to design the experiment. They have shown the improvement in micro hardness and good wear resistance of the machined surface due to the presence of cementite, intermetallic compound of iron, chromium and nickel and chromium carbide. Kumar et al. [12] analyzed MTR and SR on OHNS workpiece using CrB_{2}-Cu powder metallurgy electrode. It was established that desired deposition of hard composite layer was found on workpiece. Chundru et al. [13] studied the surface modification of Ti6Al4V alloy using TiC/Cu P/M electrode made with particle size varying from nano- to micron size. Taguchi method was used to design the experiment. They indicated that high reactive surface area of nanoparticles made greater surface alloying than the other tool electrodes. Hence, better surface roughness and improved hardness values were obtained.

The present study investigates the surface modification of tool steel Calmax (Uddeholm) by using a Cu-ZrO_{2} green compact P/M tool electrode. The effect of peak current (I_{p}) and pulse-on duration (T_{on}) on the material transfer rate and the surface roughness was investigated. The machined surface was characterized with scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS).

2. Experimental procedure

In the present work, experiments were carried out on tool steel Calmax (Uddeholm) using tool electrodes manufactured by Powder Metallurgy process. The chemical composition of the workpiece is shown in Table 1. The workpieces were rectangular blocks with dimensions 85×29×7mm. The electrode was produced by powder metallurgy technique by mixing Cu and ZrO_{2} powder at 70:30 weight ratio. The powders were homogeneously mixed. The powder mixture was compacted under 100 MPa pressure using a hydraulic press. The electrode was made in cylindrical shape with a diameter of 20mm and height of 15mm. Kerosene is used as dielectric fluid.
Table 1. Chemical composition of workpiece material Calmax (Uddeholm).

|       | C    | Si   | Mn   | Cr   | Mo   | V    |
|-------|------|------|------|------|------|------|
| Typical Analysis % | 0.6  | 0.35 | 0.8  | 4.5  | 0.5  | 0.2  |

A die sinking electrical discharge machine (Agie Charmilles Roboform 350 Sp) was used to perform the experiments. The selected input parameters are given in Table 2. Peak current and pulse duration were used to investigate the effect of the material transfer rate (MTR) and surface roughness (SR). Fig. 1 shows the experimental set up of EDM and the workpiece after EDM machining.

Table 2. Input parameters.

| Parameters                      | Values                        |
|--------------------------------|-------------------------------|
| Peak Current - $I_p$            | 5, 7 and 9 A                  |
| Pulse-on duration - $T_{on}$    | 12.8, 25 and 50 μs            |
| Duty Factor $\eta$              | 0.5                           |
| Dielectric Fluid                | Kerosene                      |

The material transfer rate was calculated by measuring the weight difference of the workpiece before and after EDM for a particular time period. MTR calculated using equation 1:

$$MTR = \frac{W_i - W_f}{t}$$

where $W_i$ and $W_f$ the weight of the workpiece before and after the machining (g) and $t$ the machining time (min). Surface roughness of the machined surface is measured on random surface area by TOPO 01P contact profilometer. ISO 25178-2 was used to analyze the experimental results. The roughness parameters that analyzed are the sum of the maximum valley depth and maximum peak height, $R_z$ and arithmetical mean of local peaks, $R_a$ within a definition area. The results of MTR and surface roughness parameters are shown in Table 3. The surface morphology was further analyzed by SEM, equipped with EDS to confirm the material transfer.

![Figure 1. (a) Experimental set up and (b) Workpiece after EDM process.](image)
Table 3. Experimental results.

| $I_p$ (A) | $T_{on}$ (μs) | MTR (gr/min) | Ra (μm) | Rz (μm) |
|-----------|--------------|--------------|---------|---------|
| 5         | 12.8         | 0.0228       | 3.72    | 61.08   |
| 5         | 25           | 0.0072       | 4.34    | 88.04   |
| 5         | 50           | 0.0117       | 6.27    | 101.96  |
| 7         | 12.8         | -0.2493      | 5.75    | 99.93   |
| 7         | 25           | 0.0103       | 4.89    | 84.8    |
| 7         | 50           | 0.0082       | 7.12    | 129.14  |
| 9         | 12.8         | 0.0333       | 4.31    | 64.62   |
| 9         | 25           | 0.0465       | 5.07    | 68.21   |
| 9         | 50           | 0.0205       | 6.29    | 111.38  |

3. Results and discussion

3.1 Material Transfer Rate

The MTR is one of the important performance measures and is dependent on the process parameters. MTR was measured by taking the mass difference of the workpiece before and after EDM for a particular time period. The MTR for each sample are listed in Table 3. The negative value of MTR represents the net material removal and the positive values represent net material addition. The material transfer rate during EDM for different $I_p$ and different $T_{on}$ are illustrated in Fig. 2.

![Main Effects Plot for MTR (g/min)](image)

Figure 2. Main effect plot of the MTR.

From the main effect plot it can be observed that the MTR is reduced by an increase in peak current from 5 to 7A and receives a negative value for $I_p = 7A$. With a further increase in peak current, MTR is also increased. As the pulse on duration is increased from 12.8 to 25 μs, MTR is also increased but it
appears to have a small decrease with longer pulse duration. From the interaction plot it becomes obvious that the material transfer rate is influenced by the machining parameters.

3.2 Surface roughness of the machined surface

The morphology of the machined surface is due to the amount of energy released during the EDM process. This morphology includes micro-irregularities, macro-deviations and surface waviness. The surface roughness is evaluated by the sum of the maximum valley depth and maximum peak height, $R_z$ and an arithmetical mean of local peaks, $R_a$ within a defined area of the micro-irregularities. The peak current and pulse duration influence the SR. Pulse duration allows the plasma column to expand beyond the point of electrical discharge, leading to larger diameter craters. On the other hand, the peak current affects the depth of the crater. The measured surface roughness parameters, $R_a$ and $R_z$, for each sample are listed in Table 3.

Figure 3 shows the main effect plots and the interaction plots Ra and Rz. From the main effect plot in Fig. 3 it can be observed that the $R_a$ is increased with an increase in peak current. In pulse duration main effect plot it can be observed that $R_a$ elevates slowly with an increase in pulse duration from 12.8 to 25 $\mu$s, and with further increase in pulse duration, $R_a$ is also increased up to 42.9%. Fig. 3 (b) shows that in the peak current main effect plot, the $R_z$ is increased as the peak current increases from 5 to 7 A, and it is getting lower for 9 A. However, $R_z$ is increased up to 51.7% with an increase in pulse duration.

![Main Effects Plot for SRa](image)

(a)

![Main Effects Plot for SRz](image)

(b)

**Figure 3.** Main effect plot (a) for $R_a$, and (b) for $R_z$.  

3.3 Surface analysis
As has been stated above, the morphology of the machined surface is due to the energy that released during EDM, which causes melting and evaporation of the material, followed by rapid cooling. Only a small amount, about 15% or less, of the molten material is flushed away by the dielectric fluid [14]. The un-expelled molten metal which had not been flushed away by the dielectric re-solidified and gets deposited in the crater and in the surroundings to form the recast or white layer.

Examinations by SEM (Fig. 4) revealed that the machined surface covered with a distribution of craters along with irregular flow marks of molten metal. Also, micrograph shows the presence of globules of debris formed by expelled molten metal which re-solidified and gets deposited on the workpiece surface. Micro cracks and micro voids were observed on the surface of sample. The rapid heating and cooling cycles and the micro-structural transformation during machining induce residual stresses, i.e. thermal and tensile stresses, within the machined surface, that lead to micro cracks formation on the surface. Figure 4 shows that as the pulse on current and time is increased the surface has higher roughness with an intense presence of debris and the formation of microcracks.

4. Conclusions
The present study was carried out using Cu-ZrO₂ P/M green compact electrode for surface modification of tool steel Calmax (Uddeholm). Peak current (Iₚ) and the pulse-on time (Tₚₒₜ) are used input parameters. Material transfer rate has been calculated, surface roughness has been measured, and the machined surface has been observed with scanning electron microscopy. From the experimental results, the following conclusions are drawn.

- Surface modification of tool steel Calmax (Uddeholm) was successfully carried out by using Cu-ZrO₂ P/M green compact electrode.
- Peak current and pulse on duration parameters have significant influence over MTR and SR.
- The experimental results show that the higher depositions was achieved 46.5 mgr.min for the combination of pulse current 7A and pulse on time 25 μs.
- The Ra varies from 3.72 μm for the combination of Iₚ=5A and Tₚₒₜ=12.5 μs to 6.29 μm for the combination of Iₚ=9A and Tₚₒₜ=50μs.
- Micro cracks and micro voids are observed in the workpiece surface.
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