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Surface Modification for EN-19 steel in Powder Mixed Electrical Discharge Machining Process due to Complex Material Transfer Phenomena

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Abstract

The presented research paper is a study of surface morphology and change in composition of EN-19 steel work surfaces. Powder mixed electrical discharge machining (PMEDM) process was applied to investigate the work surface. Energy Dispersive X ray (EDX) analysis was done for selected workpiece samples to confirm presence of additional elements in machined surfaces. Composition testing was done on spectrometer with the objective to confirm the material transfer on machined surface. Quantitative analysis has also been done to investigate changes in machined surface constituents. Scanning electron microscopy of selected samples has also been carried out to analyse the microstructure. The paper reports resulted changes in surface structure of machined object due to complex material transfer phenomena between workpiece and electrode.

Keywords: EDM, EDX, PMEDM, Machining, SEM

1. Introduction

The present requirement of machining is good surface finish with easy manufacturing. One of the popular non-traditional machining technologies applied since more than half century is Electrical Discharge Machining (EDM). It's working principle is use of the eroding effect on the electrodes by successive electric spark in a dielectric fluid. These days, EDM is a widely used machining process in many applications of industrial areas. One more advantage of the process is its ability of machining hardened tool steels. However, the process has limitations of poor machining efficiency along with poor surface finish. These limitations restrict its further applications. These issued were addressed in relatively new improvements in EDM process. One of such method is electrical discharge machining with mixing of fine powder particles in dielectric fluid. This hybrid method of machining is called as powder mixed electrical discharge machining (PMEDM). These mixed fine powder particles influence the machining performance significantly. These powder particles are electrically conductive in nature and thus insulating strength of dielectric liquid is reduced by their presence. Consequently, there is an increased spark gap between tool electrode and work piece. As a result, this process is much stable with improved material removal rate (MRR) with lower surface roughness.

2. Literature review

Fundamental principle of PMEDM process has been thoroughly investigated and described by the researchers and engineers [1-3]. Researchers investigated PMEDM process by mixing of silicon powder in dielectric liquid [4-6]. Researchers also reported significant improvement in surface characteristics of corrosion resistance, hardness and wear resistance by applying this PMEDM method [7-8]. Saleem et al., (2018) and Patel et al. (2018) reported machined surface improvement by mixing aluminium powder particles in dielectric liquid [9-10]. Process parameters were optimized by researchers using response surface methodology (RSM) [11-12]. Experiments were conducted experiments to study the effects of mixing powder in dielectric on machining performance [13-14]. Effect silicon powder mixed dielectric on machining performance of AISI D2 die steel was reported [1]. Effect of electrode area on topography and surface roughness was reported by experimentation [15]. Influence of micro powder suspension along with ultrasonic vibration in micro-EDM processes was investigated in one research work [16]. Kung et al. (2009) investigated PMEDM for cobalt-bonded tungsten carbide material for material removal rate and electrode wear ratio [17]. Researchers have studied influence of using micro nickel powder on PMEDM performance factors [18]. EN-19 steel with round shaped electrodes was investigated to optimize the PMEDM process parameters for different shape of triangular electrodes [19]. The same researchers have also reported the influence of chromium powder mixed dielectric on surface roughness [20]. An experimental study was conducted with different dielectrics on material removal characteristics [21]. A modified tool design was proposed for effectively removing the debris particles [22]. This design also helps in drilling holes without any central core. Torres et al. (2015) proposed the models for various EDM performance measures [23]. Sharma et al. (2020) investigated effect of PMEDM on surface modification of titanium alloy [24].

The objective of the literature review is aimed of reporting the work of various researchers in the chosen area of PMEDM and also to identify the literature gap existing due to untouched areas. After critically and elaborately scrutinizing

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the reported published work, following conclusive remarks can be made:

- As compared to traditional EDM process, PMEDM is still a relatively less explored area.
- Maximum reported literature on tool design in EDM process is relating to parametric optimization, improving the performance measures and selecting of suitable work-tool interface. There is not enough published work on surface modification in machined surfaces in PMEDM.

In this experimental research, different combinations of selected process parameters have been investigated for EN-19 steel. These selected variable parameters were duty cycle, average current, electrode diameter and Ni micro powder particles concentration in dielectric. Careful examination of published literature reveals that EN-19 steel material with this type of parametric combination was not investigated for surface modification study. Also, by scrutiny of published literature, it was confirmed that the selected workpiece-chromium powder combination was not investigated for surface modification studies. Surface morphology and change in surface composition of produced surface has been chosen to be studied. SEM and EDX analysis have been carried out to study surface microstructure and presence of additional elements in machined surface. Also, Composition testing on spectrometer was done to study the material transfer and changes in the machined surface constituents.

3. Description of experiments

3.1 Set up applied for experiments

Figure 1 presents line diagram for applied experimental set up. T 3822 EDM machine from 'Electronica' company was used for conducting experiments. The salient points of this PMEDM experimental set up design are:

- ➢ To avoid particle filtering, the powder particles must not be allowed to enter the main dielectric tank.
- ➢ There must be continuous stirring and circulation of dielectric in order to prevent powder particle settling and to maintain uniformity in particle concentration.

In this setup, valve arrangements are used to disconnect main dielectric sump from dielectric. A flush mixing arrangement is provided in experimental set up to obtain homogeneous and even powder particle distribution in dielectric fluid. This arrangement is shown in Figure 1. For this purpose, a plastic pipe frame with 25 mm diameter pipes was used. The pipe frame had the holes of 3 mm diameter in it.

A liquid pump (power- 1.5 horsepower, maximum discharge - 5500 litre per hour) is used to suck the dielectric from bottom level of tank. The sucked dielectric is then pumped in the pipe frame. This pumped liquid output is further divided into two branches as shown in Figure 1. The first branch is connected to the flushing nozzle. Flushing nozzle flow is adjusted by adjusting valve opening. This flushing nozzle has opening of 4 mm and adjusted flow through it is 500 litre /hour. Approximately uniform turbulence is developed into the dielectric tank due to continuous sucking of dielectric by pump and then flush mixing via pipe frame holes from all sides and via flushing nozzle at centre. This set-up design makes sure a uniform and homogeneous powder particle concentration in entire dielectric tank. The setup also ensures that the fine powder particles must not settle at tank bottom. Magnetic 'V' block was used to hold the job and two permanent magnets were provided into the tank to collect the separated iron particles from work piece. Since tool wear rate is not so significant like MRR, no arrangement was provided to separate copper from dielectric.

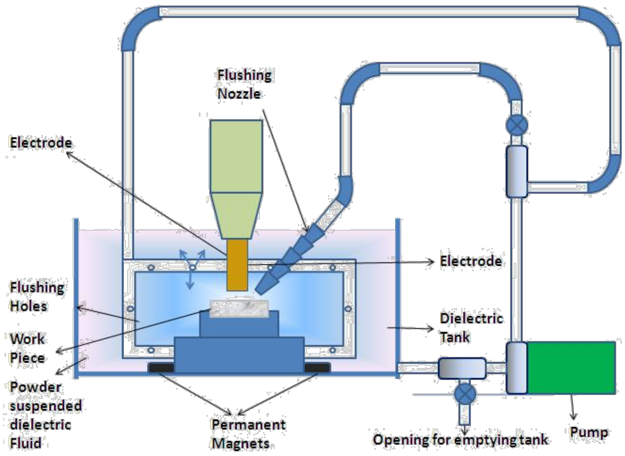

Fig. 1. Line diagram of experimental setup

3.2 Materials used in Experimentation

Selection of work piece, electrode, powder and dielectric materials was based on literature review, availability and applications. The selected as work piece material was EN-19 steel because of its wide applications and easy availability. From literature review, it can be concluded that EN-19 steel is yet to explored for PMEDM process.

EN-19 is an important steel having multiple and wide applications. This steel is used in fabricating small cross section components requiring low tensile strength together with heavy forging. Many automobile and general engineering parts like clutches, shafts, axles, presses and punches parts, gear rods and piston rods are fabricated by this steel. Therefore, study of this EN-19 steel machined with PMEDM is a promising research area.

Optical emission spectrometer was used to determine chemical composition of EN-19 steel material. The findings are summarized in Table 1. Manufacturer's specifications of work piece are presented in Table 2.

Table 1. Percentage of elements in EN-19 Steel

EN-19 steel composition	C %	Si %	Mn %	Cr %	Mo %	Fe
	0.37	0.37	0.57	1.1	0.24	Rest

Table 2. Manufacturer's specifications of EN-19 steel

EN-19 steel composition	
C %	0.37
Si %	0.37
Mn %	0.57
Cr %	1.1
Mo %	0.24
Fe%	Rest

Tool electrode material was made of commercial copper. As per manufacturer's specifications, this copper had 99% purity and had the electrical conductivity as 5.69×10^7 S/M. Spectrometer analysis was used to confirm the composition of copper as electrode material. Dielectric fluid used in experimentation was commercial kerosene. Table 3 presents the specifications of dielectric fluid.

Table 3. Specifications of dielectric fluid

Specifications for Kerosene oil	
Dielectric constant	1.8
Electrical conductivity	1.6×10^{-14} S/m
Density	730 kg/m^3
Dynamic viscosity	0.94 m Pas

Chromium powder was selected as powder for mixing in dielectric. Literature review reveals that this powder is relatively less explored in PMEDM field. The properties of this powder are summarized in **Table 4**.

Table 4: Chromium powder's specifications

Particle size	**45-55 µm**
C %	0.01
Cr %	99
P %	0.015
S %	0.015
Al %	0.08
Si %	0.09
Fe %	0.01
Sieve analysis 325 Mesh	97%
Electrical conductivity	7.9 x 106 S/m

4. Design of study

4.1. Design variable's selection

For identifying the most relevant process parameters affecting the work piece quality in PMEDM process, an Ishikawa cause–effect diagram is prepared. This diagram is presented in Figure 2. As presented in diagram, process parameters in PMEDM can be classified into following main categories:

- Parameters (Electrical): peak and average current, duty cycle, pulse-on and pulse-off time, supply voltage, polarity.
- Parameters(non-electrical): working time, gain and nozzle, flushing electrode lift time.
- Parameters (related to powder): powder type and concentration, powder shape and other properties such as conductivity, etc.
- Parameters (electrode characteristics): material and size and shape of electrode.

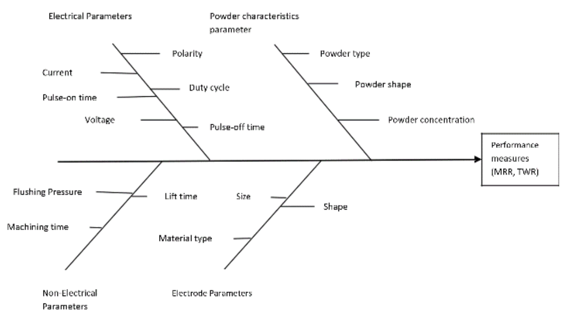

Fig. 2. Ishikawa cause–effect diagram

Selected parameters for this experimental study were:

- Average current (A)
- Duty cycle (%)
- Powder concentration (g/l)
- Diameter of electrode (mm)

The parameters were chosen based on preliminary experiments, literature review, sensitivity analysis and feasibility studies. Pilot experiments were conducted by using one variable at one-time approach. Average current and duty cycle are electrical parameters. Average current is measured in units of amperage and is an indicator of amount of power used in discharge machining. This is the most important machining parameter. The cut surface area governs the amperage required in in die-sinking EDM. For rough cutting operations or for large cavities higher amperage is needed. Higher amperage improves the MRR, but with poor surface finish and tool wear.

Pulse duration percentage relative to the complete cycle time is defined as duty cycle or duty factor. This is another chosen process parameter. It's higher value generally results in higher cutting efficiency. This factor is calculated in percentage by dividing the pulse duration time by total cycle time (pulse-on-time + pulse-off-time).

Powder concentration is a very important process parameter in PMEDM and was considered by most of the researchers in PMEDM field. In this research work, a circular electrode profile was investigated. For round electrodes, electrodes diameter was considered as design factor.

4.2 Plan for testing

To study surface morphology and composition changes due to migration of materials, SEM, EDX and spectrometer testing studies were performed on machined surfaces. For assessing the surface morphology of PMEDMed machined surfaces, SEM studies were conducted. 8 samples were prepared for SEM testing. Wire cut EDM and hand hacksaw were used to prepare samples. The parametric combinations of machined surfaces selected for SEM investigations are shown in Table 5.

Table 5. Parametric combinations for machined surfaces chosen for SEM/EDX studies

S.N.	Current	Duty cycle	Powder concentration	Electrode diameter	Studies
1	4	54	2	8	SEM/EDX
2	8	54	2	8	SEM/EDX
3	4	54	6	8	SEM/EDX
4	8	54	6	8	SEM/EDX
5	4	54	2	16	SEM
6	8	54	2	16	SEM
7	4	54	6	16	SEM
8	8	54	6	16	SEM

Machined surfaces with constant duty cycle were chosen since this parameter did not show any significant effect in developed models in published literature. Also, published literature confirms that electrode shape has no significant effect on material transfer and surface morphology. Powder concentration and average current are most dominant factors. The research work aims at showing the effects of these most dominant factors on material transfer phenomena and surface morphology. Also, for practical reasons, different sets of samples were prepared for SEM/EDX and spectrometer testing. Compositions testing of PMEDMed surfaces were carried out by EDX and spectrometer testing to determine migration of elements from dielectric, powders and electrode material to the machined surfaces. EDX analysis was performed on the samples prepared as per plan as shown in Table 5. Plan for spectrometer testing on selected samples is shown in Table 6. All the testing was performed on machined surfaces with round electrodes since by EDX testing it was confirmed that electrode profile has not any significance effect on migration of material. Data for percentage of elements in material before machining were taken from Table 1.

Table 6. Plan and results of spectrometer testing

Parameter setting				Carbon%		Chromium%	
A	B	C	D	Before	After	Before	After
4	63	4	12	0.35	0.86	Nil	Nil
6	63	4	12	0.35	1.03	Nil	0.25
8	63	4	12	0.35	1.62	Nil	0.12
6	63	2	12	0.35	1.15	Nil	0.15
6	63	4	12	0.35	1.18	Nil	0.76
6	63	6	12	0.35	1.21	Nil	2.13

5. Results and discussion

5.1 SEM results

The SEM photographs are shown in Figure 3. to Figure 10. These photographs reveal that the micro geometry of the surfaces is practically unaffected by electrode profile and is predominantly dependent on electrical parameter. Here average current variation shows an impact on machined surfaces. Analysis and observations of SEM results showed that the machined surfaces are in nature very. Very tiny craters with re-solidified grains were observed on the machined surface. The reason was not only the excess melting and rapid solidification but also because of electro discharge random attacks.

Machining damages like micro-voids, micro cracks and ridge rich surfaces were also observed on machined surfaces. The reason for ridge-rich surfaces was melted material during machining and blast out of the surface due to discharge pressure. The expelled gas bubbles from molten material in solidification process may be the cause of the micro-voids. Thermal stress is the cause for micro cracks. This residual stress is due to non-uniform distribution of temperature and drastic heating and cooling rate. More, the machined surface morphology was chiefly dependent on the applied discharge energy. With the application of varying pulsed current, the surface characteristic shows varying valleys and hillocks. The variation of pulsed current results in different types of deeper voids or cracks and more clear defects. Fine dispersion of hard particles can be seen in the three microstructures.

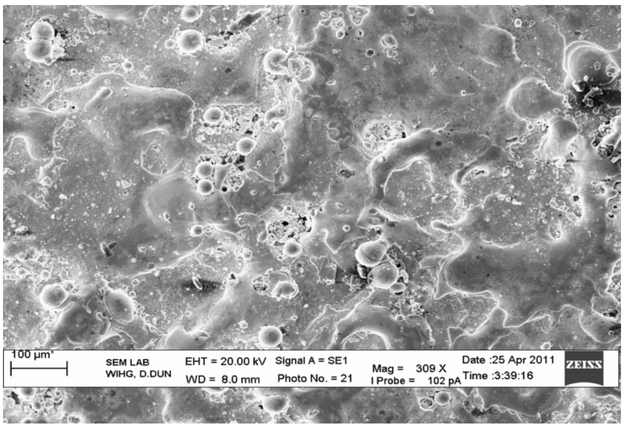

Fig. 3. Machined surface of EN-19 steel with round electrodes (Current = 4 A, Duty cycle = 54 %, Powder concentration = 2g/l, Electrode diameter = 8 mm)

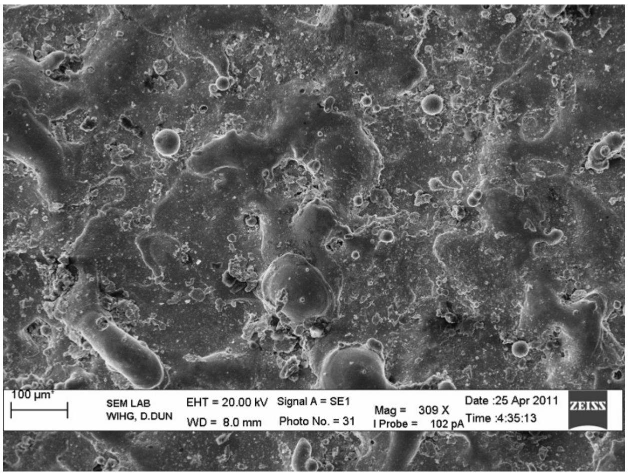

Fig. 4. Machined surface of EN-19 steel with round electrodes (Current = 8 A, Duty cycle = 54 %, Powder concentration = 2g/l, Electrode diameter = 8 mm)

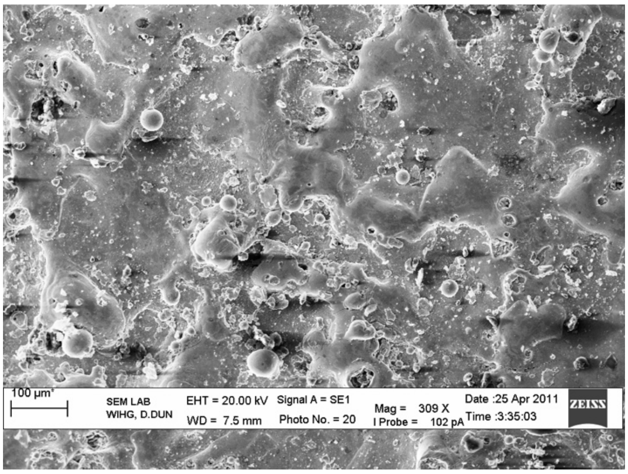

Fig. 5. Machined surface of EN-19 steel with round electrodes (Current = 4 A, Duty cycle = 54 %, Powder concentration = 6 g/l, Electrode diameter = 8 mm)

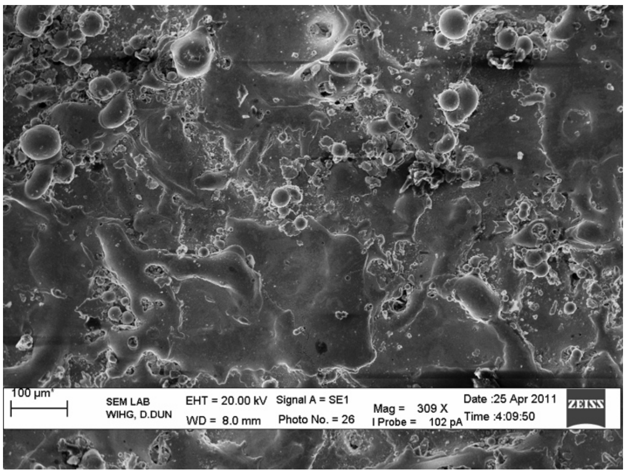

Fig. 6. Machined surface of EN-19 steel with round electrodes (Current = 8 A, Duty cycle = 54 %, Powder concentration = 6 g/l, Electrode diameter = 8 mm)

5.2 Composition testing results

The EDX patterns for EN-19 steel round electrodes are shown in Figure 11 to Figure 14. It is evident from these patterns that the machined surfaces have increased percent of carbon. The carbon content in machined surfaces was found as increased with increasing current. Migration of chromium into machined surface was also detected particularly at high powder concentration. The EDX pattern is almost same for both types of profiles - round and triangular confirming insignificance of profile parameter on surface composition change. Figure 14 shows exceptional EDX pattern. It is because EDX was performed on some impurity point. The EDX patterns show no trace of copper on the machined surfaces confirming no transfer of electrode material on the machined surfaces within set parametric range.

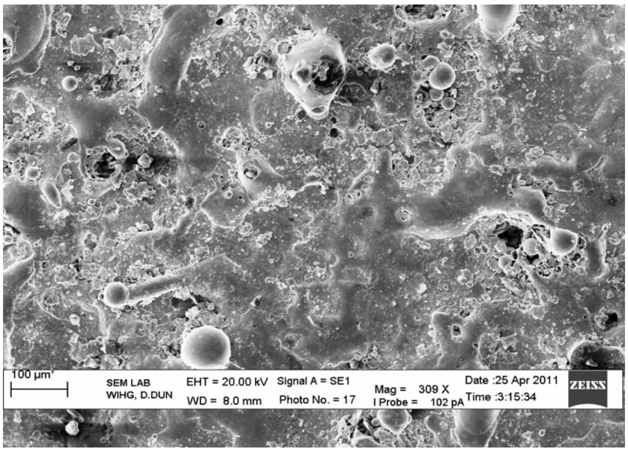

Fig. 7. Machined surface of EN-19 steel with round electrodes (Current = 4 A, Duty cycle = 54 %, Powder concentration = 2g/l, Electrode diameter = 16 mm)

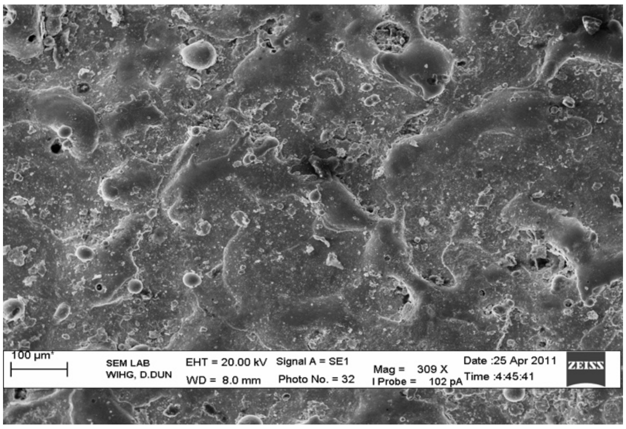

Fig. 8. Machined surface of EN-19 steel with round electrodes (Current = 8 A, Duty cycle = 54 %, Powder concentration = 2g/l, Electrode diameter = 16 mm)

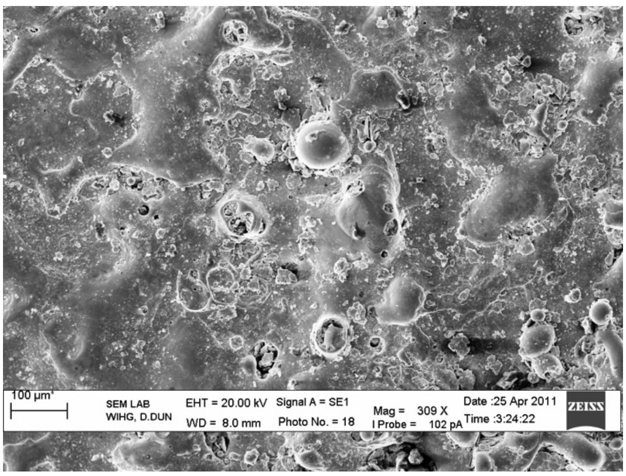

Fig. 9. Machined surface of EN-19 steel with round electrodes (Current = 4 A, Duty cycle = 54 %, Powder concentration = 6 g/l, Electrode diameter = 16 mm)

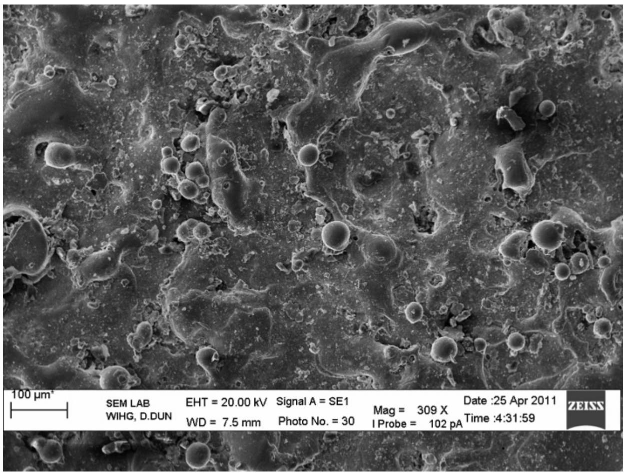

Fig. 10 Machined surface of EN-19 steel with round electrodes (Current = 8 A, Duty cycle = 54 %, Powder concentration = 6 g/l, Electrode diameter = 16 mm)

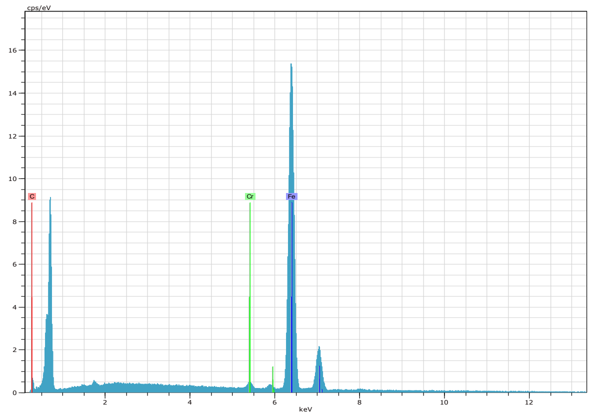

Fig. 11. EDX pattern of EN-19 steel with round electrodes (Current = 4 A, Duty cycle = 54 %, Powder concentration = 2g/l, Electrode diameter = 8 mm)

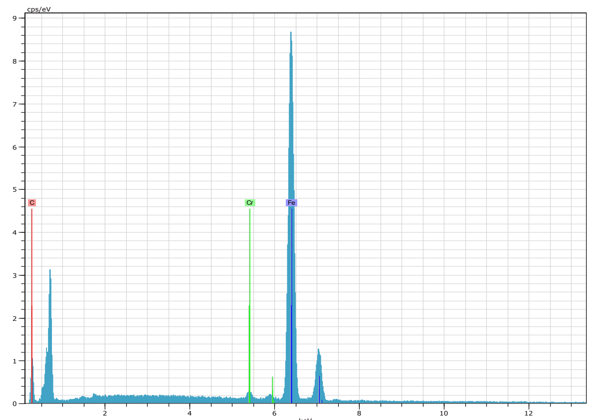

Fig. 12. EDX pattern of EN-19 steel with round electrodes (Current = 8 A, Duty cycle = 54 %, Powder concentration = 2g/l, Electrode diameter = 8 mm)

The results of spectrometer testing were plotted on column chart as shown in Figure 15. and Figure 16. The result reveals an increase in carbon percentage in all machining condition. The percentage of carbon in machined surfaces increase steadily with increase in average current but it is not sensitive to increase in concentration. The percentage of chromium increases with concentration level but both EDX and spectrometer testing results shows its non-uniform distribution on machined surface having erratic pattern. Chromium percentage is not so much affected by current variation.

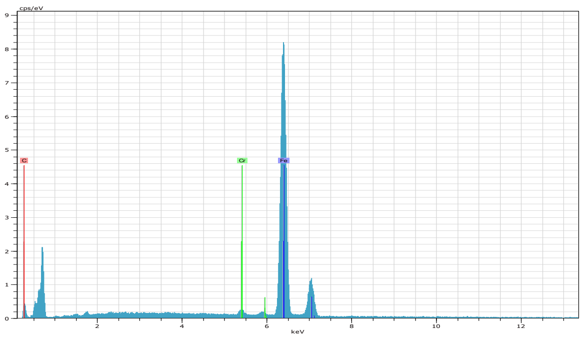

Fig. 13. EDX pattern of EN-19 steel with round electrodes (Current = 4 A, Duty cycle = 54 %, Powder concentration = 6 g/l, Electrode diameter = 8 mm)

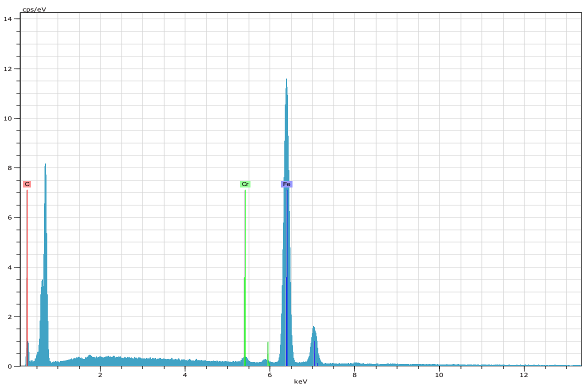

Fig. 14. EDX pattern of EN-19 steel with round electrodes (Current = 8 A, Duty cycle = 54 %, Powder concentration = 6 g/l, Electrode diameter = 8 mm)

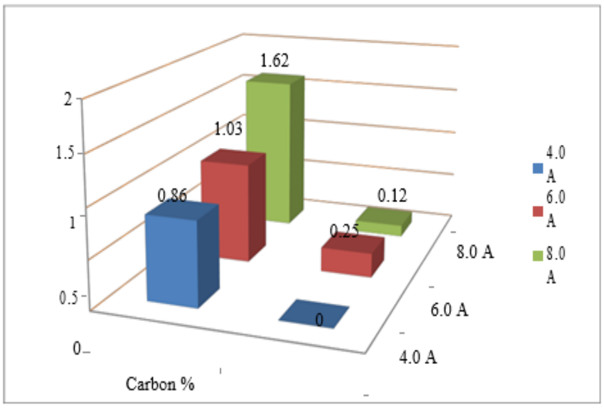

Fig. 15. Column chart showing percentage of carbon and chromium at different current levels

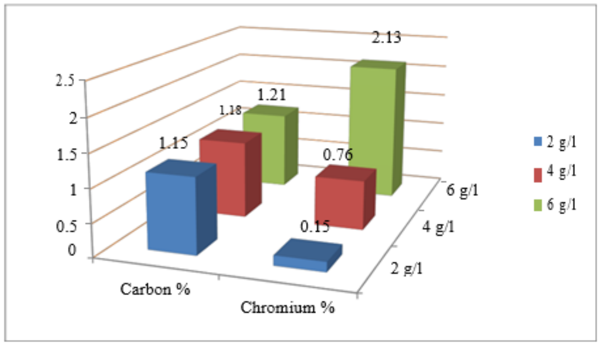

Fig. 16. Column chart showing percentage of carbon and chromium at different concentration levels

6. Conclusions

Following conclusions were drawn from analysis of SEM and composition testing results.

-- SEM photographs reveal that the micro geometry of the surfaces is practically unaffected by electrode profile and is predominantly dependent on electrical parameter. The average current variation showed a significant impact on machined surfaces. Tiny craters, re solidified grains, micro voids and cracks, dispersion of micro particles are visible on machined surfaces.

-- There was a substantial increase in carbon percentage of the machined surfaces. Average current emerged as dominant factor influencing migration of carbon from dielectric to machined surfaces.

-- For EN- 19 steel, migration of chromium from powder material to machined surfaces was reported.

--Electrode profile has not any significant effect in both SEM and composition testing results.

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