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The Analysis of Particle Size Effect on Performance of WC/Cu P/M Compact Sintered Electrode in EDM Process

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Abstract

The main aim of this study is to evaluate the influence of particle size variations on electric discharge machining (EDM) electrodes made with a combination of Tungsten carbide (WC) and Copper (Cu) powders using the powder metallurgy (P/M) method. The electrodes are in cylindrical shape of 15 mm diameter and are made with following sizes i.e., Nano Particles (NP), a mix of Nano and Micron Particles (NMP) and Micron Particles (MP). Electrodes, thus made in combinations were used to study the performance during surface modification of Inconel 718 alloy using EDM. The electrodes were made with wt% 40, 50& 60 of WC and the rest is Cu, whereas the compaction ranges 200-400Mpa. Among the unconventional machining processes, EDM is the most preferred surface modification process to machine very hard materials like Inconel 718 alloy. Machining was conducted by varying parameters viz., pulse on time, polarity, peak current, %WC in tool composition, Particle size, and compaction pressure. The performance indicators in the present investigation are material removal rate (MRR) and tool wear rate (TWR). The results were analyzed using MINITAB 14 software, and it was noted that the improvement in MRR was due to the influence of particle size and peak current. A highest MRR of 9.90 mg/min was attained with NP electrode and a peak current of 13A. The highest TWR of 20.70 mg/min was also observed at the machining condition where highest MRR was observed. The results of the MRR and TWR values show the significant influence of all the six process variables on EDM process.

Keywords: EDM, WC- Cu, P/M compact sintered electrode, MRR, TWR, Inconel 718;

1. Introduction

Inconel 718 is a super alloy of nickel, chromium and molybdenum combination. It is an excellent property of high yield tensile, creep rupture and oxidation resistance at high temperatures. It can resist the pitting and fracture corrosive environments strictly [1-2]. Application of Inconel 718 in industry is numerous. From the aviation to chemical industry, this alloy is widely used due to its superior properties vis-à-vis non-corrosive and fatigue-resistant nature, and creep resistance. Conventional machining process falls short at increased temperatures owning to high strength of Inconel 718, low elastic modulus and thermal conductivity. Thermoelectric process done by EDM due to the process a series of discrete sparks between work piece and tool, both submerged in a dielectric fluid with elimination of the mechanical stress, chatter, and vibration during machining as there is no direct contact between the electrode and the work piece [3]. In general, Copper and copper alloys, Tungsten, graphite, zinc and brass used in making these EDM electrodes have both plus, and minus advantages. Researchers had to spend a good time in producing a composite electrode with combinations of various materials using power metallurgy (P/M) technique. Alloys of most metals and nonmetals of intricate shapes can be manufactured by Powder Metallurgy method [4]. It is important to note that the tool electrodes produce through P/M technique are one among the least expensive. Because of the cited reasons, electrodes thus produced are useful for machining materials like Inconel 718, a difficult machinable alloy.

Genichi Taguchi, an expert and renowned quality engineer in Japan also considered, “father of quality engineering [5], categorized quality as quality control checked through off-line and on-line. Together are cost effective to their respective domains based on the decisions taken. The first one; is the quality control which is an off-line talk about the improvement in quality within the product and process development stages, whereas the second one is an On-line quality control that refers to monitoring of the running manufacturing processes for verification of the quality levels produced [6]. Although the Taguchi method has limitations, it has effectively solved single response problems [7].

The P/M electrode's particle size has a predominant effect among the electrode parameters on the performance of the EDM and properties of EDMed workpiece[8]. The particle size used (on an average) in the earlier research was Li et al., 23µm of W-Cu [9], Das and Misra 44µm of TiC-

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Cu [10], Cogun et al., 70 µm of Cu-B_4C [3], Bai and Koo 15 µm Al-Mo [11]. Venkata Rao et.al 20-40 nm & 30-50 µm of TiC and Cu [12].From the literature, most of the P/M electrodes were done by micron particle size with a small variation in microns. Liquid phase sintering is governed by the fine size of particle [7]. The surface roughness of the EDMed surface machined with composite electrode is higher when compared to distinct solid material [8] and the value of roughness was rising in proportion to the increase in the P/M electrode particle size. Corner wear can also be minimized by selecting small particle size that has high strength and density. In addition to that, the particle size of the composite electrode is another important factor that greatly affects the EDM's process stability [9]. Process stability is highly sensitive to changes in particle size. It is known that for improved machining efficiency, it is essential to enhance process stability. From the above discussion, it is evident that particle size has a major influence on both the attributes of EDMed surface and stability of the process, hence preferred particle size to be as small as possible.

The existing literature is concentrated on composite electrodes made with micron-size powders and none of the work is reported on electrodes made with nano size powders, as per the awareness of the author. In the present investigation, the performance of WC/Cu electrode made with nano-material is compared with the micron-sized composite electrode, and the material used for machining is Inconel 718 alloy.

2. Experimental Methods and Materials

The electrodes are fabricated by varying the WC powders in percentages by weight of 40, 50 and 60 and rest of with Cu powder. The high hardness of WC powder (about 9.0-9.5 Mohs) and its melting point of 2870°C were utilized in the present investigation. In addition, the high thermal and electrical conductivity of Cu and its binding ability throughout compaction were also the reasons for using the same. They were compacted from 200 to 400 MPa using a Carver model compaction machine. The P/M electrode was attached to a metallic copper with glue, while Inconel 718 alloy with Φ20 mm and 10 mm thick cylindrical-shaped was used as the workpiece. The workpiece composition and properties are presented in Table 1. The factors and their levels are shown in Table 2.

Mixed Orthogonal Array (OA) of size L18 ($2^1 \times 3^5$) with six parameters was selected and experiments conducted where in 2-level parameter is one, and 3-level parameters are five. The parameters pertaining to tool and process namely polarity, peak current, pulse on-time, size of particle, %WC in WC/Cu tool and pressure of compaction were preferred for the study and details placed in the Table 2. Die Sinking EDM (Sparkonix S25) was used for experiments and the EDM Oil is the dielectric fluid. Lateral flushing with a pressure of 0.5 Pa was maintained during the experiments. Figure 1 shows the machining set up which consists of workpiece, work clamping set-up and electrode (tool). The tool tip of the EDM is the exact replica of the shape to be produced on the workpiece.

Scanning electron microscope (SEM) and X-ray diffraction (XRD) were utilized for extraction of Images from the samples of experiment. The received machined workpiece material is extracted from SEM images, whereas for identification of inter-metallic phases generated during machining, the X-pert pro Material Research Diffraction (MRD) was used. In this work, the material's loss in weight per time after machining was used to obtain each of MRR and TWR. After machining, the results were used to generate models, which identify the main effects. Using these models, the general behavior of the electrode in conjunction with the machining parameters is presented in the following sections.

Table 1. As received EDMed workpiece of Inconel 718alloy chemical composition

Elements	Ni	Fe	Cr	C	Cu	Nb	O	Mo	Ti	Al
	42.2	17.2	16.4	12.5	0.27	4.0	3.03	3.0	0.9	0.5

Table 2. Experimental parameters and their levels

Parameters		Symbol	Level1	Level 2	Level 3
A:	Polarity	POL	Positive (P)	Negative (N)	---
B:	Peak current (Amp)	IP	7	10	13
C:	Pulse on-time (µsec)	TON	4	8	12
D:	Particle size	PS	NP	NMP	MP
E:	% WC in WC/Cu tool	%WC	40	50	60
F:	Compaction Pressure(MPa)	CP	200	300	400

2.1. Electrodes (WC/Cu) Fabrication

Electrodes were made by mixing the powders (99.5%) of electrolytic copper (Cu) and titanium carbide (WC) in proportionate ratios of weight as per Table 3. Electrode particle sizes vary from 20-40nm and 30-50nm for nano and micron sizes referred to as Nano(NP) and Micro(MP) electrodes. The NMP electrode is made by blending of nano and micron powders in equal weight proportions. Powder and Liquid wax, which is the binder, are mixed by the Mortar and Pestle process. Liquid Wax comprises 1/100th of the weight of the mixture. Mixing is carried out for half an hour, after which compacting is carried out at pressures of 200, 300 and 400 MPa. For the current application, the dimensions of the die are Φ15mm and length 50mm. The entire operation was carried out on a 200 Ton Universal C.T. machine.

Sintering of the compacts is carried out in a vacuum furnace by varying the temperature linearly (@ 5^0C/min) up to 350^0 C and maintained at the temperature for a 60-minute duration. Subsequently the temperature is raised ramp of 10^0C/min to 950^0C and held for one hour in Argon filled environment as shown in Figure 2. Cracking is avoided by cooling the components for 4½ hrs at a constant rate of 5^0C/min. An adhesive with good electrical properties is utilized to join the Electrodes to brass rods of size ø12mm and length 50 mm.

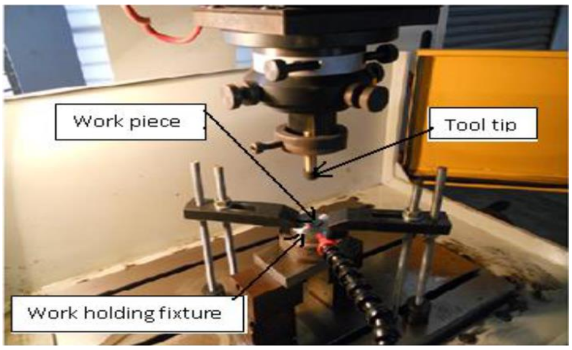

Figure 1. Sparkonix S25 Model Die sinking EDM Machine and experimental setup

Table 3. Tool electrodes and their composition in weight percentages

Electrode	NP (Both)	NMP (Each 50%)	MP (Both)
P/M processed sintered WC/Cu electrode - 1	WC40%Cu60%	WC(20+20)%Cu(30+30)%	WC40%Cu60%
P/M processed sintered WC/Cu electrode - 2	WC50%Cu50%	WC(25+25)%Cu(25+25)%	WC50%Cu50%
P/M processed sintered WC/Cu electrode - 3	WC60%Cu40%	WC(30+30)%Cu(20+20)%	WC60%Cu40%

3. Results and Discussion

Taguchi's method was used to optimize settings of parameter for MRR and TWR with the analysis of Signal to Noise (S/N) ratio. The logarithmic transformation of Loss function is evaluated. The parameters selected for MRR and TWR would be 'Higher' and 'Lower' respectively for better performance as mentioned in Equation 1 and 2.

The ratio of S to N for Material Removal Rate

$$\eta = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (1)$$

S/N ratio for Tool wear rate

$$\eta = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}y_i^2\right) \quad (2)$$

'y'is the responses measured individually
'n' is the measurement sample in numbers

The experimental results of MRR and TWR with varying values of S/N are indicated in Table 4. At each level of experimental data, taking all the six parameters into consideration Mean S/N ratio is evaluated for MRR and TWR and tabulated in Tables 5 & 6 respectively. The variation between the lowest and highest value of S/N is indicated by Delta. Better performance is said to have been achieved with higher value of S/N and is termed as optimal level. Each parameter with its optimal levels can be seen for both MRR and TWR in Figures 3 & 4 respectively. In order to arrive for better MRR and TWR, optimal combination of machining parameters is used. For peak current (IP), pulse on time (TON), compaction pressure (CP) and wt. % of WC level 3 means high, 2 means medium, and 1 means low. For polarity (POL), 1 means positive, and 2 means negative, and for particle size (PS) 1 means NP electrode, 2 means NMP electrode, and 3 means MP electrode. In case of MRR, positive polarity (A1) at high level of peak current (B3), high level of pulse on time (C3), using NP electrode (D1), low level of WC% (E1) and low level of compaction pressure (F1) gives better results. Whereas in case of TWR, positive polarity of tool electrode (A1), low level of peak current (B1), low level of pulse on time (C1), MP electrode (D3), lower level of WC% (E1) and higher level of CP (F3) gives optimum results. To sum up, the optimal combination for MRR and TWR is A1B3C3D1E1F1 and A1B1C1D3E1F3 respectively.

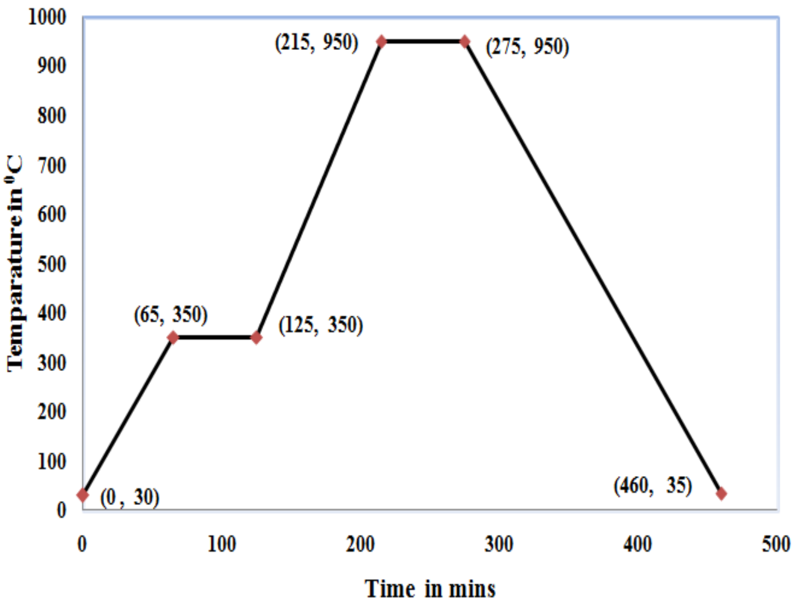

Figure 2. Sintering cycle for electrode perpetration

Table 4. Experimental layout using L18 (21x35) Orthogonal Array and Performance characteristics calculation

RUNS	POL	IP	TON	PS	%WC	CP	MRR		TWR	
							Mean MRR (mg/min)	S/N(dB)	MeanTWR (mg/min)	S/N(dB)
1	P	7	4	NP	40	200	9.10	19.1808	16.00	-24.082
2	P	7	8	NMP	50	300	7.80	17.8419	16.10	-24.137
3	P	7	12	MP	60	400	7.10	17.0252	15.25	-23.665
4	P	10	4	NP	50	300	9.00	19.0849	17.80	-25.008
5	P	10	8	NMP	60	400	7.85	17.8974	17.65	-24.935
6	P	10	12	MP	40	200	8.75	18.8402	16.45	-24.323
7	P	13	4	NMP	40	400	8.35	18.4337	16.00	-24.082
8	P	13	8	MP	50	200	9.15	19.2284	17.70	-24.96
9	P	13	12	NP	60	300	9.90	19.9127	20.70	-26.319
10	N	7	4	MP	60	300	6.80	16.6502	16.25	-24.217
11	N	7	8	NP	40	400	8.55	18.6393	16.95	-24.583
12	N	7	12	NMP	50	200	7.95	18.0073	18.45	-25.32
13	N	10	4	NMP	60	200	7.65	17.6732	18.30	-25.249
14	N	10	8	MP	40	300	7.75	17.786	16.40	-24.297
15	N	10	12	NP	50	400	8.70	18.7904	18.30	-25.249
16	N	13	4	MP	50	400	7.75	17.786	16.65	-24.428
17	N	13	8	NP	60	200	9.90	19.9127	20.35	-26.171
18	N	13	12	NMP	40	300	9.10	19.1808	18.20	-25.201

Table 5. S/N ratio Response table of MRR

Level	POL	IP	TON	PS	%WC	CP
1	18.61	17.89	18.13	19.25	18.68	18.81
2	18.27	18.35	18.55	18.17	18.46	18.41
3		19.08	18.63	17.89	18.18	18.10
Delta	0.34	1.18	0.49	1.37	0.50	0.71
Rank	6	2	5	1	4	3

Table 6. S/N ratio Response table of TWR

Level	**POL**	**IP**	**TON**	**PS**	**%WC**	**CP**
1	-24.61	-24.33	-24.51	-25.24	-24.43	-25.02
2	-24.97	-24.84	-24.85	-24.82	-24.85	-24.86
3		-25.19	-25.01	-24.32	-25.09	-24.49
Delta	0.36	0.86	0.50	0.92	0.66	0.53
Rank	6	2	5	1	3	4

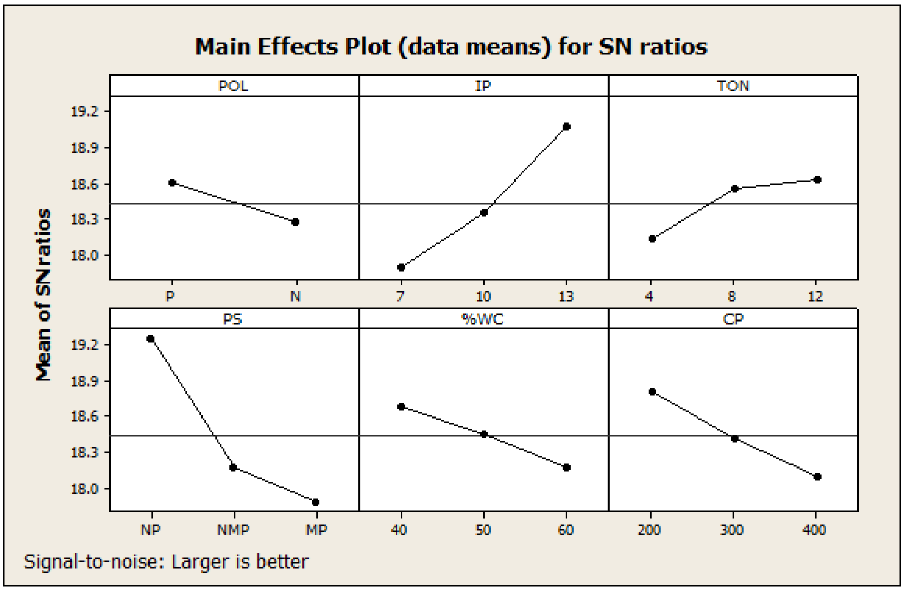

Figure 3. Main effect plots for MRR

3.1. Analysis of variance for MRR and TWR

ANOVA is a statistical method used to interpret experimental data to make the necessary decisions, concerning the parameters that affect the performance of the process. Based on this, parameters can be categorized into significant and insignificant machining parameters. Each parameter's influence on MRR and TWR are estimated and assessed in terms of percentage contribution (%P). ANOVA results were presented in Figure 5 for both MRR and TWR with 95% (α=0.05) confidence level. The contribution of individual parameters to the values of MRR and TWR are evaluated and shown in Tables 7 & 8 respectively. If p value is less than 0.05, it has significant effect on the performance measures. It is observed that all parameters are significant, but particle size and peak current are most significant (44.40% and 30.59%) for MRR. In case of TWR, all parameters are also significant, but particle size and peak current are most significant (28.92% and 25.52%). Both the MRR and TWR are significantly influenced by the parameters PS, IP, TON, %WC and CP. In continuation, experimental analysis viz. SEM studies for structural analysis at micro level, for Chemical analysis EDX is used, for phase analysis were carried out by XRD on the work surfaces made under optimum conditions and also on as received work pieces as presented below. The optimality of each parameter influencing the MRR and TWR are presented below.

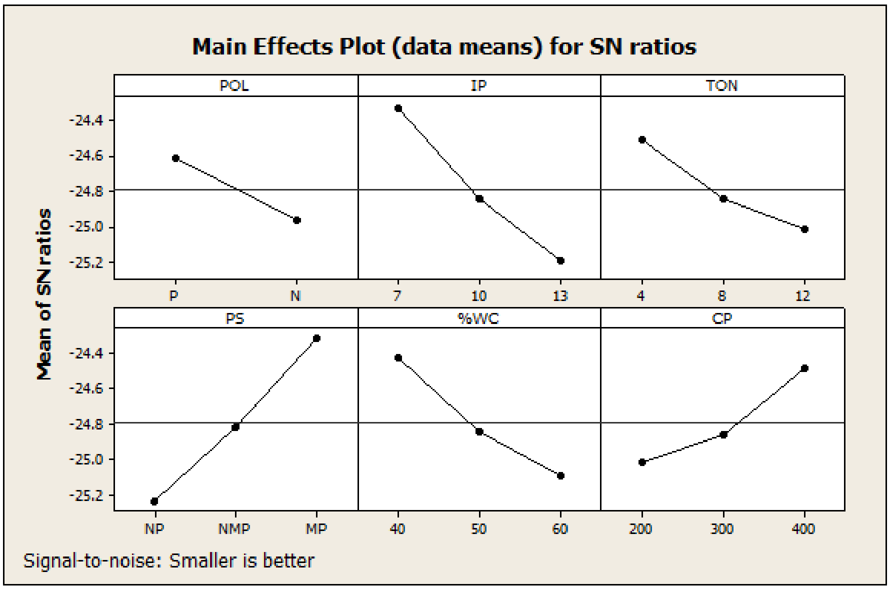

Figure 4. Main effect plots for TWR

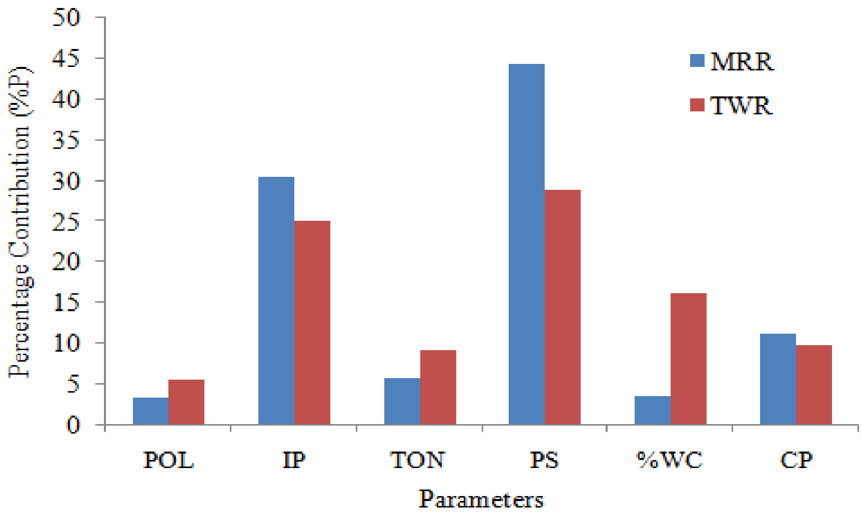

Figure 5. ANOVA for MRR and TWR

Table 7. ANOVA for MRR

Source	DF	Seq SS	Adj SS	Adj MS	F	Probability	% contribution
POL	1	0.4512	0.4512	0.4512	22.93	0.003	3.43
IP	2	4.0269	4.0269	2.0135	102.33	0.000	30.59
TON	2	0.7719	0.7719	0.3860	19.62	0.002	5.86
PS	2	5.8436	5.8436	2.9218	148.5	0.000	44.40
%WC	2	0.4803	0.4803	0.2401	12.20	0.008	3.65
CP	2	1.4703	1.4703	0.7351	37.36	0.000	11.17
Error	6	0.1181	0.1181	0.0197			
Total	17	13.1624					

Table 8. ANOVA for TWR

Source	DF	Seq SS	Adj SS	Adj MS	F	Probability	% contribution
POL	1	2.1356	2.1356	2.1356	6.87	0.040	5.70
IP	2	9.4033	9.4033	4.7017	15.13	0.005	**25.08**
TON	2	3.4658	3.4658	1.7329	5.58	0.043	9.25
PS	2	10.8400	10.8400	5.4200	17.44	0.003	**28.92**
%WC	2	6.0833	6.0833	3.0417	9.79	0.013	16.23
CP	2	3.6925	3.6925	1.8462	5.94	0.038	9.85
Error	6	1.8644	1.8644	0.3107			
Total	17	37.4850					

a) Polarity: It is noticed that positive polarity generates high MRR. Therefore, to exploit usage of positive polarity, Anode (discharge spot) and Cathode will be work piece and tool respectively. As a result, huge amount of particles of tool is transferred to work surface thereby resulting high MRR. In this case, the TWR is more than the MRR. The reason is being that WC has more density than copper, both of which emanate from the tool and WC is flushed out due to the flushing pressure of the die electric medium. It has been found that work material with low thermal conductivity would absorb less quantity of heat during machining, leading to low MRR. The low thermal conductivity coupled with high melting temperature of workpiece resulted in poor MRR, which led to increased TWR.

b) Peak Current: With the increase in the peak current, the MRR increases, and the thermal conductivity also increase. The reason is attributed to the availability of more energy when the current increases, thereby causing a stronger spark impact. Due to the increase in the thermal conductivity, there is a mild decrease in the MRR due to the decrease of availability of heat between the gap of electrode and work material. The result of availability of less heat leads to low MRR and high TWR.

c) Pulse on-Time: The current and pulse on-time have the direct relationship on the MRR and TWR. The outputs increase with increasing current and pulse on-time. The highest MRR obtained with the P/M electrode is 9.90 mg/min with the peak current of 13A and pulse duration of 12 µs. The rate of tool wear is higher compared to the material removal from the workpiece. The maximum value obtained for TWR is 20.70 mg/min which is also higher than the maximum MRR obtained under the same machining conditions because the following reasons/attributes are responsible for reducing MRR viz. (1) Reduction of WC and Cu particle size, (2) Thermal conductivity of WC increases, (3) surface to volume ratio changes and (4) shielding effect of nanoparticles [10]. Hence any of the attributes that makes such type of electrode is apt for work piece surface modification.

d) Particle Size: The NP electrode composite has resulted low values of MRR and TWR. In EDM process, with the increase in density of NP electrode, the amount of WC & Cu particles dropped from the electrode should increase. The smaller particles would be eroded first owing to their reactive surface area being much higher than that of the coarser ones. It is reported that EDM electrodes made with nano particles would have higher MRR and lower TWR than micro sized electrodes [12]. The use of sintered electrode increases the wear due to the fact that the thermal conductivity of composite material is greater than that of raw material [11]. It is observed in the present investigation on MRR and TWR increase and if nano particles are used, the reactive surface increases (over micron size particles [12] and [13]) leading to more erosion of material and increased MRR. The MRR is considerably low in case of nano-sized particles over micron sized particles.

e) Significance of %WC Composition: The density of WC is very high over Copper. The thermal conductivity of the composite tool electrode is improved in presence of low or high weight percentage of WC as it becomes denser. It is evident to observe that MRR is high, at 40% of WC due to the transfer of percentage of Copper particles from tool to work surface. Hence, the tool erosion rate at 60wt% of WC is low over the 40 & 50wt% compositions of WC.

f) Compaction Pressure: In general, low thermal conductivity, low melting temperature of Inconel 718 results in poor heat absorption due to this poor removal of work material in EDM [13]. Therefore, because the tool electrode has high thermal conductivity, more heat absorption capacity, and high melting point, it causes more material to transfer from tool to work surface. But it is observed that lower compaction pressures show high MRR and TWR. At lower value of CP, the particles bonded loosely on the tool do not withstand shock and higher temperature produces more heat absorption during machining causing more removal of material on the work surface.

3.2. Confirmation experiment

Based on the earlier evaluated combinations of specific factors and levels, an experiment for confirmation is performed. A new experiment is worked out finalizing the optimum conditions where in machining parameters of optimum level are considered. Finally, the prediction and verification of the improvement of performance characteristics is done. The improvements in the performance characteristics [14] are predicted by S/N ratio and optimum level of machining parameters and are given in Equation (3).

$$\eta_{opt} = \eta_m + \sum_{j=1}^{k} (\eta_j - \eta_m) \qquad (3)$$

where

η_{opt}= predicted optimal S/N ratio

η_m= total mean of the S/N ratios

η_{j}= mean S/N ratio at the optimal levels and

k= number of main design parameters that affect the quality characteristics.

The confirmation test results are shown in Table 9 and it is observed that the experimental optimal mean value for MRR is 8.7843 mg and the estimated optimal mean value for TWR is 14.249 mg.

3.3. Significance of Particle Size effect on MRR

The experimental values of MRR are shown in Table 4 and the resultant signals to noise ratio values are in Table 5. ANOVA and F-test values are indicated in Table 7. In that, all considered factors are significant, but the most important factors are Particle size (44.9%) and Peak current (30.59%) when compared to other factors like CP (11.17%), TON (5.67%), %WC (3.65%) and POL (3.43%). The machining condition is A1B3C3D1E1F1 for best MRR. i.e.. Positive polarity, 13A peak current, 12µs pulse on-time, NP electrode, 40% of WC in tool electrode and 200MPa compaction pressure. Figure 6 shows the SEM image of workpiece at optimum MRR machining condition. The EDS spectrum of as received EDMed Inconel 718 and machined at optimum MRR conditions is shown in Figures 7 & 8 respectively. Formation of tungsten trioxide (WO_3) phase as shown in XRD image in Figure 9 indicates the small and less time of oxygen atoms diffused into the metal due to low discharge energies at optimum MRR optimum conditions.

Table 9. Confirmation test results and comparison with predicted results

Output Parameter	Best Parametric Experimental Conditions	Predicted	Actual	Error%
MRR (mg/min)	[A1B3C3D1E1F1] Polarity is Positive, 13A of peak current, 12µs of pulse on-time, NP electrode, 40% WC in tool electrode and 200MPa of compaction pressure.	9.4712	8.7843	7.82
TWR (mg/min)	[A1B1C1D3E1F3] Polarity is Positive, 7Aof peak current, 4µs of pulse on - time, MP electrode, 40% WC in tool electrode and 400MPa of compaction pressure.	13.2389	14.2490	7.09

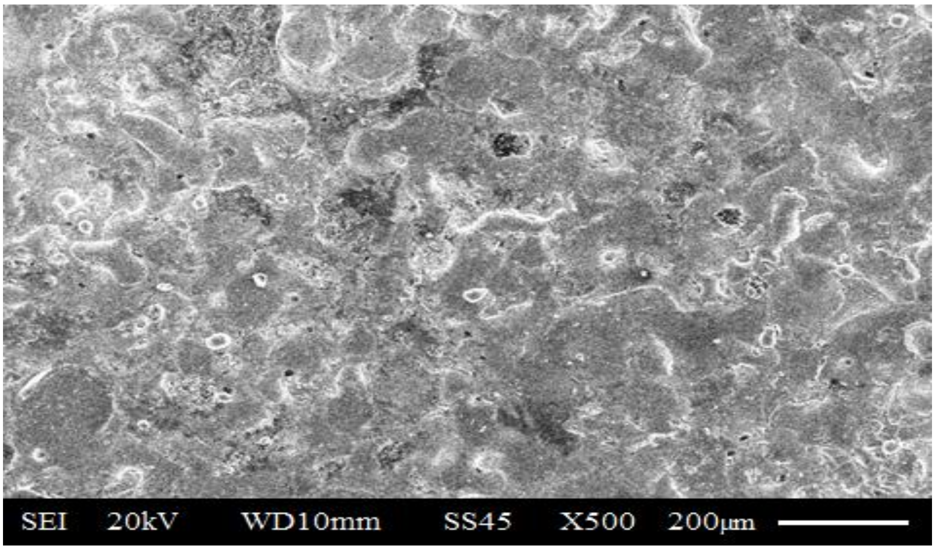

Figure 6. SEM image at optimal MRR machining condition

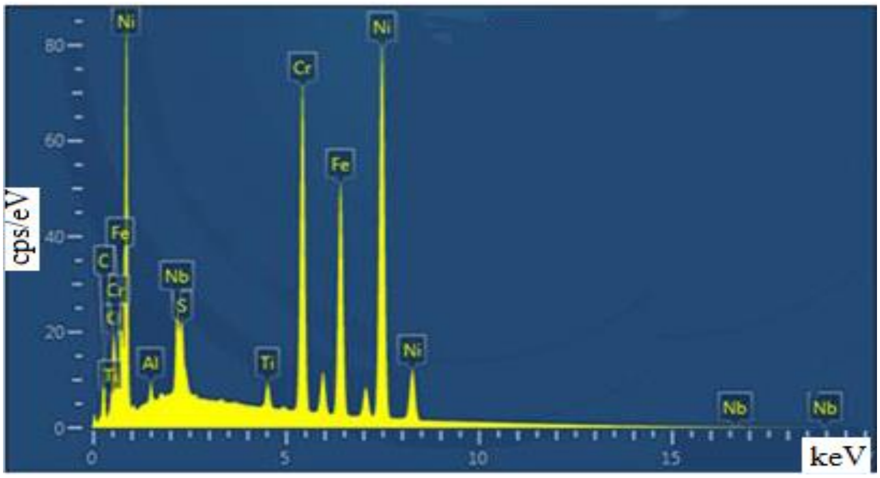

Figure 7. EDS plot for as received Inconel 718 alloy

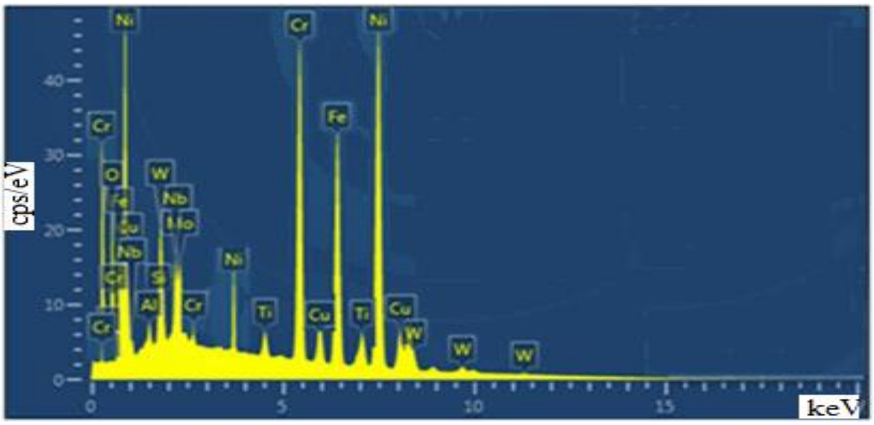

Figure 8. EDS plot of surface obtained at optimal MRR condition

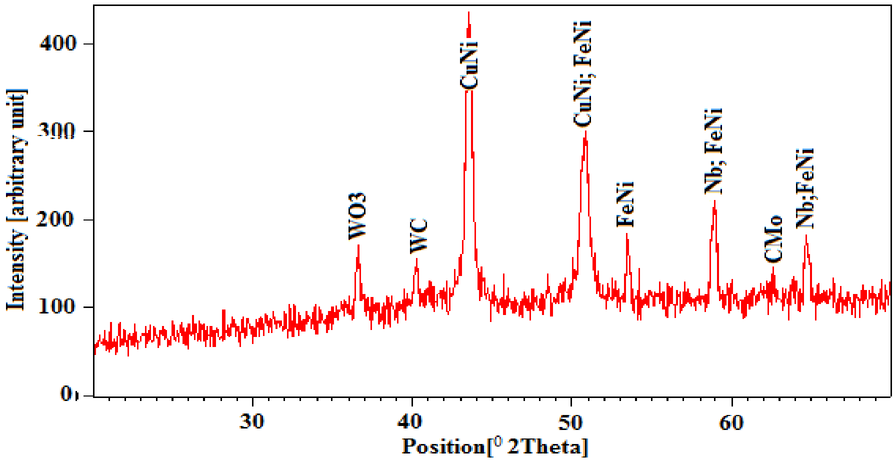

Figure 9. XRD pattern of machined surface at optimal MRR condition

3.4. Significance of Particle Size effect on TWR

Experimental results of TWR and its corresponding signal to noise ratio values are given in Table 4 and 6 respectively. ANOVA results are listed in Table 8. The ANOVA results and F-test values indicate that the most significant factors are Particle size (28.92%) and Peak current (25.08%). The machining condition A1B1C1D3E1F3 gives the best TWR. **i.e.** Positive polarity, 7A peak current, 4μs pulse on time, MP electrode, 40% of WC in tool electrode and 400 MPa compaction pressure. SEM image of TWR at optimum machining conditions can be seen in Figure10 and the spectrum obtained for surface machined at optimal TWR conditions is shown in Figure 11. It is reported that EDM electrodes made with micron particles would have higher TWR, because the density of WC is more when compared to Cu. The XRD image in Figure 12 shows the machined component at optimum TWR condition. The lower value of IP and TON at optimal tool wear conditions generates the lower temperature conditions. These lower temperatures are responsible for the formation of Hagg carbide (Fe_5C_2) and ferrous carbides (Fe_7C_3) which are usually forms at lower temperature in the ferrous carbide series [16].

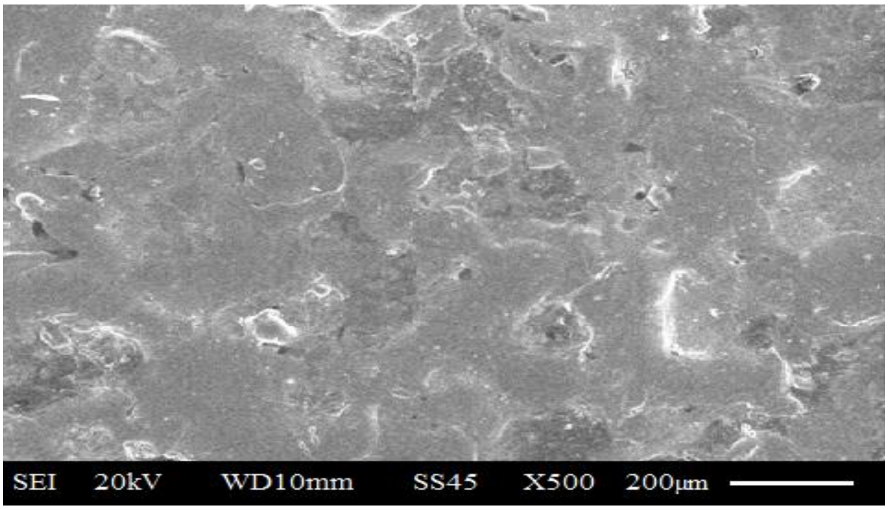

Figure 10. SEM image at optimal TWR machining condition

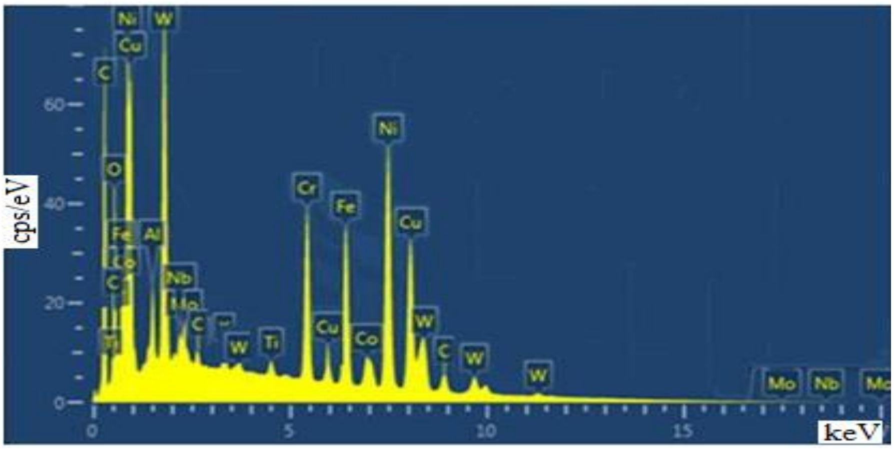

Figure 11. EDSplot of surface obtained At optimal TWR condition

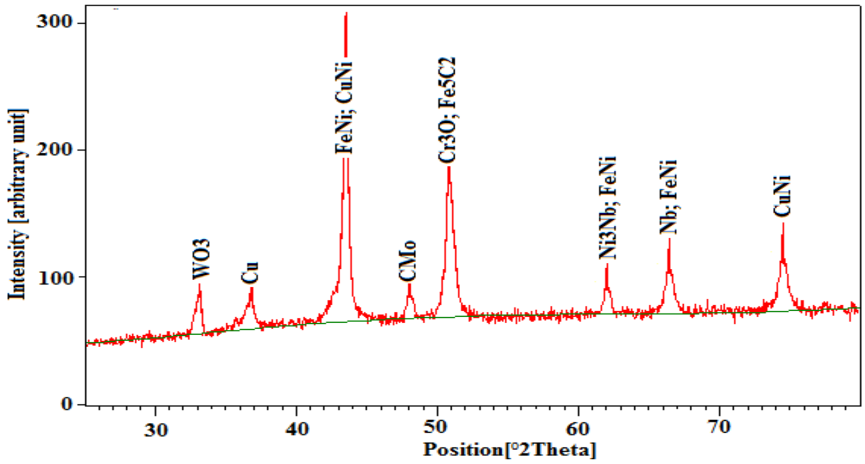

Figure12. XRD plot of the surface machined at optimal TWR condition

4. Conclusions

The influence of input parameters on the performance characteristics of EDM process with Cu-WC mixed ceramic compact sintered electrode was investigated using MRR and TWR as the basic criteria. The following conclusions are drawn from the results.

1. Material removal rate at most favorable condition (i.e. A1B3C3D1E1F1) is increased with increases of IP, TON and decreased with increase in the PS, %WC and CP. It is noticed that MRR is directly proportional to the IP and TON.
2. Tool wear rate at optimum condition (i.e. A1B1C1D3E1F3) was increased with decreases of IP, TON, %WC and increased with increase in the PS, and CP. It was noticed that TWR was inversely proportional to the IP, TON and %WC.
3. The experimental analysis shows that POL, IP, TON, PS, %WC and CP have significantly influenced MRR and TWR. The parameters, Particle size and peak current would be more contribution to MRR and TWR, when compared to other input parameters.
4. At optimal combinations of parameters, the MRR and TWR values obtained are 9.90mg/min and 13.23 mg/min respectively. The use of NP electrodes in the present study has considerably reduced the MRR values when compared to TWR. i.e., the surface modification was done by the small particle sizes.

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