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ORIGINAL ARTICLE

Effect of the addition of conductive powder in dielectric on the surface properties of superalloy Super Co 605 by EDM process

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Abstract The present work investigates the effect of addition of graphite powder in dielectric on the surface properties of superalloy Super Co 605 in electrical discharge machining (EDM) process. Addition of conductive powders in the dielectric medium affects the energy distribution and sparking efficiency by lowering the dielectric strength, which consequently alters the surface finish and micro-hardness after machining. These powders also form part of the plasma channel in the molten state and alloy with the recast layer under appropriate machining conditions. Experiments were carried out with graphite tool electrode. While the improvement in micro-hardness was found to be lower, surface finish improved significantly with powder-mixed dielectric. The results show that an optimization between micro-hardness and surface finish can be achieved by this method of machining. The polarity of machining, peak current and pulse on-time were found to have a significant effect on surface properties, whereas pulse off-time, discharge voltage and fluid pressure were insignificant factors. Scanning electron microscope (SEM) images of the surface reveal a smoother surface, and spectroscopy analysis indicates substantial increase in carbon percentage.

Keywords Electrical discharge machining · Powder-mixed EDM · Superalloy · Super Co 605 · Micro-hardness

1 Introduction

Electrical discharge machining (EDM) is one of the modern non-conventional material removal processes and is capable of machining the materials such as superalloys accurately and economically. The application of the process in the industry for the production of geometrically complex cavities moulds and dies, automotive, aerospace and surgical components, as reported by Abbas et al. [1], shows its wide range of use in research work. However, due to poor surface finish and lower machining efficiency, its further applications were restricted. The improvements in the performance of powder-mixed electrical discharge machining (PMEDM) over EDM, as reported by Kansal et al. [2], explored new area for the technology.

The research work reported so far on conductive powder-mixed dielectric was focused on improving the response parameters such as material removal rate (MRR), tool wear rate (TWR) and surface roughness (SR) with normal polarity. Kumar et al. [3] noted that the study of such machining on surface modification began only a decade ago. Chow et al. [4] studied the addition of aluminium or silicon carbide powder in the dielectric fluid which affects the machining criteria such as an increase in MRR, electrode wear rate (EWR) and SR for micro-slit machining of titanium alloy. Tzeng and Lee [5] presented the effects of various powder characteristics on the efficiency of electrical discharge machining of SKD-11. The particle concentration, size, density, electrical resistivity and thermal conductivity of powders were important characteristics that significantly affect the machining performance. Jeswani [6] reported that graphite powder concentration in the dielectric has an important influence on MRR and TWR while using discharge energy levels. Kumar et al. [7] realized the potential of graphite powder as an additive in enhancing machining capabilities of additive-mixed EDM on Inconel 718. The addition of graphite powder enhances machining rate significantly. Bai [8] examined the effects of the electrical

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Fig. 1 Setup for powder-mixed EDM

discharge alloying process of improving the high-temperature oxidation resistance of the nickel-based superalloy Haynes 230. The oxidation resistance of the sample alloyed with positive electrode polarity was better than that of the unalloyed superalloy. The actual temperature of the oxidation resistance of the alloyed layer was achieved at 1100 °C. Patowari et al. [9] brought out the use of artificial neural network model in surface modification by EDM using tungsten-copper powder metallurgy sintered electrodes. The study adds more insight in the surface modification phenomenon. Pecas and Henriques [10] reported the effect of electrode area on the surface quality, using simple and powder-mixed dielectric. The significant improvement in performance was stated with powder-mixed dielectric. Kang et al. [11] investigated the characteristics of nickel-based heat-resistant alloy after EDM and presented that MRR and EWR behaved non-linearly, whereas the morphological and metallurgical features have a constant trend of change with respect to pulse duration. Ash [12] carried out the performance of two graphite electrodes for a seal slot in a jet engine turbine vane of nickel-based alloys and showed that quality of the electrode has a significant effect on MRR and relative electrode wear.

Surface modification of a workpiece by conductive powder in dielectric also had an important influence on the micro-hardness of the machined surface. Ming and He [13] reported the increase of MRR and surface micro-hardness and decrease of TWR with surface quality improvement while studying the effect of additives in a dielectric fluid. Furutani et al. [14] described the influence of discharge current and pulse duration with titanium powder suspended in dielectric. Both the parameters affected the titanium carbide layer deposition on working surface. The maximum hardness of deposition achieved was 2000 HV. Using small discharge energies, Klocke et al. [15] studied the effect of powder-suspended dielectrics and reported that the physical properties of the powder additives play an important role in changing the recast layer composition and morphology. Kumar and Batra [16] investigated the surface modification of die steel materials by EDM method using tungsten powder-mixed dielectric. The improvement of more than 100 % in micro-hardness was observed with the transfer of tungsten and carbon to the surface of the workpiece. Yan et al. [17] studied the effect of urea solution in the water as a dielectric for modification of titanium surface. A hard layer of TiN was formed on the surface, with good wear-resistant characteristics. MRR and TWR declined, with an increase in pulse duration and achieved micro-hardness of 250 HK. Rajesh et al. [18] investigated the surface integrity evaluation issues while machining Inconel 718 through EDM. The distinctive morphology of the machined surface was due to the massive amount of heat discharge during sparking which causes melting and vaporization of the material, followed by swift cooling. The surface quality was deteriorating at high pulse current and pulse on-time. Guu and Huo [19], in their work, studied the effect of machining parameters on surface characteristics of Fe-Mn-Al alloy. The depth of micro-cracks, micro-voids and machined damage increases with an increase in the amount of pulsed current and pulse on-duration. Wang et al. [20] explored the surface characteristics such as composition and micro-hardness of nickel-based superalloy through Taguchi analysis. Boujelbene et al. [21], in their research work, studied the influence of machining parameters on the surface integrity of X200Cr15 and 50CrV4 steel. The result indicated that increasing energy discharge increases instability while the quality of workpiece surface becomes rougher and the white layer thickness increases causing micro-cracks.

Table 2 Process parameters with their levels

Symbol	Process parameters	Levels		
		1	2	3
A	Polarity	+	−	
B	Peak current (A)	3	6	9
C	Pulse on-time (μs)	20	50	100
D	Pulse off-time (μs)	20	40	60
E	Discharge voltage (V)	25	30	35
F	Flushing pressure (kg/cm^2)	0.5	0.75	1

Table 1 Chemical composition of Super Co 605 workpiece

Element	C	Mn	Si	S	P	Cr	Ni	W	Fe	Co
%	0.096	1.26	0.12	0.0020	0.017	19.44	10.55	1.40	0.09	Bal.

Table 3 Observed value of micro-hardness and their calculated S/N ratio for EDM

Exp	Process parameters						Micro-hardness (HV)			S/N (dB)
	A	B	C	D	E	F	R1	R2	R3	
1	+	3	20	20	25	0.5	401	404	410	52.15
2	+	6	50	40	30	0.75	613	608	610	55.71
3	+	9	100	60	35	1	742	740	744	57.41
4	+	3	20	40	30	1	457	459.9	462.8	53.25
5	+	6	50	60	35	0.5	636	640	631.8	56.07
6	+	9	100	20	25	0.75	741	734	730	57.33
7	+	3	50	20	35	0.75	377	380.8	378.8	51.57
8	+	6	100	40	25	1	541	539.8	544.9	54.68
9	+	9	20	60	30	0.5	813	823	804	58.21
10	−	3	100	60	30	0.75	490	488.9	491.7	53.81
11	−	6	20	20	35	1	1192	1198	1210	61.58
12	−	9	50	40	25	0.5	1513	1510	1507	63.58
13	−	3	50	60	25	1	644	639.8	641.9	56.15
14	−	6	100	20	30	0.5	1108	1116	1112	60.92
15	−	9	20	40	35	0.75	1610	1609	1606	64.13
16	−	3	100	40	35	0.5	472	474.7	477	53.53
17	−	6	20	60	25	0.75	1321	1319	1317	62.40
18	−	9	50	20	30	1	1484	1480	1470	63.39

The available research work focuses on two important parameters, discharge current and pulse duration, which are affecting the material transfer from conductive powder-mixed dielectric. Some of the research work also addresses tool polarity for surface modification, but the impact of parameters, such as dielectric fluid pressure and pulse off-time, has not been investigated. This study investigates the effect of simple and conductive powder-mixed dielectric on the micro-hardness of cobalt-based superalloy Super Co 605.

2 Experimentation

2.1 EDM equipment

Experiments were carried out on Electronica-make electrical discharge machine; model ELEKTRA EMS 5535. The dielectric fluid flow system was modified for circulation of graphite powder-suspended dielectric medium in desired quantities to prevent contamination of the whole dielectric fluid. The machining tank was developed with a stirring system and a dielectric circulation pump to ensure uniform distribution of powder particles in the dielectric circulation system as shown in Fig. 1. Special fixture was designed for holding the workpiece in the machining tank.

2.2 Material selection and sample preparation

The cobalt-based superalloy has the ability to retain their strength at elevated operating temperatures. This superalloy is used in the aviation sector, in gas turbine and for high-temperature applications. The current work is aimed to have a useful contribution in the field of gas turbine blade manufacturing.

Table 4 Pooling of error variance for micro-hardness with EDM

Factors	DOF	SS	Variance	*F* ratio	*F* ratio	Exptd SS	Contribution (%)
A	1	103.35	103.35	108.41	173.12	102.75	34.85
B	2	167.52	83.76	87.86	140.30	166.32	56.41
C	2	16.80	8.40	8.81	14.07	15.61	5.29
D	2 (P)	Pooled	Pooled	Pooled	Pooled	Pooled	Pooled
E	2 (P)	Pooled	Pooled	Pooled	Pooled	Pooled	Pooled
F	2 (P)	Pooled	Pooled	Pooled	Pooled	Pooled	Pooled
Error (P)	12	7.16	0.60			10.15	3.44
Total	17	294.83				294.83	

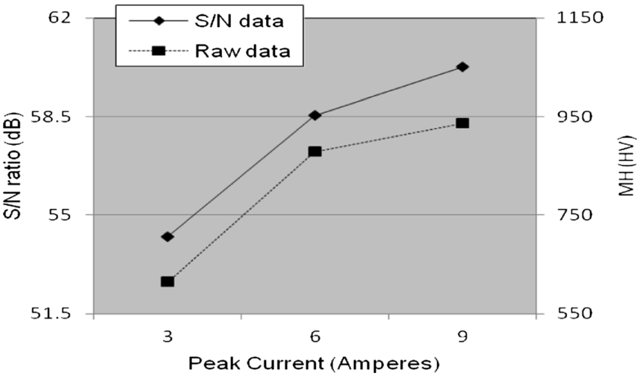

Fig. 2 Effect of peak current on micro-hardness and its S/N ratio for EDM

Super Co 605 (specimen 200 mm×50 mm×7 mm) and cylindrical graphite (ϕ 16 mm) are used as workpiece and electrode material for experimentation. The samples are prepared for plane parallel flat top and bottom surface before machining process. Graphite powder (10 g/l) was mixed with EDM oil as dielectric for machining of the workpiece. The chemical composition of Super Co 605 is shown in Table 1.

2.3 Process parameter selection and scheme of measurements

The range of the process parameters was selected based on literature survey, preliminary investigation and widely practiced limits and machine constraints. The polarity, peak current, pulse on-time, pulse off-time, discharge voltage and flushing pressure were selected as the process variables to investigate their influence on the micro-hardness. Experiments were conducted in the given range of different input parameters to select their levels, as shown in Table 2, with a 10-min work time. L_{18} ($2^1 \times 3^7$) orthogonal array has been used which contains 18 experimental runs at various combinations of input variables. The first sets of 18 experiments were conducted without using graphite powder, and the second set of 18 experiments was conducted with graphite powder mixed in dielectric.

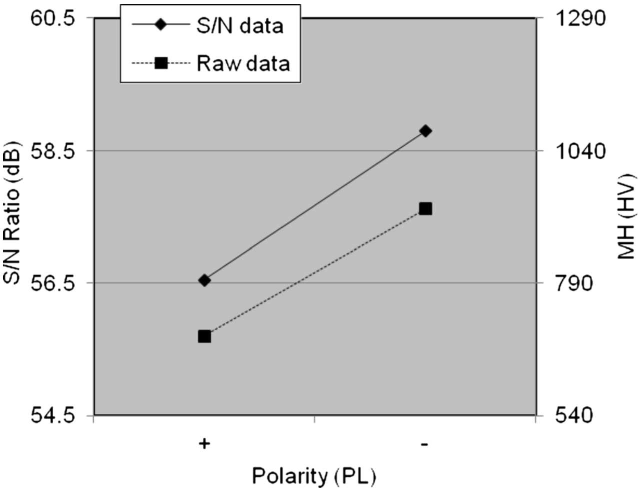

Fig. 3 Effect of polarity on micro-hardness and its S/N ratio for EDM

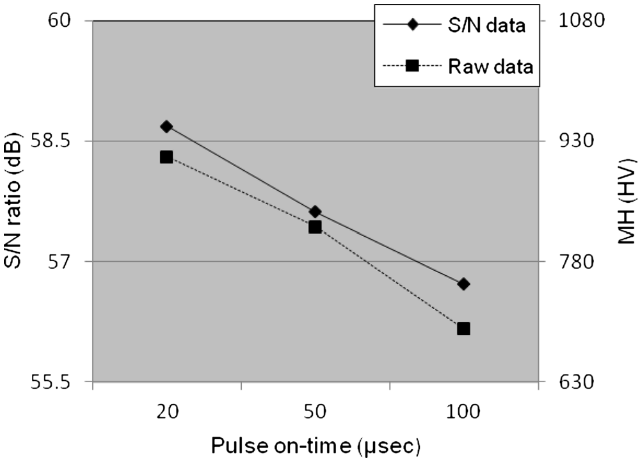

Fig. 4 Effect of pulse on-time on micro-hardness and its S/N ratio for EDM

The EDMed surface was polished with MD-Plus cloth and diamond suspension DiaPro Plus (3 μm). The polished surface was cleaned thoroughly to remove dirt and cloth fibres. The measurement of micro-hardness is carried out using the micro-hardness tester model HV-1000B under the load of 1000 g, with an indentation time of 10 s and with a hardness measuring range of 5–3000 HV. The distance between indentations and the distance from the centre of the indentation to the edge of the specimen is kept at 3 d_m (mean diagonal of an indent in mm) and 2.5 d_m, respectively. The value of micro-hardness is calculated by taking the average of three measurements per work sample.

2.4 Experimental design by Taguchi approach

Taguchi defines a set of suitable orthogonal arrays, for the optimization of process parameters. The combination of standard experimental design techniques and analysis methods produces consistency and reproducibility rarely found in any other statistical method. The response parameters are converted to signal-to-noise (S/N) ratio for the quality characteristic evaluation, then the ANOVA for S/N ratio is calculated. Confirmation experiments are conducted based on optimal parameter levels.

The quality characteristic is also considered to be continuous and non-negative and it would be as large as possible. The higher-the-better (HB) principle is considered for micro-hardness:

$$\left(\mathrm{S}/\mathrm{N}\right)_{\mathrm{HB}}\mathrm{ratio} = -10\log\left[\left(\Sigma yi^{-2}\right)/n\right] \tag{1}$$

Table 5 Observed value of micro-hardness and their S/N ratio for PEDM

Exp	Process parameters						Micro-hardness (HV)			S/N (dB)
	A	B	C	D	E	F	R1	R2	R3	
1	+	3	20	20	25	0.5	504.8	515.1	510	54.15
2	+	6	50	40	30	0.75	731	733	723.3	57.26
3	+	9	100	60	35	1	807	813.1	819	58.20
4	+	3	20	40	30	1	574.1	580	571	55.19
5	+	6	50	60	35	0.5	713.8	719	730	57.16
6	+	9	100	20	25	0.75	811	808.8	806.6	58.16
7	+	3	50	20	35	0.75	449	453	451.3	53.09
8	+	6	100	40	25	1	637	633.3	635	56.06
9	+	9	20	60	30	0.5	968.8	964	966.9	59.70
10	−	3	100	60	30	0.75	510	504	498.9	54.05
11	−	6	20	20	35	1	930	934	928	59.38
12	−	9	50	40	25	0.5	1162	1156	1161	61.29
13	−	3	50	60	25	1	572	578	574	55.19
14	−	6	100	20	30	0.5	1009	1011	1007	60.08
15	−	9	20	40	35	0.75	1313	1315	1318	62.38
16	−	3	100	40	35	0.5	487	483.8	491	53.75
17	−	6	20	60	25	0.75	1161	1166	1164	61.32
18	−	9	50	20	30	1	1222	1225	1218	61.74

where y_i is the *i*th result of the experiment, *n* is the repeated number of *i*th experiment and the summation is for $i=1$ to *n*.

To judge the experimental value of the S/N ratio with that of the predicted value, the confidence interval (CI) of S/N_{pred} is calculated at the 95 % level.

3 Results and discussion

3.1 Micro-hardness

The micro-hardness and its S/N ratio based on orthogonal array are shown in Table 3 and the corresponding pooling estimates of error variance in Table 4. The peak current dominates the performance characteristics of micro-hardness, with 56.41 % in contribution followed by polarity (34.85 %) and pulse on-time (5.29 %). The S/N ratio data graph in Fig. 2 shows that the micro-hardness increases with peak current. Higher discharge current strengthens the pulsation energy which results in a thicker heat-affected zone (HAZ). Consequently, the micro-hardness of the surface increases. Micro-hardness also increases with polarity change as shown in Fig. 3. The tool wear rate is more with negative tool polarity as compared to positive tool polarity. The percentage of carbon diffused on the machine surface increases as the tool material is graphite. The significant transfer of carbon element on the machined surface increases micro-hardness. Higher pulse on-time decreases the micro-hardness as shown in Fig. 4; this is due to expansion of the discharge column. The higher pulse on-time is directly proportional to the heating of the surface. The process of heating releases stresses on the

Table 6 Pooling of error variance for micro-hardness with PEDM

Factors	DOF	SS	Variance	*F* ratio	*F* ratio	Exptd SS	Contribution (%)
A	1	22.69	22.69	28.50	43.49	22.17	14.25
B	2	115.01	57.51	72.23	110.20	113.97	73.23
C	2	11.67	5.83	7.33	11.18	10.63	6.83
D	2 (P)	Pooled	Pooled	Pooled	Pooled	Pooled	Pooled
E	2 (P)	Pooled	Pooled	Pooled	Pooled	Pooled	Pooled
F	2 (P)	Pooled	Pooled	Pooled	Pooled	Pooled	Pooled
Error (P)	12	6.26	0.52			8.87	5.70
Total	17	155.64				155.64	

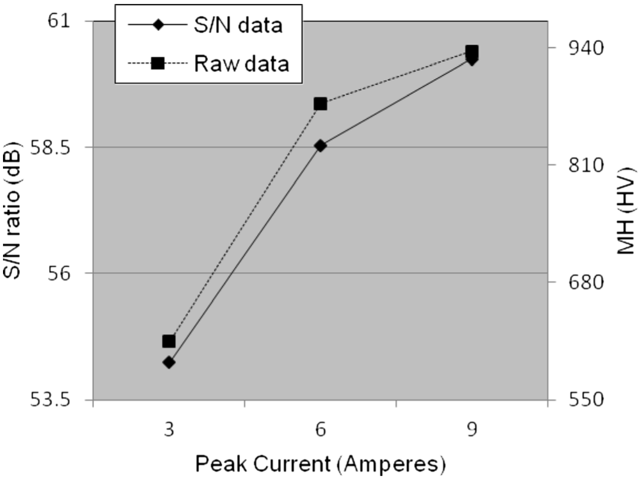

Fig. 5 Effect of peak current on micro-hardness and its S/N ratio for PEDM

machined surface; as a result, the micro-hardness of the EDMed surface reduces. The process of heating and cooling affects the micro-hardness of the surface. Enrichment of the carbon layer on the machined surface coming from dielectric cracking also improves the hardness. Optimal results for micro-hardness are given by the parameters $A_2B_3C_1$. Peak current, polarity and pulse on-time significantly affect the micro-hardness of the EDMed surface.

The experimental data obtained during powder-mixed electrical discharge machining (PEDM) for micro-hardness and its S/N ratio are shown in Table 5. The pooling estimates of error variance are tabulated in Table 6. The peak current dominates with 73.23 % in contribution followed by polarity (14.25 %) and pulse on-time (6.83 %). The S/N ratio data graphs for peak current, polarity and pulse on-time are shown in Figs. 5, 6 and 7, respectively. The optimal result of micro-hardness is given by the parameters ($A_2B_3C_1$). The response in terms of improvement in micro-hardness has been summarized in Table 7 and, correspondingly, the surface roughness in Table 8.

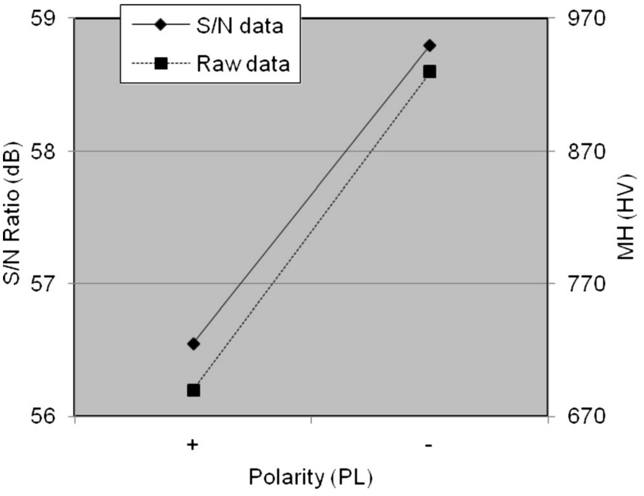

Fig. 6 Effect of polarity on micro-hardness and its S/N ratio for PEDM

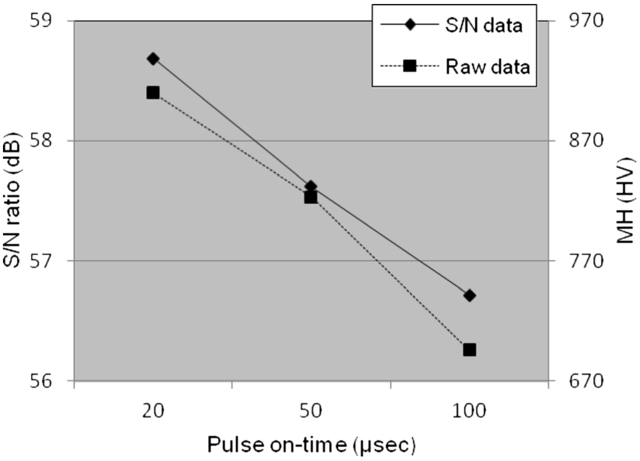

Fig. 7 Effect of pulse on-time on micro-hardness and its S/N ratio for PEDM

The surface roughness improves with PEDM as compared to simple EDM. The addition of powder also improves surface asperities and decreases crater development characteristics of the EDM process. The improvement in micro-hardness with simple EDM (401.31 %) is more than PEDM (309.95 %). The spectroscopy analysis for simple and powder-mixed EDM reveals that carbon percentage significantly changes in the heat-affected zone than in the substrate, which leads to the increase of micro-hardness on the machined surface. The micro-hardness induced on the machined surface increases surface hardness, and it improves resistance to wear. During the manufacturing of turbine blades, the parameters such as surface finish, crater size and micro-hardness are important for achieving better surface integrity to improve part performance, functionality and service life.

3.2 Confirmation experiments

The objective of the confirmation experiment is to validate that the selected control parameter values will produce better results than those produced in the initial part of the experiment. The predicted value of S/N ratio is calculated and performance response for predicting S/N ratio is obtained. The confidence interval (CI_{CE}) of predicted response is

Table 7 Comparative analysis of micro-hardness

Process	Micro-hardness (HV)		
	Best value achieved	% Improvement	Optimum process parameters
Before machining	320.82	–	–
Simple EDM	1608.30	401.31	$A_2B_3C_1D_2E_3F_2$
PEDM	1315.2	309.95	$A_2B_3C_1D_2E_3F_2$

Table 8 Comparative analysis of surface roughness

Process	Surface roughness (Ra in microns)		
	Best value achieved	% Improvement	Optimum process parameters
Simple EDM	2.23	–	$A_1B_1C_1D_1E_1F_1$
PEDM	1.99	11.04	$A_1B_1C_1D_1E_1F_1$

Table 9 Results of confirmation experiments for micro-hardness

	Optimal control parameters		Confidence interval (range)
Level	Predicted $A_2B_3C_1$	Experiment $A_2B_3C_1D_2E_3F_2$	
Micro-hardness EDM (HV)	1610.91	1608.30	1374.52–1887.96
Micro-hardness PEDM (HV)	1315.27	1315.20	1134.63–1524.67

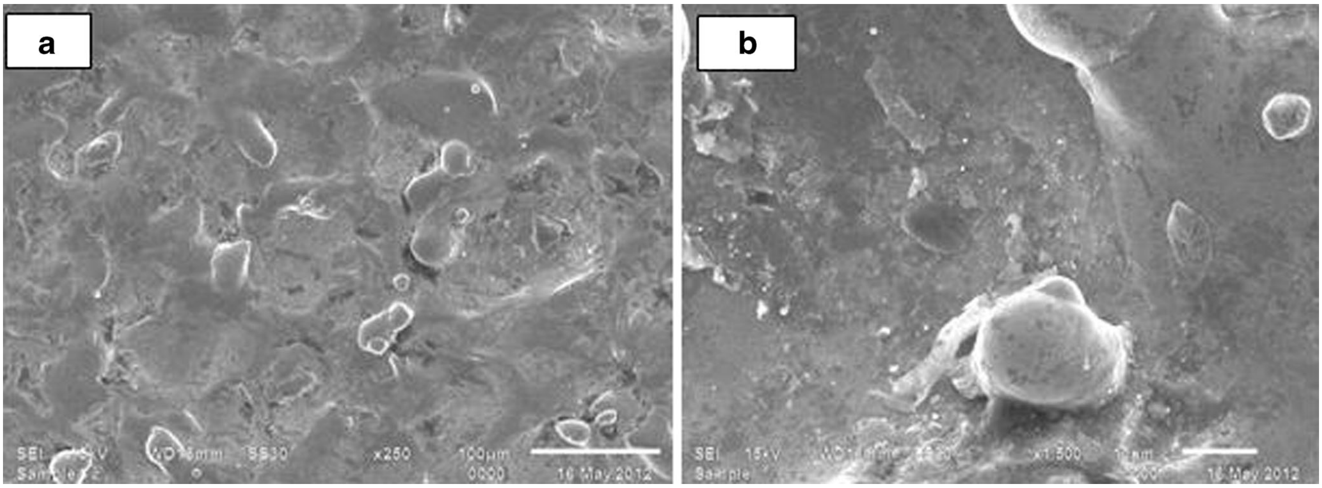

Fig. 8 SEM micrographs for EDM with the orthogonal array No. 15 ($A_2B_3C_1D_2E_3F_2$) **a** ×250 and **b** ×1500

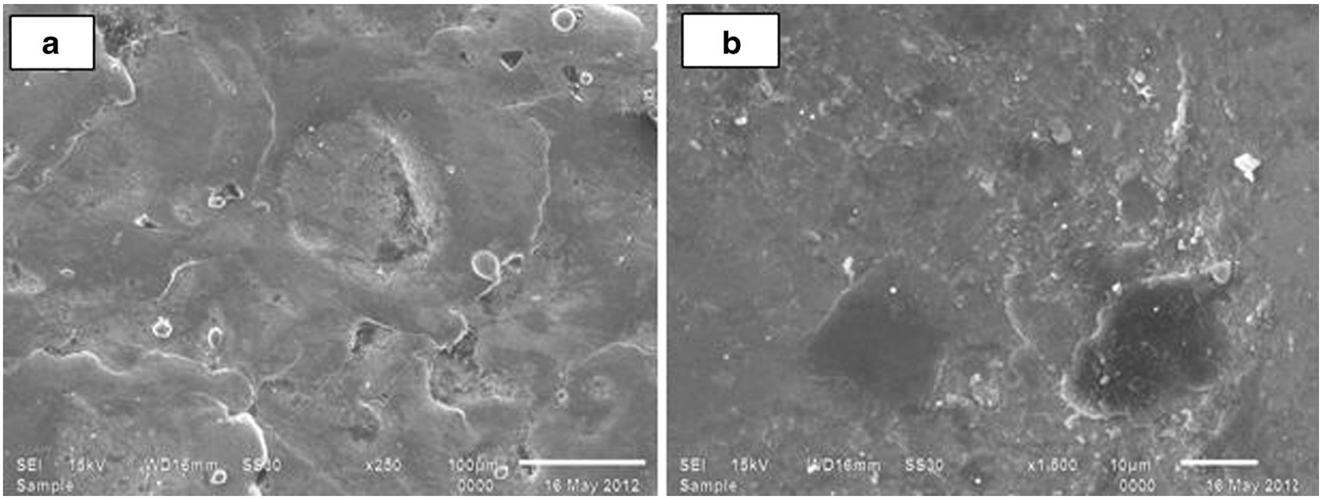

Fig. 9 SEM micrographs for PEDM with the orthogonal array No. 15 ($A_2B_3C_1D_2E_3F_2$) **a** ×250 and **b** ×1500

calculated at 95 % level. The experiments previously conducted at run 15 with parameter setting $A_2B_3C_1D_2E_3F_2$ are compared as confirmation tests for micro-hardness in Table 9, which indicates that the results is within optimum range of confidence intervals. Figure 8a, b shows scanning electron microscope (SEM) view of experiment 15; the microstructure reveals the existence of different sizes of craters and pockmarks throughout the workpiece. The higher magnification micrograph clearly indicates that there are patches of the bigger size of the crater in the structure. The SEM micrograph in Fig. 9a, b shows that the PEDM surface with same parameter setting, crater size and pockmark reduces due to controlled energy in a powder-mixed dielectric fluid. Surface defects such as globules, debris, melted drops and cracks are not seen except for crater scattering.

4 Conclusions

An application of conductive powder in dielectric to improve the performance characteristics of the micro-hardness in the electrical discharge machining of superalloy Super Co 605 has been reported in this paper. The following results are derived from the experimental data.

a) It was possible to improve the micro-hardness of 320.82 to 1608.30 HV by normal EDM and from 320.82 to 1315.2 HV by powder-mixed EDM. Correspondingly, the surface finish improved from 2.23 to 1.99 μm by the addition of graphite powder.
b) Significant amount of powder gets alloyed with the machined surface. In this case, an increase in the percentage of carbon is expected to impart self-lubricating properties to the workpiece.
c) Machining with conductive powder smoothens the surface asperities and reduces the typical crater formation characteristic of the EDM process.
d) Micro-hardness is influenced by peak current, polarity and pulse on-time for simple and powder-mixed electrical discharge machining process.
e) The optimal process parameters include the negative polarity of electrode, 9 A peak current and 20-μs pulse on-time for good performance characteristics. The results are within confidence interval range for simple and graphite powder-mixed dielectric.
f) The surface quality deteriorates at high current with the formation of a recast layer as spherical droplets solidify on machined surface, and a reduction in defect size is noticed while machining with powder-mixed dielectric.

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