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Experimental Investigation of Different Additives used for Surface Modification of EN31 Steel by EDM Process

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Abstract The present work describes an advance method of surface modification by electric discharge machining. In this work, additive mixed powder metallurgy copper tungsten electrode has been used for the surface modification of En-31 die steel. Three additives zinc stearate, calcium stearate and nickel were used in P/M composite electrode and their effect was analysed. The effect of compaction pressure, peak current, pulse on time and pulse off time on surface deposition rate, surface roughness and micro hardness of the deposited layer has been investigated. During pilot experimentation surface modification process was carried out with three different additives viz. zinc stearate, calcium stearate and nickel. The performance parameters predicted that calcium stearate is the best additive. Therefore further experimentation were carried out by using calcium stearate as additive in the manufacturing P/M electrode and its effect on surface modification of En-31 steel has been investigated. Central composite rotatable design (CCRD) technique was used for design of experiments and subsequent results have been analysed. Analysis of variance had been performed to check the adequacy of the developed mathematical models as well as significance of each term comprising the models. The maximum surface deposition rate achieved was 1.4mg/min at 7.5 Amps peak current, 20 µsec pulse on-time, 100 µsec pulse off-time and 700 MPa compaction pressure. The best value of surface finish obtained was 5.24 µm at 4.5 Amp peak current, 10 µsec pulse on-time, 200 µsec pulse off-time and 1100 MPa powder compaction pressure. The maximum value of micro hardness observed was 78.3 HRC at 7.5 Amps peak current, 10 µsec pulse on-time, 100 µsec pulse off-time and 700 MPa compaction pressure.

Keywords: *electric discharge machining, additive, response surface methodology, central composite rotatable design, analysis of variance*

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1. Introduction

Surface modification is a process to alter the surface of engineering component to achieve improvement in properties such as high hardness, wear resistance, high temperature resistance, without making any significant change to bulk characteristics of the structure. The last decade has seen an increasing interest in the noval application of Electrical Discharge Machining (EDM) process, with particular emphasis on the potential of this process for surface modification. Since EDM is already being used extensively for the manufacture of press tool, dies and punches where a hard and abrasion-resistant machined surface is a major requirement, researchers are exploring various ways to adapt this technique for surface hardening of work pieces. Efforts are being made to create new, harder alloys on the surface of machined components with the aim of increasing their working life and wear resistance [1]. EDM is an important 'non-traditional manufacturing method', developed in the late 1940s and has been accepted worldwide as a standard processing manufacture of forming tools to produce plastic moldings, die castings, forging dies, etc. Electrical discharge machining is a process of utilizing the material removal phenomenon of electrical-discharge in dielectric. Therefore, the electrode plays an important role, which affects the material removal rate and the tool wear rate.

Many kinds of surface modification methods such as Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD) have been developed to increase the life of tools or molds. These methods need special equipment which is costly and the operation is complex. Therefore, these applications do not find wide application in ordinary tool and mold workshop. These conventional methods of material deposition are only possible in highly clean and dust free environment. EDM can be used in any normal atmosphere for complex tool coating purposes which is highly required in industry. The components manufactured by normal EDM technique needs removal of white recast layer before applying a hard metal or ceramic coating on them. An alternative approach is the surface modification (coating) process at the time of EDM, which dispenses with the need for secondary processing (coating) thereby, providing lower cost and more flexibility.

Many researchers have investigated the impact of suspended particles such as graphite, titanium and molybdenum in dielectric fluid during EDM process.

They have found the net improvement in surface properties of machined surface such as wear resistance and hardness. [2,3,4,5]. Amoljit S. Gill and Sanjeev Kumar [6] has studied the effect of EDM on surface roughness of En-31 during surface alloying using Cu-Cr-Ni electrode manufactured by powder metallurgy (P/M) process. Experimental result show that a hard alloyed surface with a surface roughness of 3.19 µm can be generated using EDM with P/M tool. The increase in machined surface micro hardness is related to the formation of carbides containing Chromium. In another study M.P. Samuel and P.K. Philip [7] conducted an experiment to show the effect of P/M electrodes on electric discharge machining. It was found that P/M are technological viable in EDM and the EDM related properties of these electrode can be controlled varying compaction and sintering variables. P/M electrodes are found to be more sensitive to pulse current and pulse duration than conventional solid electrodes. It was concluded that under certain processing and operating condition P/M electrodes can cause net material addition rather than removal. In 2003, M. Murugan and D. Nadanasabapathy [8] investigated the relationship of process parameters in electro-discharge of LM25 aluminum alloy with WC/Co composite produced using powder metallurgy technique. The Response Surface Methodology (RSM) was used to plan and analyze the experiments with Face-Centered Composite Design (CCD). It was concluded that material transfer rate was higher at short pulse duration than at long pulse duration. Tool Wear Rate (TWR) decreases with increase pulse duration. Another researcher Li Li and Y.S. Wong [9] studied the effect of TiC in copper-tungsten electrode on EDM performance. The distribution of particle size becomes narrower with increasing TiC. A uniform dispersion of fine titanium carbide (TiC) particles in the Cu-W system and a narrower particle size distribution provide the possibility of obtaining dense electrodes. The densification is also improved by the addition of Nickel due to good solubility of Ni with Cu and W. The surface roughness decreases with increase of relative density and vice versa.D. K. Aspinwal et al. [10] conducted a review by using powder dispersed in dielectric fluid and refractory Powder Metallurgy (P/M) electrodes for the work piece modification in electrical discharge machining of AISI H13 tool steel. They had found about 100% increase in surface hardness of AISI H13 steel work material in die sinking EDM process, by using tungsten carbide-cobalt (WC/Co) electrode at high operating voltage (~270 V). They used Glow Discharge Optical Emission Spectroscopy (GDOES) and Energy Dispersive X-ray (EDX) equipment to analyze machined surface layer and concluded that increase in surface hardness was due to the presence of tungsten (W), Cobalt (Co) and carbon (C) in the machined surface. J. Simao et al. [11] studied the use of partially sintered electrodes made up from WC/Co to deposit an alloyed surface layer of uniform thickness of 30 µm on AISI H13 steel work piece by EDM process. Taguchi experimental design technique was used to identify the effect of key operating factors on output measures. Effect of machining parameters such as open circuit voltage, peak current, pulse on time, electrode polarity and capacitance, on Material Removal Rate, Surface Roughness and work piece surface micro-hardness were analyzed. It was concluded that with proper selection of appropriate operating values from these data, helps to achieve best work piece characteristics. Parmod K Patowari and P K Mishra [12] has analyzed the characterization of the deposited hard layer on C-40 grade plain carbon steel by using specially prepared powder metallurgy compact tool of Cu-W. The deposited layer vary in thickness from 3-785µm.Tungsten carbide was found in the deposited layer having micro hardness of the order of 9.81-12.75 GPa. Sanjeev Kumar et al. [13] conducted a review on surface modification by electrical discharge machining process and found that the field of surface modification using EDM process is still at the experimental stage. The effect of discharge current and pulse duration and duty factor was taken into consideration in various research works but variation in pulse interval has not been taken into consideration. Most of the researchers have studied the impact of powder-mixed dielectrics on EDM performance such as MRR, Surface Roughness and TWR etc. with normal polarity. The study of the impact of this method on surface modification has been taken up by very few researchers.

The important issue in manufacturing is modeling. The manufacturing processes are defined by the process variables that are dynamically interacting with each other. Some of prominent researchers have reported the result related to the modeling of the machining operations. Cogun et al. [14] developed the mathematical model for surface finish of EDMed surface of AISI 2080 tool using Fourier’s series. The tool steel was machined by varying pulse duration, discharge current and dielectric flushing pressure. It was observed that increasing the discharge current, pulse duration and dielectric flushing pressure; increased the surface roughness. Surface profile information obtained was transferred to computer, digitized and then modeled in the form of Fourier series.

Patowari et al. [15] successfully modeled the material transfer in EDM process using artificial neural networks. The average layer thickness and material transfer rate was selected as out responses. Artificial Neural Network models were developed for correlating the material transfer rate and average layer thickness with different process parameters like peak discharge current, pulse duration, duty factor, compaction pressure and sintering temperature. It was observed that the trend of predicted and target values from training and testing were very much close to each other. The predicted results were matching well with the experimental results. Sharif and Noordin [16] developed the mathematical models to study an electrical discharge machining process of titanium material adding silicon carbide (SiC) powder in dielectric medium. RSM based models were used for defining the mathematical correlation between the input and process performance parameters. It was observed that the input variables like gap voltage, peak current and pulse on-time has more effect on MRR and SR. Sidhu and Banwait [17] developed RSM model for surface modification of En-31 die steel taking into account the effects of the compaction pressure of powder metallurgy electrodes. For a given work, the model was shown to give more reliable material removal rate, surface deposition rate and surface finish prediction under different process conditions.

It can be seen from available literature that very limited research work on surface modification has been done using En-31 die steel as work material with composite electrode which is a popular mould and die material. The surface modification using tool electrode parameters is very scant. No research has been conducted to see the effect of additives in P/M electrode on surface modification. Therefore in the present work attempts have been made to:

- To carry out the study for understanding the fundamental characteristics and working principle of surface modification of die steel using EDM process.
- To analyse the surface deposition mechanism of surface modification of die steel material (EN-31) used in manufacturing dies.
- To study and analyse the effect of three additives viz. zinc stearate, calcium stearate and nickel.
- To study the impact of calcium stearate additive on the surface modification of the work piece material.
- To analyse the influence of various parameters of EDM process on Surface Deposition Rate and Surface Finish and micro hardness of modified layer through graphical representation.
- To develop a response surface methodology (RSM) model to correlate the input process parameters with output responses.

For analyzing the surface modification, following input/out parameters were taken pulse on-time, pulse off-time, peak current, compaction pressure, surface deposition rate, surface roughness, and micro hardness. The P/M semi-sintered additive mixed tool electrodes formed at different powder compaction pressure was used in experimental investigations.

2. Experimentation

In the present work, experiments were conducted on En-31 steel using tool electrode made by powder metallurgy (P/M) process. The work pieces, made of En-31 die steel material of 20m×15m rectangular shape with 6 mm thickness were used. The initial hardness of these work pieces was of 24-26 HRC. Table 1 gives the composition of the work piece used. Semi-sintered (P/M) tool electrode made up of 9%copper, 90% tungsten and 1% additive was used in A25 spark generator integrated type TOOLCRAFT (India) die sinking EDM machine for the surface modification process as shown in Figure 1.

2.1. Pilot Experimentation

During the pilot experimentation phase, three different additives were used in the preparation of the composite electrode and the effect were observed on the surface deposition rate, surface roughness and micro hardness of the deposited layer on En-31 steel during surface modification process. These three additives were Zinc stearate, Calcium stearate and Nickel. These additives enhances the properties of composite electrodes. Zinc stearate and calcium stearate act as lubricants in the powder metallurgical electrodes. Nickel helps in the densification of composite tool due to good solubility of nickel with copper and tungsten [18].

The percentage ratio by weight of each additive in metallic powder was kept 1%. The mixing was done on a lathe machine at a speed of 35 r.p.m. for an hour. This was the lowest available speed on the lathe machine. Then it was compacted at a pressure of 500, 900 and 1300 MPa. A single acting die was used for compaction of powder having punch and ejector pin diameter as 10 mm. The powder used to fabricate P/M electrode was compacted at various pressures using hydraulic compaction machine. The green compact was sintered in the muffle furnace at a temperature of 300°C. In the present study, muffle furnace with natural atmosphere was used for sintering the P/M composite electrode. After sintering operation, the machine tool grinder (Model: DS3CD, Make: Solid) was used to grind the leading face of the P/M composite tool electrodes to make it at right angle to its axis. A pictorial view of P/M composite electrode after sintering is shown in Figure 2. This P/M composite electrode was used in EDM machine and effect of an input variable on the response was recorded, keeping the middle values of other input parameters constant.

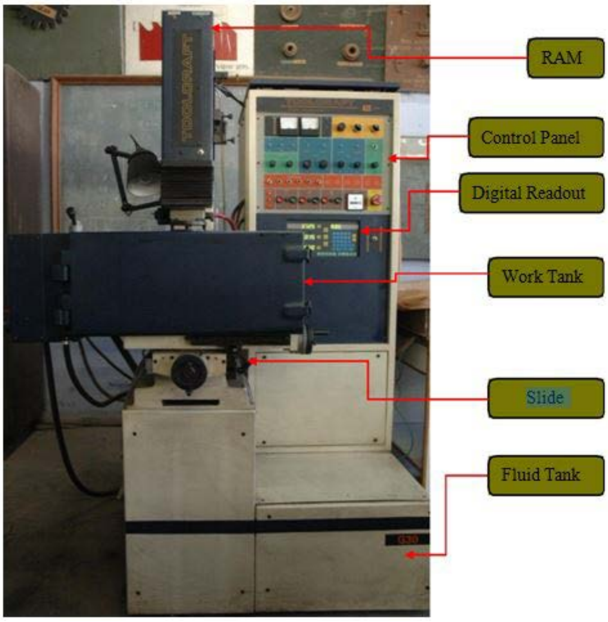

Figure 1. EDM machine used for experimentation

Table 1. Chemical composition of EN-31steel

Elements	C	Si	Mn	P	S	Cr	Fe
Wt. %	1.09	0.25	0.53	0.07	0.07	1.0	Balance

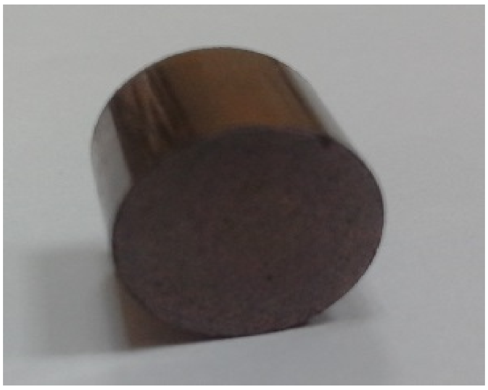

Figure 2. Additive mixed Cu-W P/M composite electrode

During EDM process, EDM-30 was used as dielectric fluid with side flushing technique. The machining time was fixed for all experiments as 10 minutes.

The input process parameters and machining conditions were chosen based on literature reviews.

- Metal powder composition: Cu9-W90 (Additive 1%)
- Peak discharge current: 3- 9 Amperes
- Pulse on-time: 5-25 µsec
- Pulse off-time: 50-250 µsec
- Compaction pressure: 500-1300 MPa
- Sintering temperature: 300°C
- Polarity: Negative.

Surface Deposition Rate (SDR), Surface Roughness (SR) and Micro Hardness (MH) were taken as three output process parameters for the present research work. SDR is the net addition of material on work surface per unit time (mg/min). It was determined by weighing work piece before and after machining and dividing by machining time. SDR for each work piece machined, was measured and recorded. Surface roughness is quoted as µm (micron). In the present experimental work, Mitutoyo portable roughness tester, 'Surftest SJ-301' contact type measurement instrument was used to measure the surface roughness. As the thickness of modified layer during surface modification is less than 20 µm, so the micro-hardness tester was used for hardness testing.

(a) Effect of peak Discharge Current

Three additives zinc stearate, calcium stearate and nickel were added one by one in the P/M composite electrode of Cu-W. The percentage of additive was fixed to 1% by weight. The peak discharge current(Ip) was varied in three steps as 3, 6, and 9 Amps. The values of pulse on-time (T_{on}), pulse off-time (T_{off}), powder compaction pressure (P_c), powder composition and sintering temperature were selected as 15 µsec, 150 µsec, 900 MPa, Cu9-W90 and 300°C respectively. The effect of variation of input process parameter, Ip with three different additives on the performance/output process parameters obtained is given in Table 2.

(b) Effect of compaction pressure

For pilot experimentation, the levels of compaction pressure selected were 500, 900 and 1300 MPa. The values of other input parameters were kept constant as peak discharge current=6 Amp, pulse on-time=15 µsec, pulse off-time 150 µsec, composition Cu9-W90 (1% additive) and sintering temperature=300°C. The data obtained for performance parameters were recorded and is given below in Table 3.

Table 2. Effect of Peak Discharge Current on Output Parameters

Additive Used	Output Parameters	Peak Current, I_P		
		3 Amp	6 Amp	9Amp
Zinc Stearate	Surface roughness(µm)	8.2	7.93	6.82
	Surface deposition rate (mg/min)	0.053	0.166	1.2614
	Micro-hardness (HRC)	68.9	70.2	74.5
Calcium Stearate	Surface roughness(µm)	8.82	7.69	7.53
	Surface deposition rate (mg/min)	0.18	0.78	1.28
	Micro-hardness (HRC)	68.5	70.3	71.6
Nickel	Surface roughness(µm)	9.87	9.16	8.4
	Surface deposition rate (mg/min)	0.02	0.027	0.122
	Micro-hardness (HRC)	62.8	64.6	65.9

Table 3. Effect of Compaction pressure on Output Parameters

Additive Used	Output Parameters	Compaction Pressure, P_C		
		500 MPa	900 MPa	1300 MPa
Zinc Stearate	Surface roughness(µm)	9.4	8.9	8.3
	Surface deposition rate (mg/min)	0.25	0.16	0.06
	Micro-hardness (HRC)	78.4	74.3	72
Calcium Stearate	Surface roughness(µm)	7.4	6.41	5.4
	Surface deposition rate (mg/min)	0.46	0.19	0.01
	Micro-hardness (HRC)	71.6	69.3	67.4
Nickel	Surface roughness(µm)	9.2	8.6	8.1
	Surface deposition rate (mg/min)	0.03	0.02	0.016
	Micro-hardness (HRC)	66.5	65.8	65.2

Table 4. Effect of Pulse on-time on Output Parameters

Additive Used	Output Parameters	Pulse on-time, Ton		
		5 µsec	15 µsec	25 µsec
Zinc Stearate	Surface roughness(µm)	8.42	9.1	11.28
	Surface deposition rate (mg/min)	0.12	0.51	0.94
	Micro-hardness (HRC)	72.1	71.6	71.3
Calcium Stearate	Surface roughness(µm)	6.05	6.3	6.97
	Surface deposition rate (mg/min)	0.19	0.63	0.86
	Micro-hardness (HRC)	71.4	69.9	61.9
Nickel	Surface roughness(µm)	8.3	9.7	11.01
	Surface deposition rate (mg/min)	0.21	0.29	0.44
	Micro-hardness (HRC)	63.9	62.4	61.9

(c) Effect of pulse-on time

For experimentation, the levels of pulse on-time were selected as 5, 15, and 25 µsec respectively. The values of other input parameters were kept fixed as peak discharge current=6 Amp, pulse off-time=15 µsec, powder compaction pressure 900 MPa, powder composition Cu9-W90 (1% additive) and sintering temperature at 300^{o}C. Surface modification was done with die-sinking EDM and the data obtained for performance parameters are given in Table 4.

(d) Effect of pulse-off time

The pulse off-time (T_{off}) was varied from 5 to 500 µsec to analyse its impact on output parameters by holding the peak discharge current, pulse on-time, compaction pressure, powder composition and sintering temperature at 6 Amp, 15 µsec and 900 MPa, Cu9-W90 (1% additive) and 300°C respectively. The result obtained is given in Table 5.

The inferences drawn from the pilot experiments are as follows:

- The best surface finish and maximum surface deposition rate was achieved when using 1% calcium stearate as an additive in P/M Cu-W composite electrode.
- The increase of peak discharge current resulted in rise of surface finish and improves the surface deposition rate during surface modification of En-31 die steel.
- Micro-hardness was also increased with the increase of peak discharge current.
- The pulse off-time was affecting all the three performance parameters. All performance parameters decrease with the increase in pulse off-time.
- The surface roughness, surface deposition rate and micro hardness decreases with the increase in powder compaction pressure.
- Minimum surface roughness of 5.04 at pulse off time of 250µs and maximum surface deposition rate of 0.128mg/min was achieved at a peak current of 9 Amp using calcium stearate as additive in P/M Cu-W composite electrode.

2.2. Main Experimentation

Based on the pilot experiments executed by using different additives in P/M composite electrode, the best surface roughness, surface deposition rate and micro hardness was achieved by using calcium stearate as an additive and therefore it was selected for main experimentation. Calcium stearate was used as only additive in Cu-W P/M composite electrode for final experimentation work. RSM methodology was used to plan the number of experiments. The experimental work was conducted strictly as per the planned schedule. The input parameters and their levels were selected for subsequent experimentation and are shown in Table 6.

Experiments were carried out strictly as per designed experimental plan based on rotatable central composite design. It was composed of 30 experiments which consist of 24 corner points, 6 centre points and 8 axial runs. Appendix-I shows the design of experiments matrix with actual and coded values of input process parameters along with output responses.

The Central Composite Rotatable Design (CCRD), ANOVA and F-test values, P-values were used to plan the experiments and subsequent analysis was done of data collected during main stage of experimentation work. The experiments were conducted to investigate the impact of different setting levels of input process parameters on output (performance) parameters.

Table 5. Effect of Pulse off-time on output parameters

Additive Used	Output Parameters	Pulse off-time, T_{off}		
		50 µsec	150 µsec	250 µsec
Zinc Stearate	Surface roughness(µm)	8.05	7.9	7.6
	Surface deposition rate (mg/min)	0.15	0.12	0.09
	Micro-hardness (HRC)	78.7	74.3	69.6
Calcium Stearate	Surface roughness(µm)	6.17	5.91	5.04
	Surface deposition rate (mg/min)	0.25	0.12	0.06
	Micro-hardness (HRC)	74.7	72.6	68
Nickel	Surface roughness(µm)	9.48	9.6	6.23
	Surface deposition rate (mg/min)	0.02	0.012	0.003
	Micro-hardness (HRC)	67.5	62.3	61.8

Table 6. Experimental input variables along with selected levels

S. No.	Process parameters	Units	Levels				
			-2	-1	0	+1	+2
1.	Peak discharge current (I_p)	Amp	3	4.5	6	7.5	9
2.	Pulse-on time (T_{on})	µs	5	10	15	20	25
3.	Pulse-off time (T_{off})	µs	50	100	150	200	250
4.	Compaction pressure (P_c)	MPa	500	700	900	1100	1300

The maximum surface deposition rate achieved was 1.4 mg/min at 7.5 Amp peak current, 20 µsec pulse on-time, 100 µsec pulse off-time and 700 MPa compaction pressure. However, setting parameter values at 4.5 Amp peak current, 10 µsec pulse on-time, 200 µsec pulse off-time and 700 MPa compaction pressure resulted in lowest surface deposition rate of 0.02 mg/min. The best value of surface finish obtained was 4.47 µm at 7.5 Amp peak current, 10 µsec pulse on-time, 200 µsec pulse off-time and 1100 MPa powder compaction pressure and the parameters setting at 6 Amp peak current, 15 µsec pulse on-time, 150 µsec pulse off-time and 500 MPa compaction pressure resulted in highest surface roughness i.e. 7.97 µm. The maximum and minimum value of micro hardness observed was 78.3 HRC and 57.6 HRC. The maximum value was observed at 7.5 Amp peak current, 10 µsec pulse on-time, 100 µsec pulse off-time and 700 MPa compaction pressure.

2.1. Mathematical Modelling

The experimental results obtained during main stage of experimentation were used to develop the mathematical models through Response Surface Methodology (RSM). Commercial available software (Design Expert 6.0) was used to develop the mathematical models. The experiments which have to be carried out in order to determine coefficients of model are recorded in Table 2. The surface deposition model, surface roughness model and micro hardness model are shown below in equations (1) (2) and (3) respectively.

$$\begin{aligned} SDR = &+0.73 + 0.29 I_P + 0.12 T_{on} - 0.15 T_{off} \\ &-0.12 P_C - 0.04 I_P{}^2 - 0.071 T_{on}{}^2 - 0.038 I_P T_{off} \\ &-0.093 I_P P_C - 0.074 T_{on} T_{off} + 0.036 T_{on} \end{aligned} \quad (1)$$

$$\begin{aligned} SR = &+6.49 - 0.36 I_P + 0.18 T_{on} - 0.44 T_{off} \\ &-0.52 P_c - 0.05 I_P{}^2 - 0.11 T_{off}{}^2 - 0.05 P_c{}^2 \\ &-0.02 I_P T_{on} - 0.02 I_P T_{off} - 0.02 I_P P_c \\ &-0.02 T_{on} T_{off} - 0.02 T_{on} P_c - 0.02 T_{off} P_c \end{aligned} \quad (2)$$

$$\begin{aligned} MH = &+69.1 + 0.82 I_P - 0.88 T_{on} - 4.13 T_{off} \\ &-1.14 P_C + 0.34 I_P{}^2 + 0.5 T_{on}{}^2 - 0.41 T_{off}{}^2 \\ &+0.3 P_C{}^2 - 0.5 I_P T_{on} + 0.5 I_P T_{off} - 0.5 I_P P_C \\ &+0.5 T_{on} T_{off} - 0.5 T_{on} P_C + 0.5 T_{off} P_C. \end{aligned} \quad (3)$$

2.2. Analysis of Experimental Results

Statistical analysis of the experimental results was carried out with Analysis of Variance (ANOVA) to obtain the percentage contribution and significance of the factors. The ANOVA process helps to analyse the factors having interaction effect, main effects, less significant and noise. Therefore this becomes helpful in deciding the factors which are most appropriate for performing the required analysis therefore increasing the product robustness. The ANOVA results for surface deposition rate model, surface roughness model and micro hardness model are shown in Table 7, Table 8 and Table 9 respectively.

The P-values shown in Table 7 revealed that peak current is significant even at 99 % confidence level for the surface deposition rate and contributes 56.1% towards surface deposition rate. Further, it was observed by examining the F-values that the second most important factor is pulse off-time having percentage contribution of 13.8%. It is obvious that value of surface deposition rate depends upon the spark energy (function of factor peak discharge current) in the gap as well as flushing conditions (function of pulse off-time).The lack of fit (F-value) is 116.97, which implies that the lack of fit is also significant relative to pure error even at 99% confidence level; hence, developed second order model for surface deposition rate is adequate and significant. The pure error for the sum of squares is very small (0.003) which confirms further that the surface deposition model works well as an approximation to the true response surface. The multiple regression coefficient (R-squared) for the second order model is used as a measure of agreement for fit. The R-squared for surface deposition model is 0.8510, which means that 85.10% of the variance in the surface deposition rate is explained uniquely or jointly by the independent variables. Hence, the second order model developed is fairly strong enough to be used in predicting the surface deposition rate.

The F-value in Table 8 shows that compaction pressure is the most dominant factor of all the considered factors for representing the surface roughness. At lower compaction pressure bigger lumps of electrode material fall on the work piece which increases surface roughness. It contributes 41.3% for controlling surface roughness. The second most important factor is the pulse off time. This is as expected because it is well known that surface roughness is a function of flushing conditions (function of pulse off-time). Pulse off-time is having 29.8% contribution for controlling surface roughness.

Table 7. ANOVA, F-test values for surface deposition rate

Source	Sum of Squares	DOF	Mean Squares	F-value	P-value Prob> F
Model	3.667	14.00	0.262	6.119	0.0006
I_p	2.059	1	2.059	48.098	< 0.0001
T_{on}	0.334	1	0.334	7.794	0.0137
T_{off}	0.508	1	0.508	11.854	0.0036
P_c	0.324	1	0.324	7.576	0.0148
I_p^2	0.044	1	0.044	1.020	0.3286
T_{on}^2	0.139	1	0.139	3.243	0.0919
T_{off}^2	0.000	1	0.000	0.001	0.9731
P_c^2	0.001	1	0.001	0.015	0.9030
I_pT_{on}	0.000	1	0.000	0.001	0.9716
I_pT_{off}	0.023	1	0.023	0.543	0.4725
$I_p P_c$	0.139	1	0.139	3.241	0.0920
$T_{on} T_{off}$	0.089	1	0.089	2.067	0.1710
$T_{on} P_c$	0.020	1	0.020	0.474	0.5015
$T_{off} P_c$	0.000	1	0.000	0.000	0.9905
Residual	0.642	15	0.043		
Lack of Fit	0.639	10	0.064	116.974	< 0.0001
Pure Error	0.003	5	0.001		
Cor Total	4.310	29			
R-Squared 0.8510					
Adj R-Squared 0.7119					

Table 8. ANOVA, F-test values for surface roughness

Source	Sum of Squares	DOF	Mean Squares	F-value	P-value Prob> F
Model	15.4	14	1.1	3.587	0.0097
I_p	3.12	1	3.12	10.222	0.0060
T_{on}	0.79	1	0.79	2.591	0.1283
T_{off}	4.59	1	4.59	15.028	0.0015
P_c	6.37	1	6.37	20.823	0.0004
I_p^2	0.07	1	0.07	0.236	0.6344
T_{on}^2	0	1	0	0.001	0.9814
T_{off}^2	0.35	1	0.35	1.161	0.2983
P_c^2	0.08	1	0.08	0.247	0.6262
I_pT_{on}	0.01	1	0.01	0.021	0.8869
I_pT_{off}	0.01	1	0.01	0.021	0.8869
$I_p P_c$	0.01	1	0.01	0.021	0.8869
$T_{on} T_{off}$	0.01	1	0.01	0.021	0.8869
$T_{on} P_c$	0.01	1	0.01	0.021	0.8869
$T_{off} P_c$	0.01	1	0.01	0.021	0.8869
Residual	4.59	15	0.31		
Lack of Fit	3.83	10	0.38	2.530	0.1587
Pure Error	0.76	5	0.15		
Cor Total	19.9	29			
R-Squared 0.77					
Adj R-Squared 0.55					

Table 9. ANOVA, F-test values for micro hardness

Source	Sum of Squares	DOF	Mean Squares	F-value	P-value Prob> F
Model	518	14	37	10.9	< 0.0001
I_p	16	1	16	4.73	0.0461
T_{on}	18.4	1	18.4	5.43	0.0342
T_{off}	410	1	410	121	< 0.0001
P_c	31.3	1	31.3	9.24	0.0083
I_p^2	3.12	1	3.12	0.92	0.3520
T_{on}^2	6.86	1	6.86	2.03	0.1752
T_{off}^2	4.67	1	4.67	1.38	0.2587
P_c^2	2.47	1	2.47	0.73	0.4066
I_pT_{on}	4	1	4	1.18	0.2942
I_pT_{off}	4	1	4	1.18	0.2942
$I_p P_c$	4	1	4	1.18	0.2942
$T_{on} T_{off}$	4	1	4	1.18	0.2942
$T_{on} P_c$	4	1	4	1.18	0.2942
$T_{off} P_c$	4	1	4	1.18	0.2942
Residual	50.8	15	3.39		
Lack of Fit	44.9	10	4.49	3.83	0.0755
Pure Error	5.86	5	1.17		
Cor Total	569	29			
R-Squared0.9107					
Adj R-Squared0.8274					

To test the lack of fit for the surface roughness model, lack of fit test was also performed. The calculated F-value of 2.53 indicates that the lack of fit is not significant relative to the pure error even at 99% confidence level, which implies that the second order model is adequate to represent correlations between the model response and the input parameters considered for the surface modification process. The value of R-squared of the second order roughness model is observed as 0.77. This means that the variance of 77% in the surface roughness is explained uniquely or jointly by the independent variables considered. Hence, the second order model developed is fairly strong enough to be used in predicting the surface roughness.

The P-value is shown in Table 9 which indicates that the regression model is significant even at 99% confidence level. Pulse off time is main contributors for micro hardness. It is because micro hardness depends on flushing condition.

The F value for lack of fit is 3.83 which indicate that the lack of fit is not significant relative to the pure error even at 99% confidence level, which implies that the second order model is adequate to represent correlations between the model response and the input parameters considered for the surface modification process. The value of R-square is 0.9107 which indicates that the variance of 91.07% in the micro hardness is explained uniquely or jointly by the independent variables considered.

3. Parametric Analysis

The parametric analysis has been carried out to study the effects of input process parameters on output responses such as surface deposition rate, surface roughness and micro hardness during surface modification of En-31.

3.1. Effects of Input Parameters on Surface Deposition Rate

The effect of peak current and pulse off-time on SDR while holding the values of other parameters as centre value is shown in Figure 3 as three dimensional plot. It can be seen that with the increase in peak current the surface deposition rate is more and there is small decrease in SDR with increase in pulse-off time.

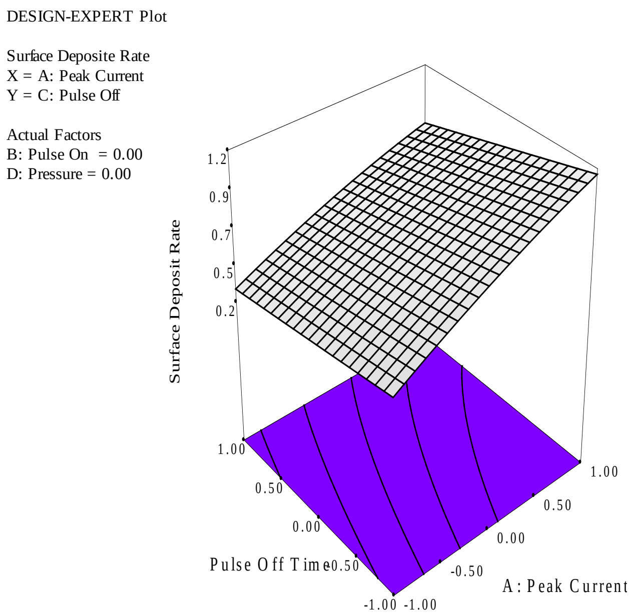

Figure 3. Variation of Surface Deposition Rate V/s Peak current and Pulse off-time

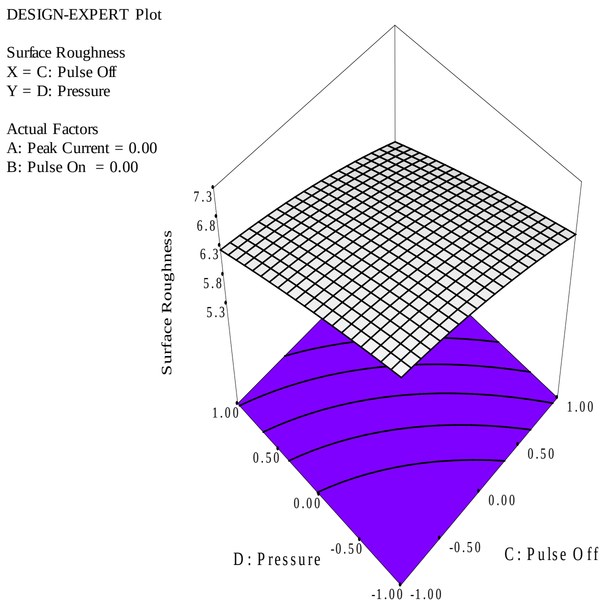

Figure 4. Variation of Surface Roughness V/s Pulse off-time and Compaction pressure

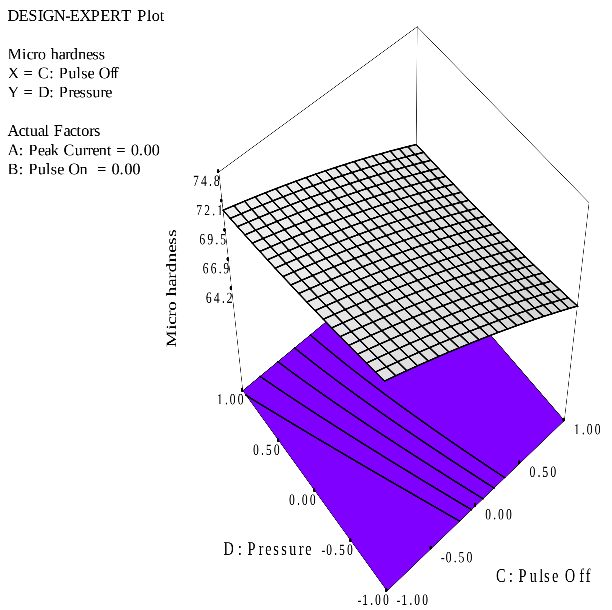

Figure 5. Variation of Micro Hardness V/s Pulse off-time and Compaction pressure

3.2. Effects of Input Parameters on Surface Roughness

The three dimensional plot of surface roughness shown in Figure 4 depicts increase in surface roughness while decreasing compaction pressure and pulse off-time. The compaction pressure was varied from 500 MPa to 1300 MPa and pulse off-time was varied from 50µsec to 250µsec.

3.3. Effects of Input Parameters on Micro Hardness

The micro hardness decreases slightly by increasing the compaction pressure and decreases more by increasing the pulse-on time as shown in Figure 5. The figure shows that pulse off- time has more effect than compaction pressure on the micro hardness.

4. Microstructure Analysis

In the present work Scanning Electron Microscope (SEM) combined with Energy Dispersive Spectroscopy (EDS) was used to carry out the microstructure studies along with elemental analysis.

4.1. SEM micrograph Analysis

Figure 6 depicts the micrograph of test specimens of En-31 steel along with coating of surface modification process. The microstructure shows significant surface layer changes as a result of machining with copper-tungsten electrode. In Figure 7 small granules of coated material is shown. It is due to the migration of tungsten and copper from the copper-tungsten composite electrode in the presence of EDM-30 dielectric fluid. Tungsten forms hard, abrasion-resistant particles in carbon steels and promotes hardness and strength at elevated temperatures. It can exist in different forms in die steels. It may dissolve in the ferrite or cementite phases of the iron-carbon system or it may be present as independent carbide in the form of WC, W_2C, etc.

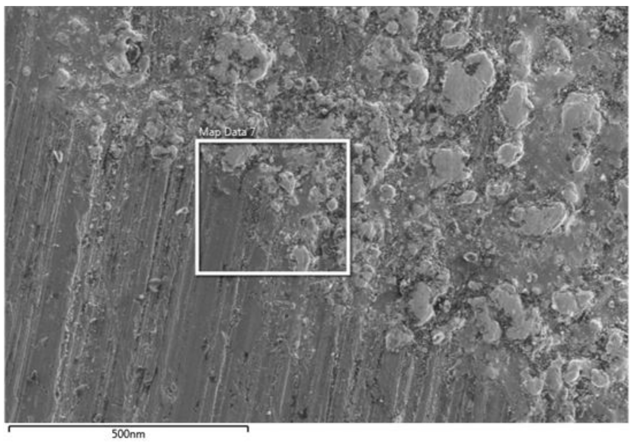

Figure 6. SEM micrograph of En-31die steel and coated layer

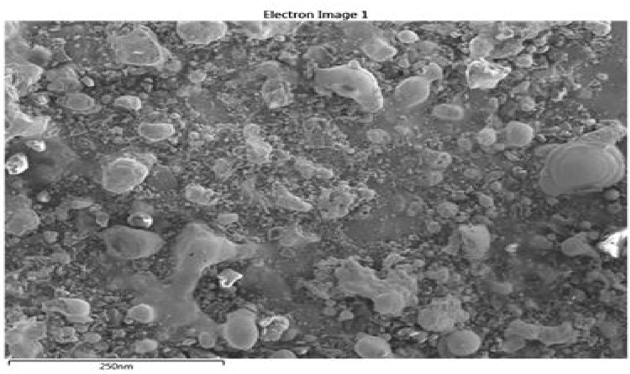

Figure 7. SEM-micrograph of En-31 steel after Surface modification process

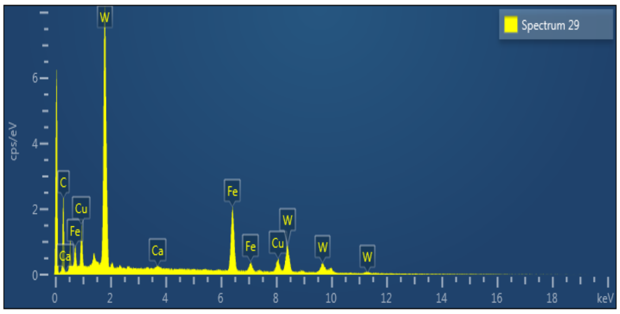

Figure 8. EDS Spectrum of deposited layer on En-31 steel

4.2. Energy Dispersive Spectroscopy

Energy Dispersive Spectroscopy (EDS) was carried out to examine the elemental information about the constituents of the deposited layer. It is used together with the SEM for the micro-chemical analysis. The constituents in the yellow box on SEM micro-graph were recorded and the results obtained are shown as EDS spectrum in Figure 8.

EDS shows the X-ray peaks corresponding to different energy orbits of tungsten, copper, calcium and ferrous elements detected in deposited layer. The peaks are close to the standard binding energy values for different elements thereby confirming the presence of tungsten, copper, calcium and ferrous elements in the deposited layer.

5. Conclusions

After analysing the results of surface modification of En-31 steel using additive mixed P/M tool electrode in EDM process the following conclusions are drawn:

- The maximum surface deposition rate achieved is 1.4 mg/min at 7.5 Amp peak current, 20 µsec pulse on-time, 100 µsec pulse off-time and 700 MPa compaction pressure.
- The best value of surface finish obtained is 4.47 µm at 7.5 Amp peak current, 10 µsec pulse on-time, 200 µsec pulse off-time and 1100 MPa powder compaction pressure.
- The maximum and minimum value of micro hardness observed was 78.3 HRC and 57.6 HRC. The maximum value was observed at 7.5 Amp peak current, 10 µsec pulse on-time, 100 µsec pulse off-time and 700 MPa compaction pressure. However, the minimum value was obtained at 6 Amp peak current, 15 µsec pulse on-time, 250 µsec pulse off-time and 900 MPa powder compaction pressure.

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Appendix-I Design matrix and Experimental results of performance parameters

Run No.	Input Process Parameter								Observed Responses		
	I_p		T_{ON}		T_{OFF}		P_C		SDR (mg/min)	SR (μm)	MH (HRC)
	Actual	Coded	Actual	Coded	Actual	Coded	Actual	Coded			
1	4.5	-1	20	1	200	1	1100	1	0.15	5.52	63.6
2	6	0	15	0	250	2	900	0	0.74	5.95	57.6
3	7.5	1	20	1	200	1	700	-1	0.8	5.76	68.5
4	6	0	15	0	150	0	900	0	0.72	6.82	70.3
5	7.5	1	20	1	100	-1	700	-1	1.4	6.8	77.6
6	7.5	1	10	-1	200	1	700	-1	1.08	5.48	69.2
7	4.5	-1	20	1	200	1	700	-1	0.1	6.53	65.4
8	7.5	1	20	1	100	-1	1100	1	1.08	5.79	67.8
9	6	0	15	0	150	0	900	0	0.76	6.82	70.3
10	7.5	1	20	1	200	1	1100	1	0.48	4.75	66.7
11	4.5	-1	10	-1	200	1	700	-1	0.02	6.25	66.1
12	6	0	15	0	150	0	900	0	0.72	6.3	69.3
13	6	0	15	0	150	0	900	0	0.7	5.91	68
14	6	0	15	0	150	0	900	0	0.71	6.25	67.8
15	6	0	15	0	150	0	900	0	0.75	6.82	68.9
16	4.5	-1	20	1	100	-1	1100	1	0.38	6.56	72.7
17	4.5	-1	20	1	100	-1	700	-1	0.7	7.57	74.5
18	6	0	5	-2	150	0	900	0	0.32	6.59	71.7
19	7.5	1	10	-1	200	1	1100	1	0.1	4.47	67.4
20	6	0	25	2	150	0	900	0	0.89	7.49	68
21	6	0	15	0	50	-2	900	0	1.05	7.2	74.8
22	4.5	-1	10	-1	200	1	1100	1	0.08	5.24	64.3
23	7.5	1	10	-1	100	-1	700	-1	1.02	6.52	78.3
24	3	-2	15	0	150	0	900	0	0.18	7.53	68.5
25	6	0	15	0	150	0	1300	2	0.77	5.67	67.8
26	6	0	15	0	150	0	500	-2	0.97	7.97	70.3
27	4.5	-1	10	-1	100	-1	700	-1	0.32	6.97	75.2
28	4.5	-1	10	-1	100	-1	1100	1	0.08	6.28	73.4
29	9	2	15	0	150	0	900	0	1.28	6.12	69.9
30	7.5	1	10	-1	100	-1	1100	1	0.7	5.51	76.5