Surface Roughness Evaluation for EDM of En31 with Cu-Cr-Ni Powder Metallurgy Tool

Amoljit S. Gill, Sanjeev Kumar

Abstract**—**In this study, Electrical Discharge Machining (EDM) is used to modify the surface of high carbon steel En31 with the help of tool electrode (Copper-Chromium-Nickel) manufactured by powder metallurgy (PM) process. The effect of EDM on surface roughness during surface alloying is studied. Taguchi's Design of experiment (DOE) and L18 orthogonal array is used to find the best level of input parameters in order to achieve high surface finish. Six input parameters are considered and their percentage contribution towards surface roughness is investigated by analysis of variances (ANOVA). Experimental results show that an hard alloyed surface (1.21% carbon, 2.14% chromium and 1.38% nickel) with surface roughness of 3.19µm can be generated using EDM with PM tool. Additionally, techniques like Scanning Electron Microscope (SEM) and Energy Dispersive Spectroscopy (EDS) are used to analyze the machined surface and EDMed layer composition, respectively. The increase in machined surface micro-hardness (101%) may be related to the formation of carbides containing chromium.

Keywords**—**Electrical Discharge Machining, Surface Roughness, Powder metallurgy compact tools, Taguchi DOE technique.

I. Introduction

En31 is a high carbon bearing steel with composition similar to that of SAE 52100 steel. It is known for high wear resistance and generally used for components subjected to high wear, abrasion or high surface loading. It is used commonly in ball and roller bearings, dies and punches, beading rolls and spinning tools. Because of the frequent use, workpieces made of it often encounter problems like corrosion, wear and high temperature oxidation of the surface in many applications. After long-term use, their precision and accuracy is likely to decline, thereby shorten their life cycles. Therefore, many researchers have worked to find a method of surface modification that can increase the life of workpiece without losing its intrinsic material properties. Conventional surface modification techniques for enhancing the surface properties (mechanical/physical/topographical) of components subject to wear, corrosion or oxidation, etc. include: carburising, nitriding, chromium plating, chemical/physical vapour deposition (CVD/PVD), ion beam techniques and plasma arc spraying [1]. These are secondary processes which require expensive set-up so adds to the total cost and time. In order to increase the applications of En31, a simple and rapid surface modification technique that can increase the resistance of the material surface against corrosion, wear and high temperature oxidation must be developed.

Electrical Discharge Alloying (EDA) is a new process that uses an electrical discharge machine (EDM) for surface modification. The electric discharge between the tool electrode and the base material can melt both. During this process a part of the molten material from the tool and the constituents of the dielectric (pyrolytic Carbon) get transferred to the machined surface. The base material thus undergoes surface alloying. Research is going on to investigate the performance of tool electrode manufactured by powder metallurgy (PM) process. Mohri et al. [2] used composite tools made of copper, aluminum, tungsten carbide and titanium with hydrocarbon dielectric for surface modification of carbon steel and aluminum. The presence of tool materials in the surface layers significantly changes the surface characteristics. Li Li et al. [3] investigated the performance of liquid phase sintered TiC/Cu/W tool and reported increase in material removal rate and tool wear rate. Simao et al. [4] used TiC/WC/Co and WC/Co PM tool electrodes in green compact and fully sintered form and noticed increase in the alloyed layer micro-hardness up to 950 $HK_{0.025}$ when sintered TiC/WC/Co tool electrode is used. Aspinwall et al. [5] tried WC/Co, W/CrC/Co and TiC/WC/Co as tool electrodes for machining and found up to 100% increase in the surface hardness due to the presence of W, Co and C on the machined surface. Bai and Koo [6] reported a strongly adheres alloyed layer of thickness about 40–50µm by using Al–Mo composite electrode. Further Chen et al. [7] concluded that using semi-sintered electrodes, a suitable modified layer (180–210µm) could be generated in a short machining time (about 600 sec).

The performance of PM electrode depends upon the PM process parameters as well as EDM process parameters. As compared to conventional solid tool electrodes these PM tool are found to be more responsive to peak current and pulse duration [8]. Peak current is the most important machining parameter effecting both the material removal rate and tool wear rate, while flushing pressure has little effect on both responses [9]. Parameters like powder particle size, compacting pressure and sintering temperature also plays important role in the performance of the tool in EDM. Tools manufactured at higher compacting pressure and higher sintering temperature have lower deposited average layer thickness and material transfer rate as the tool materials are firmly bound [10]. Krishna and Patowari [11] used W–Cu PM tool for electric discharge coating (EDC) of mild steel and investigated the parameters which favor material transfer rate (MTR) with acceptable surface finish.

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From the literature available it can be seen that surface alloying/ modification is feasible using PM tool electrode but for its industrial applicability the investigation related to machining parameter still requires more experimental investigation. Therefore, it is used herein to modify the surface of high carbon steel En31 with better surface roughness using composite copper-chromium-nickel PM electrode. In accordance with Taguchi's DOE design, L18 orthogonal array is used to conduct the experiments. Six input parameters, namely; tool polarity (P), percentage of alloying element in tool (%Cr+Ni), peak current (Ip), pulse on-time (T-on), duty factor (τ) and discharge voltage (V) constituted the array. Micro-hardness, SEM and EDS of the machined samples are also analyzed to investigate the surface.

II. Experimentation

In the present work, experiments are conducted on high carbon steel En31 using tool electrode made by powder metallurgy (PM) process. Table I gives the composition of workpiece. Before starting the machining, work material is subjected to the standard hardening and tempering cycle [12]. Chromium together with nickel is selected as alloying element. In steels, both chromium and nickel impart toughness, strength and resistance to corrosion. So the tool electrodes (ϕ 20 mm) used are made of electrolytic copper powder (99.7% pure 325 mesh) with different chromium and nickel (325 mesh) powder weight percentage (wt. %) using the PM processing technique (Compacting pressure: 200 MPa and sintering temperature: 850ºC). The independent process parameters chosen for this experimentation are tool polarity (P), percentage of alloying element in tool (%Cr+Ni), peak current (I_P), pulse on-time (T_{on}), duty factor (τ) and discharge voltage (V). The factors and levels selected are summarized in Table II. Machining time (10 minutes) is kept constant for all experiments.

TABLE I
CHEMICAL COMPOSITION OF WORKPIECE MATERIAL

Element	C	Mn	P	S	Si	Cr	Ni	V	Mo
Wt %	0.9027	0.3828	0.04222	0.03094	0.2055	1.035	0.0657	0.0028	0.0203

TABLE II
LEVELS OF INPUT PARAMETERS

Parameter	L1	L2	L3
P (+/-)	+	-	
%Cr+Ni (%)	5	10	15
I_P (Amps)	5	10	15
T_{on} (μSec)	100	150	200
τ (%)	48	64	80
V (V)	30	40	50

Taguchi's experimental design is used for designing the experiments. Orthogonal array (OA) L18 with 17 dof is identified as the most suitable array for the combination of two level and three level experimental design. The final L18 OA listing the 18 experimental set of parameters is given in Table III.

A die-sinking Electrical Discharge Machine, model Elektra EMS 5535 of Electronica Machine Tools (India), is used for the experiments. Each machined surface is measured for surface roughness (Ra) thrice. To study the machined surface characteristics and chemical composition, the samples are examined for Scanning Electron Microscopy and Energy Dispersive Spectroscopy (SEM/EDS) on a Field Emission Scanning Electron Microscope.

TABLE III
ORTHOGONAL ARRAY L18 WITH RESULT OF SURFACE ROUGHNESS (SR)

Exp No.	P	%(Cr+Ni) (%)	I_P (Amp)	T_{ON} (μSec)	τ (%)	V (V)	SR	
							Mean SR (Ra)	S/N
1	+	5	5	100	48	30	3.33	-10.45
2	+	5	10	150	64	40	5.88	-15.38
3	+	5	15	200	80	50	7.04	-16.95
4	+	10	5	100	64	40	3.40	-10.63
5	+	10	10	150	80	50	6.64	-16.44
6	+	10	15	200	48	30	6.50	-16.26
7	+	15	5	150	48	50	5.97	-15.52
8	+	15	10	200	64	30	6.26	-15.93
9	+	15	15	100	80	40	6.12	-15.73
10	-	5	5	200	80	40	6.27	-15.94
11	-	5	10	100	48	50	7.13	-17.06
12	-	5	15	150	64	30	7.16	-17.10
13	-	10	5	150	80	30	5.71	-15.13
14	-	10	10	200	48	40	8.19	-18.26
15	-	10	15	100	64	50	6.27	-15.95
16	-	15	5	200	64	50	6.79	-16.64
17	-	15	10	100	80	30	6.03	-15.61
18	-	15	15	150	48	40	8.11	-18.18

III. Results and Discussion

Three measurements of surface roughness (SR) are taken on each machined surface and their mean values are given in Table 3. Now the aim is to find out different sets of parameters that give best surface roughness. Based on the Taguchi method, the S/N calculation is decided as "Lower the better, LB" as surface roughness is a lower the better type of response characteristic and is calculated using equation:

$$(S/N)_{LB} = -10 \log \left[\frac{1}{R} \sum_{j=1}^{R} (y_j^2) \right] \quad (1)$$

where y_j = Observed value of the SR; R = Number of repetitions

The calculated value of S/N for SR is given in Table III.

The average values of SR and the corresponding S/N ratios at levels 1, 2, and 3 of the six input machining parameters are calculated to find the main effect plots. These values are shown in main effect plots for SR, Fig. 1. Based on the experimental results, the influence of the machining parameter is discussed.

The tool polarity affects SR. It is observed that negative tool polarity gives high SR. The result is well understood by the fact that when the tool polarity is negative, the energy density on the tool is larger than that on the workpiece [13]-[15]. A high tool energy density results in high tool consumption, results in larger stock material dropping on workpiece. The percentage of alloying elements doesn't affect the surface roughness significantly. From the main effect plot it can be seen that variation of SR with percentage of alloying element is small. Tool with 10% Cr+Ni gives best SR of the machined surface. It is observed that SR increase with peak current and pulse on-time. Both these parameters affect the discharge energy. The EDM crater size and tool wear increase with the electrical discharge energy and hence SR increases. More powder material dislodges from the sintered electrode and deposit on the machined surface when the peak current and pulse on-time are set at high level, such as 15 Amp and 200 µs. Level 2 of duty factor gives best SR, the value increases at higher level of duty factor due to poor flushing. SR values increases with discharge voltage. The trend is due to increase in spark energy with increase in discharge voltage.

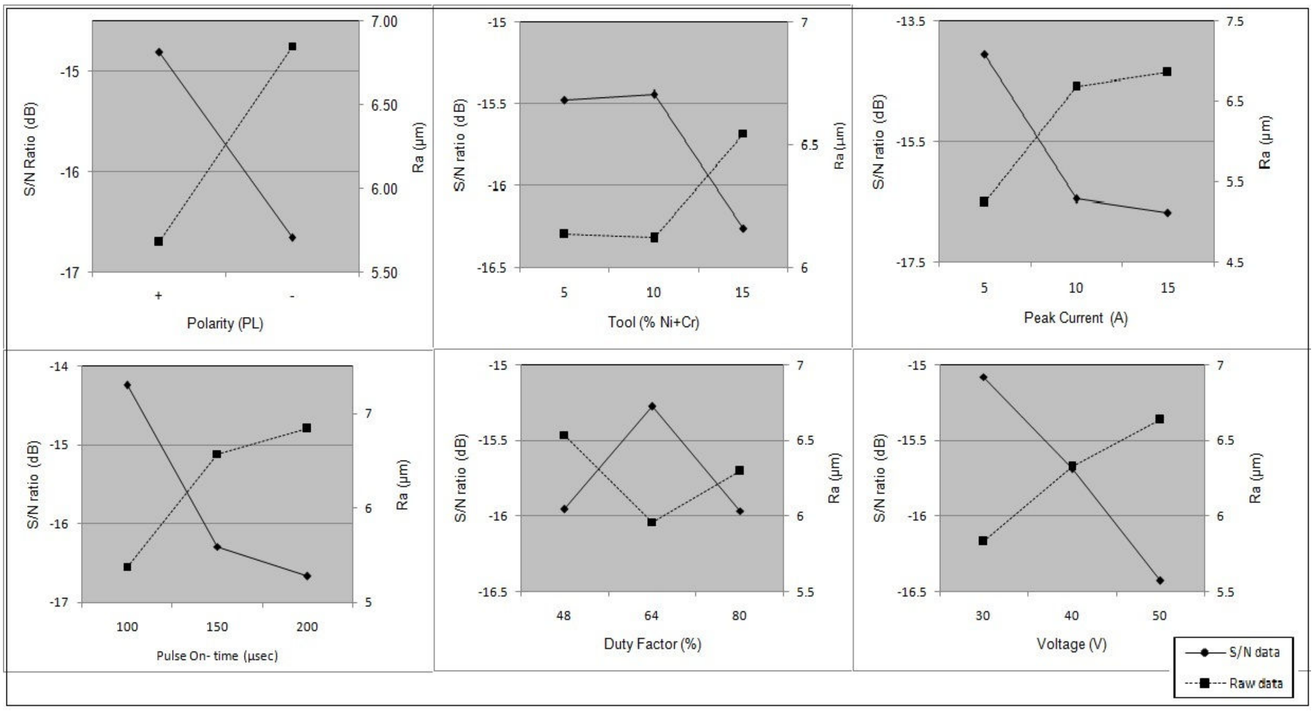

Fig. 1 Main effect plots for SR

So theoretically, the optimal combination level of the experimental parameters is as follows: positive tool polarity (A_1), 10% chromium and nickel in PM tool (B_2), 5A peak current (C_1), 100µsec pulse on-time (D_1), 64% duty factor (E_2) and 30V gap voltage (F_1). The final step is to predict and verify the improvement of the observed value through the use of the optimal combination level of machining parameters.

Theoretical value of S/N ratio under the best conditions for response parameter, denoted by η_{opt}, is given by

$$\eta_{opt} = \eta_m + \sum_{i=1}^{o} (\bar{\boldsymbol{\eta}}_i - \eta_m) \quad (2)$$

where η_m is the overall mean S/N ratio, $\bar{\eta}_i$ is the mean S/N ratio at optimum level of i[th] parameter and o is the number of design parameter that effect response parameter.

The estimated S/N ratio for SR, using the optimal level of the design parameters ($A_1B_2C_1D_1E_2F_1$):

$$\eta_{opt} = -10.23$$

and corresponding value

$$SR = \left(10^{\frac{-\eta_{opt}}{10}}\right)^{\frac{1}{2}} = 3.25\ \mu m$$

Since this combination of input process parameters did not exist in the orthogonal array, a set of three confirmation experiments were conducted. The average value of SR obtained at this setting of the experiment is 3.19µm, which better and close to the theoretical value predicted by Taguchi analysis. Micro-hardness of the sample is also measured and the average value comes out to be 1139HV (Micro-hardness of base material: 566.4 HV).

Analysis of Variance (ANOVA) is used to investigate the significance and contribution of machining parameters for the observed values. In this investigation, ANOVA and the F-test are applied to analyze the experimental data. The results of ANOVA for SR are given in Table IV. Results show that the percentage of allowing element and duty factor doesn't affect the SR significantly. Thus, these two parameters have to be considered for pooling, as shown in Table V. Peak current is the most significant factor with 32.8% contribution followed by pulse on-time, tool polarity and discharge voltage.

TABLE IV
ANOVA FOR S/N OF SURFACE ROUGHNESS

Parameter	DOF	For S/N of SR		
		Variance	F	P (%)
P	1	15.27656	37.59673*	20.7203
%Cr+Ni	2	1.295793	3.189041	3.515087
I_P	2	12.78535	31.46568*	34.68272
T_{ON}	2	10.23539	25.19005*	27.76547
τ	2	0.950771	2.339918	2.579151
V	2	2.739179	6.741321*	7.430551
Error	6	0.406327		3.306719
Total	17			

*Significant parameter ($F_{0.05,2,6}$= 5.14, $F_{0.05,1,6}$= 5.99)

TABLE V
POOLED ANOVA FOR S/N OF SURFACE ROUGHNESS

Parameter	DOF	Sum of Squares	Variance	F	Pure Sum	P (%)
P	1	15.27656	15.27656	22.04063*	14.583	19.78
%(Cr+Ni)	(2)	2.591585		Pooled		
I_P	2	25.5707	12.78535	18.44638*	24.184	32.80
T_{ON}	2	20.47079	10.23540	14.76737*	19.085	25.89
τ	(2)	1.901543		Pooled		
V	2	5.478359	2.73918	4.95202*	4.192	5.55
Error (Pooled)	10	6.93109	0.69311		11.783	15.98
Total	17	73.72750			73.727	100

*Significant parameter ($F_{0.05,2,10}$= 4.10, $F_{0.05,1,10}$= 4.96).

To investigate the machined surface in more detail, the machined surfaces produced during the confirmation experiments is studied under SEM. Fig. 2 shows the micrograph of EDMed surface machined with optimal set of parameters for surface roughness, $A_1B_2C_1D_1E_2F_1$. The micrograph shows a smooth surface as the set of parameters used produces low discharge energy and material dropped from the tool is also present. Flow marks of molten metal can also be seen on the surface. The surface shows carbon rich mixed phases. Important observation is that the surface is crack free.

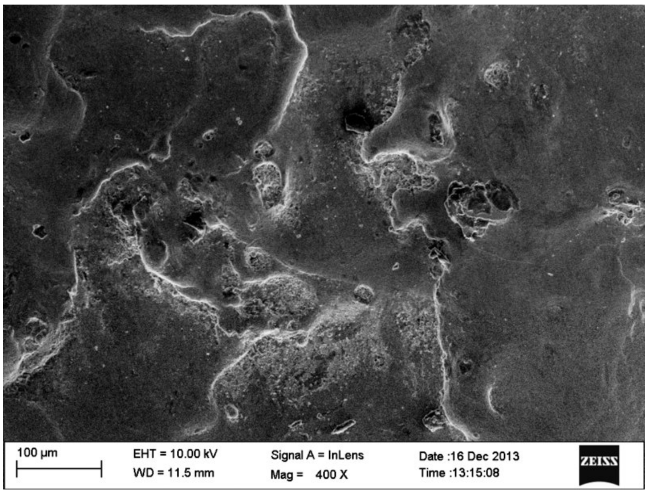

Fig. 2 SEM micrograph of machined surface (Tool polarity: +ve, tool with 10 % (Cr+Ni), Peak current: 5A, pulse on-time: 100µs, duty factor: 64% and discharge voltage: 30V)

To confirm the material alloying, the surface machined with optimal set of parameters for best SR is examined by EDS. EDS analysis (Fig. 3) shows a significant alloying of modified layer by carbon and elements from PM tool electrode. The composition of the machined surface is compared with the base material and plotted in Fig. 4. The result shows a significant material transfer (Chromium, nickel and copper) from the tool electrode to the machined surface. The increase in carbon content is due to deposition of carbon, produced due to dielectric (hydrocarbon) breakdown, on the machined surface. The increase in carbon, chromium and nickel content leads to cementite formation and alloying of the machined surface. Chromium can form independent hard carbides. The increase in hardness of machined surface is due to formation of cementite and chromium carbide during the process of machining.

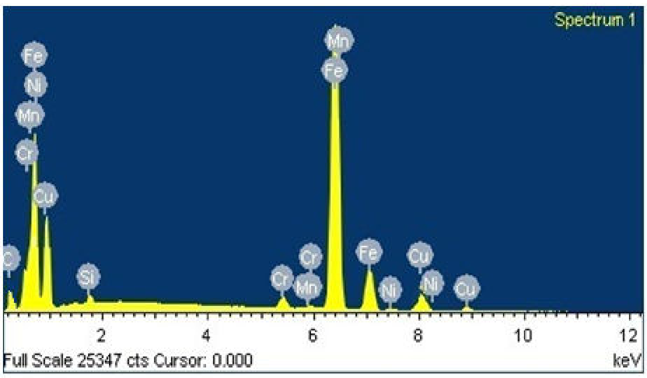

Fig. 3 EDS Spectrum of machined surface (Tool polarity: +ve, tool with 10 % Cr+Ni, Peak current: 5A, pulse on-time: 100µs, duty factor: 64% and discharge voltage: 30V)

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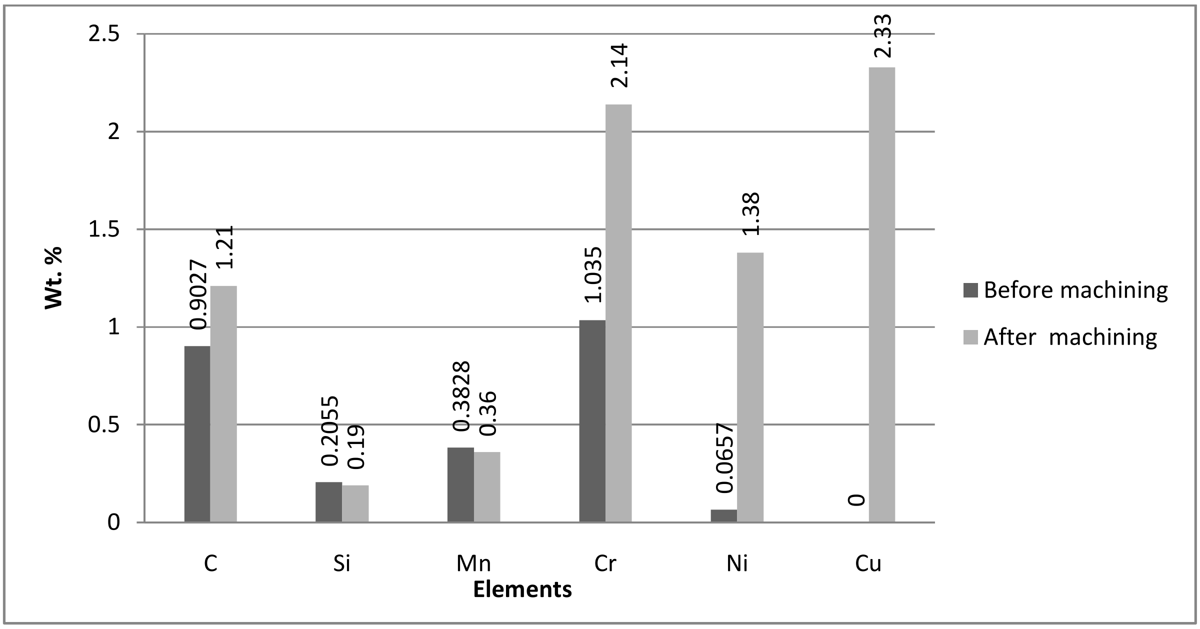

Fig. 4 Comparison of chemical composition of surface before and after machining

IV. Conclusions

This study investigates the surface modification of high carbon steel En31 by EDM using PM tool electrode made of copper- chromium-nickel powders. Surface roughness of the machined surface is investigated using Taguchi's experimental design using tool polarity, percentage of alloying element in tool, peak current, pulse on-time, duty factor and discharge voltage as input parameters. The surface machined at the optimized level of parameters is investigated for surface alloying and other surface characteristics. Based on the results following conclusions can be stated:

1. Set of parameters, i.e. positive tool polarity, tool with 10 % W, 5A peak current, 100µs pulse on-time, 64% duty factor and 30V discharge voltage, gives the best surface roughness result.
2. It has been found that peak current is the most contributing parameter towards surface roughness. Whereas, percentage of alloying elements in PM tool and duty factor doesn't affect the surface roughness significantly. So it can be stated that parameters related to discharge energy effects the surface roughness significantly in case of machining with PM tool.
3. The experimental value of surface roughness and micro-hardness of the surface machined with optimal set of parameters for surface roughness is 3.19 µm and 1139 HV (higher than the base material: 566.4 HV), respectively. No micro-crack is observed on the surface machined with optimal set of parameters. So it can be concluded that surface alloying can be done using PM tool electrode without deteriorating the quality of surface.
4. The EDS results reveal the formation of alloyed layer. A compared to base material the alloyed layer contains 1.105% higher chromium, 1.31% higher nickel and 0.3% higher carbon percentage.

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