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SCIENTIFIC PAPER

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OPTIMIZATION AND EFFECT OF DIELECTRIC FLUID WITH Zr AND Ni ON ELECTRICAL DISCHARGE MACHINING OF DIE STEEL MATERIAL

Article Highlights

- Ni, Zr, and combined Ni with Zr were selected as powder inclusion in dielectric fluid
- Combined Ni and Zr powder mixed with dielectric fluid produced better results
- TOPSIS techniques were effectively performed for multi-objective optimization
- Combined Ni and Zr dielectric conditions greatly reduce micro-cracks and craters

Abstract

This work aims to optimize the machining parameters and study the effect of powder-mixed dielectric fluid on the electrical discharge machining (EDM) process. The TOPSIS method of optimization is adopted to identify the optimal machining parameters. HCHCr die steel is preferred as a machining material. Due to their hard and ductile nature, Ni, Zr, and Ni+Zr were selected as powder inclusion in dielectric fluid. An L9 array Taguchi DOE is preferred to perform the experiments with parameters like peak off time, pulse off time, and pulse current. TOPSIS study revealed that the third level of powder dielectric fluid (Ni+Zr), 7A peak current, 9 µs pulse on time, and 2 µs pulse off time were specified as the optimal condition. Pulse on time (T_{on}) significantly impacted metal removal rate and surface roughness while machining operation on HCHCr die steel. SEM analysis was done to find the effect of powder-mixed dielectric fluid, while EDAX analysis was done to ensure the presence of powder inclusion.

Keywords: optimization, electrical discharge machining, dielectric fluid, nickel, zirconium, metal removal rate, surface roughness.

Electrical discharge machining (EDM) is a promising technique used globally for producing complex shapes in both conductive and non-conductive materials. Recently, its industrial use has been extended to produce intricate profiles and machining high materials [1,2]. However, the minimum machining rate and improper surface finish restrain the use of the EDM process. A powder-mixed machining process is a novel approach to overcome this drawback and to get a high surface finish and improved machining rate [3,4]. Modern researchers explore the performance of powder-mixed dielectric fluid in the EDM process; nickel (Ni) and aluminum oxide are commonly used as dielectric fluid inclusion particles [5]. The performance of powder metallurgy electrodes in EDM of AISI steel was studied with the Taguchi technique. It noted that electrode material, duty cycle, and current had potential effects on machining parameters, and the copper electrode was recommended for a high machining rate [6]. The aluminum powder is added to dielectric fluid during the EDM process. It found that the grain size of

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the inclusion particle significantly impacts the machining surface, surface finish, and metal removal rate (MRR). Improved MRR was achieved through increased grain size of aluminum powder in dielectric fluid [7]. Using the EDM process, kerosene was used as a dielectric fluid to make a hole. They found that the optimal machining conditions were the 60 V input voltage, 500 Ω resistance, and 1.5 µm/s feed [8].

Based on the experimental research with chromium powder mixed with dielectric fluid in EDM, and observed that MRR considerably increases with high current and duty cycle [9]. Powder concentration has a predominant effect on MRR. Surface modification in die steel material was studied using tungsten powder as dielectric fluid [10]. The research identified low discharge current, short pulse on time, and longer pulse off time as favorable machining conditions. Better MRR and minimum tool wear rate were achieved with abrasive powder mixed EDM [PMEDM] on 6061Al/Al_2O_3P/20p aluminum matrix composite (AMCs) [11]. The effects of graphite powder mixed with dielectric fluid on the machining of titanium alloy with the EDM process were investigated. They stated that increased discharge current and graphite powder concentration enhance the MRR [12]. Tool wear rate (TWR) depends on discharge current and is inversely proportional to mixed powder particle concentration [13]. The GRA (grey relational analysis) method optimized the machining parameters in the powder-mixed EDM process. They concluded that improved surface topography was achieved while machining with powder-mixed dielectric fluid [14]. When machining, adding powder particles in a proper size concentration minimizes surface roughness (Ra). The graphite electrode EDM process provides machining with high MRR and good surface roughness, followed by copper and brass electrodes, while using distilled water as dielectric fluid [15]. Experimental optimization is highly recommended to achieve repeated accurate results. Single-objective and multi-objective optimizations have been most commonly used in recent days. The Taguchi approach effectively optimizes the input parameters on MRR and TWR on powder-mixed EDM [16]. Several researchers used TOPSIS and GRA analysis to optimize the machining parameters [17–20].

The EDM process with powder-mixed dielectric fluid could be successfully carried out. Generally, alumina, Si, Gr, and Cr would be used to include dielectric fluid. Based on a detailed literature study, the EDM process was performed with kerosene dielectric fluid, a reputed powder mixture, and hard steel as work material. Identifying suitable particle inclusion for better machining conditions has scope in the EDM process. Past research reveals that Nickel powder was not used as a powder inclusion in dielectric fluid. This study is aimed to find the influence of Ni (Nickel) and Zr (Zirconium) mixed dielectric fluid in the EDM process. Due to the wide range of applications, HCHCr die steel is preferred as a workpiece. The TOPSIS optimization technique was used to optimize the machining parameters because of its simplicity and ability to provide accurate results.

MATERIALS AND METHODS

In this work, HCHCr steel with dimensions of 147 mm x 45 mm x 10 mm is used as work material. EDM uses a copper electrode with a 12 mm diameter and 20 mm length. The face of the electrode is smoothened before starting the experiments to obtain surface texture in the end face of the electrode. YBI EDM Oil BELDISCHA DCO-1000i was selected as a dielectric fluid due to flexibility and low viscosity [21,22]. Ni and Zr of 300 mesh are used as inclusion particles in dielectric fluid with a size of 46 µm dispersed uniformly. Zr is highly corrosive and resistant to saltwater, acids, alkalis, and other agents. Due to their hard and ductile nature, Ni and Zr were preferred as powder inclusion.

EDM machine (ELEMECH EDM Die Sink (Model S3500) is preferred for the experiments. A separate tank is added to the primary tank to prevent the dielectric powder flow in the main sump. This arrangement is required to avoid powder clogging in the filter system. EDM dielectric fluid circulation was done effectively with the help of the pump, which is kept inside the main tank. An L9 array Taguchi DOE is preferred to perform the experiments with parameters like peak off time, pulse off time, and pulse current. MRR and surface roughness (SR) were the machining output. MRR was calculated by Eq. (1), and the SR value was computed with the Surftest SJ-120 machine. The experimental setup is given in Figure 1. The experimental parameter and L9 DOE run order with measured output are given in Table 1.

$$MRR = \frac{(IM - FM)*1000}{Density * MT} \quad (1)$$

where IM is the initial mass in g, FM is the final mass in g, and MT is the machining time in min.

RESULTS AND DISCUSSION

Single parameter optimization

Signal-to-noise (S/N) ratio is the first stage in single parameter optimization, and it is performed in Minitab 19. For high MRR, HB is preferred. For SR, a

Table 1. Experimental values.

Exp.No	Powder	I_P (Amp)	T_{on} (µs)	T_{off} (µs)	MRR (mm^3/min)	Ra (µm)
1	Zr	5	9	2	8.931	5.756
2	Zr	6	49	6	10.068	7.771
3	Zr	7	99	9	2.082	3.825
4	Ni	5	49	9	7.271	5.446
5	Ni	6	99	2	5.863	7.273
6	Ni	7	9	6	35.381	5.792
7	Zr + Ni	5	99	6	1.965	3.26
8	Zr + Ni	6	9	9	11.095	5.766
9	Zr + Ni	7	49	2	13.872	9.101

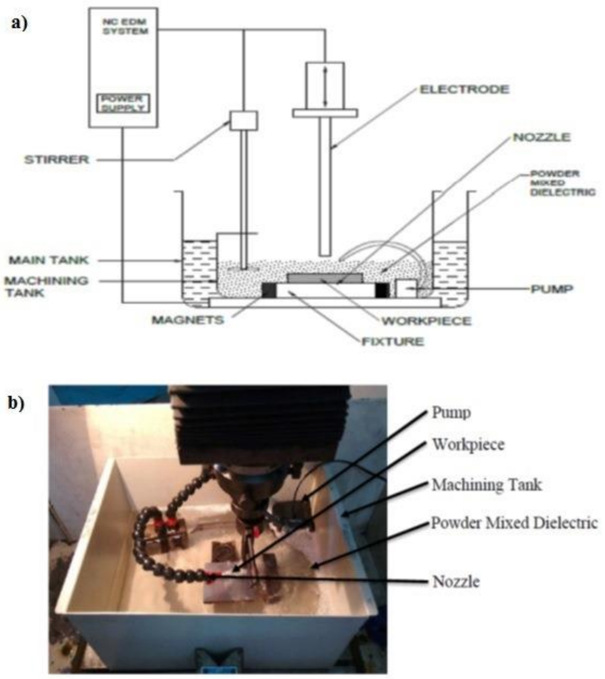


Figure 1. Experimental setup.

minimum value is preferred. The selected equation for the S/N ratio is given in Eqs. (2) and (3), respectively [23]:

SB (Smaller the better): $$S/N = -10\log\frac{1}{n}\left[\sum_{i=1}^{n} y_i^2\right] \quad (2)$$

HB (Higher the better): $$S/N = -10\log\frac{1}{n}\left[\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \quad (3)$$

where *n* represents experiments performed and *y* represents the data.

Table 2 (a) shows that pulse on time greatly impacted MRR. Peak current holds second, followed by pulse off time and powder mixture (T_{on}(µs) > IP(Amp) > T_{off}(µs) > P). Here mixed powder dielectric does induce a high machining rate. The high current and pulse time combination increases the metal melting, producing high MRR [24]. Based on the S/N ratio, Ni mixed dielectric fluids, 6 IP, 9 T_{on}, and 2 T_{off}, were optimal for high machining MRR. High MRR was achieved with a 28.68 mm^3/min rate in optimal machining conditions. The improvement in MRR was found to be 66.32%. (Optimum condition for MRR = $(P)_2$ $(I_P)_2$ $(T_{on})_1$ $(T_{off})_1$).

Table 2. Response for SN Ratios-MRR & Ra.

Level	P	I_P (Amp)	T_{on} (µs)	T_{off} (µs)
a) MRR				
1	18.778	14.039	21.220	19.075
2	15.149	18.775	20.045	16.555
3	16.538	17.651	9.200	14.835
Delta	3.629	4.736	12.020	4.240
Rank	4	2	1	3
b) Ra				
1	-15.74	-13.40	-15.23	-17.21
2	-14.89	-16.75	-17.24	-14.44
3	-14.90	-15.36	-13.05	-13.86
Delta	0.85	3.36	4.19	3.34
Rank	4	2	1	3

Similarly, the response for Ra is presented in Table 2 (b). For better Ra, T_{on} dominates higher compared to other parameters. The dominant factor for Ra is T_{on} (µs) > IP (Amp) > T_{off} (µs) >P. In both MRR and Ra, dielectric fluid does not create a significant impact. Generally, increasing and decreasing on-time pulse duration in EDM enhances the dissolution in both lateral and linear paths, which results in high MRR and Ra. It is acceptable with research work [25]. From response Table 2(b), $(P)_3$ $(I_P)_1$ $(T_{on})_3$ $(T_{off})_3$ were identified as optimal conditions for achieving improvement in Ra. Ni+Zr mixed dielectric fluid is suggested to achieve a high Ra. A rise in T_{on} generally increases the intensity of spark in EDM and induces melting of material boundary much deeper and wider. It also improves Ra. The presence of Ni + Zr in dielectric fluid promotes better Ra due to the formation of fewer surface craters in HCHCr steel [26,27]. For validating the optimal parameters, a confirmation experiment was conducted. At optimal machining condition of $(P)_3$ $(I_P)_1$ $(T_{on})_3$ $(T_{off})_3$, Ra = 1.992 µm was achieved. The confirmation value indicates the improvement of Ra from 5.756 µm to 1.992 µm.

TOPSIS analysis

In modern research, the TOPSIS method is commonly applied to optimize the machining parameters with respect to multi-objective form. The decision matrix is the initial step (step 1) of the TOPSIS method and is represented in r_{ij} (Eq. 4). Secondly, the weightage of every response was done. In the third stage, computing normalized value was based on weightage and decision matrix, given in Eq. (5).

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i-1}^{m} a_{ij}^2}} \quad (4)$$

$$Vij = Wi \times rij \quad (5)$$

In step 2, the ideal solution was computed. S+ and

S- indicated the ideal solution (positive and negative) given in Eq. (6) and Eq. (7):

$$S_i^+ = \sqrt{\sum_{j=1}^{M}\left(v_{ij} - v_j^+\right)^2} \quad (6)$$

$$S_i^- = \sqrt{\sum_{j=1}^{M}\left(v_{ij} - v_j^-\right)^2} \quad (7)$$

In step 3, CC (closeness coefficient) is computed with the help of Eq. (8).

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad (8)$$

The computed CC value and its rank are given in Table 3. Equal weightage was given while computing the normalized MRR and Ra values.

Table 3. Normalized, separation measures and CC.

SN ratio		Normalization		Weighted normalized		Separation measures		CC*	Rank
MRR	Ra	MRR	Ra	MRR	Ra	S+	S-		
19.018	-15.202	0.3103	0.3073	0.1551	0.1536	0.13033	0.15037	0.5357	4
20.059	-17.810	0.3498	0.4148	0.1749	0.2074	0.15169	0.14516	0.4890	5
6.370	-11.653	0.0723	0.2042	0.0362	0.1021	0.23148	0.14083	0.3783	8
17.232	-14.722	0.2526	0.2907	0.1263	0.1454	0.15247	0.13420	0.4681	6
15.362	-17.234	0.2037	0.3882	0.1018	0.1941	0.19698	0.08345	0.2976	9
23.740	-15.257	0.5343	0.3092	0.2672	0.1546	0.06758	0.24920	0.7867	1
5.867	-10.264	0.0683	0.1740	0.0341	0.0870	0.23302	0.15589	0.4008	7
20.903	-15.217	0.3854	0.3078	0.1927	0.1539	0.10008	0.18185	0.6450	2
22.843	-19.182	0.4819	0.4858	0.2409	0.2429	0.15808	0.20681	0.5668	3

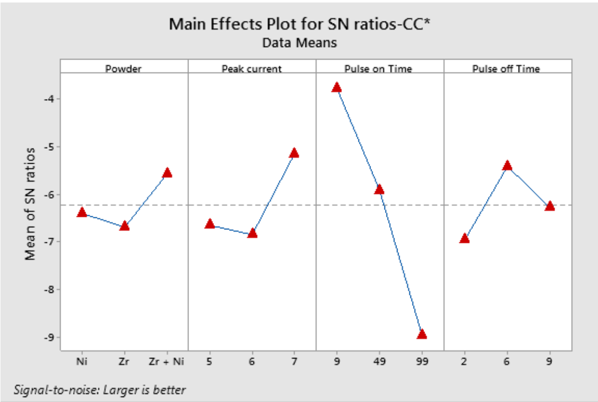


Figure 2. Mean S/N ratio - CC.*

From Table 2, the highest CC value was achieved in experiment run order 6 with the value of 0.7867. Based on the CC value, rank was given to every experiment. A lower CC value was seen in run order 5. Suggest run order with respect to CC is 6>8>9>1>2>4>7>3>5. With respect to the CC value, the mean S/N ratio plot was presented in Figure 2, and it was observed that T_{on} was indicated as the most dominant factor for achieving high MRR and Ra. *Ip* and T_{off} hold the second and third dominant factors for getting high MRR and Ra. An increase in pulse on time induces better machinability due to enhanced spark forming over the work material [28]. Powder mixed dielectric fluid created less effect on MRR and Ra. ANOVA was used to identify each parameter's contribution to machining [29]. Pulse on time holds a contribution rate of 75.47% on MRR and Ra, followed by a peak current of about 10.18%. The effect of mixed dielectric fluid represents less contribution of 4.18% on MRR and Ra. The effectiveness of the experiment was determined by computing the R^2 value [30–35]. From ANOVA, R^2 = 90.63% and R^2(adj) = 81.25%.

A validation experiment is key to the final output [30]. It represents the third level of powder dielectric fluid (Ni+Zr), 7 A peak current, 9 µs pulse on time, and 2 µs pulse off time indicated as the optimal condition. MRR increased from 8.931 mm^3/min to 28.608 mm^3/min, and Ra was enhanced from 5.756 µm to 4.845 µm. Improvement of CC on MRR and Ra was achieved by 35%. The experimental outcomes exposed that the combined (Zr+Ni) powder suspended in dielectric fluid significantly enhanced the MRR and reduced Ra [36,37]. The suspended powders in the dielectric fluid improve the machining performance [38].

SEM analysis

SEM analysis was performed to ensure surface quality in optimal conditions. Based on the multi-objective optimization technique, the third level of the powder dielectric fluid (Ni+Zr), 7 A peak current, 9 µs pulse on time, and 2 µs pulse off time was indicated as the optimal condition. Hence to identify the effect of powder-mixed dielectric fluid, three sets of SEM analyses were performed with varying dielectric fluids. First, Ni mixed, Zr mixed, and Ni+Zr mixed dielectric fluids were used for machining with optimal parameters of 7 A peak current, 9 µs pulse on time, and 2 µs pulse off time, as can be seen in Figure 3a–c, respectively.

SEM analysis shows craters on the machined surface (Figure 3a and Figure 3b) of HCHCr die steel using Zr and Ni mixed dielectric fluids. Debris on the machined surface produced large pits and micro-cracks on HCHCr steel [36,39]. At the same time, the minimum level of micro cracks and craters is noted in Figure 3c. It is due to material deposition from inclusion powders and dielectric hydrocarbon at optimum pulse on condition. Based on the SEM analysis, machining of HCHCr die steel with Zr+Ni dielectric fluid produced good results at optimal machining conditions of 7 A peak current, 9 µs pulse on time, and 2 µs pulse off time. In addition, EDAX analysis was done to ensure the presence of inclusion particles over the machined surface, represented in Figure 4–6, respectively.

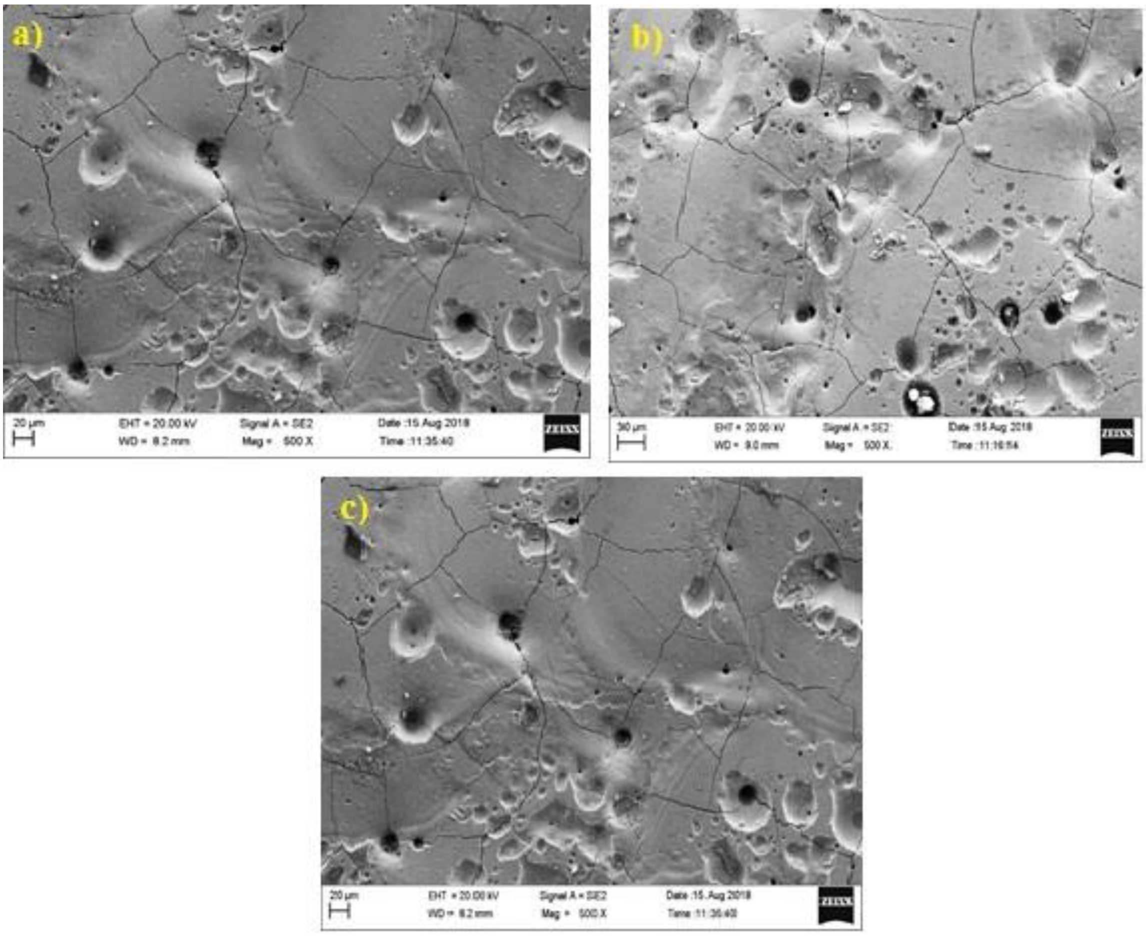
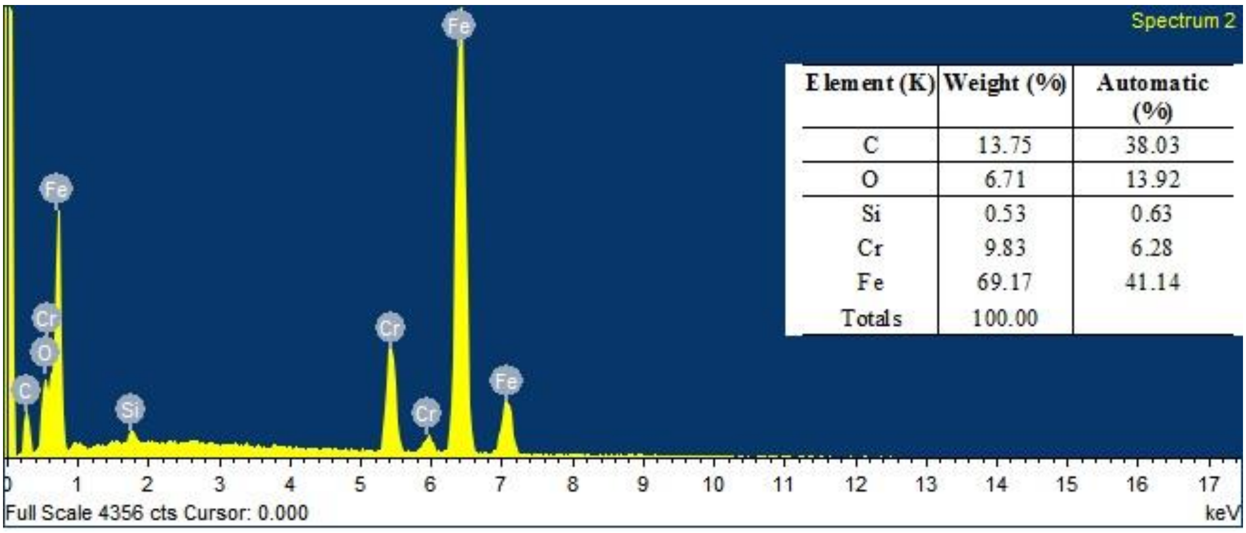


Figure 3. SEM Analysis of machined surface characteristics of powder mixed with dielectric; (a) zirconium, (b) nickel, and (c) combined zirconium and nickel.



Element (K)	Weight (%)	Automatic (%)
C	13.75	38.03
O	6.71	13.92
Si	0.53	0.63
Cr	9.83	6.28
Fe	69.17	41.14
Totals	100.00	

Figure 4. EDAX analysis of machined surface for zirconium powder mixed in the dielectric.

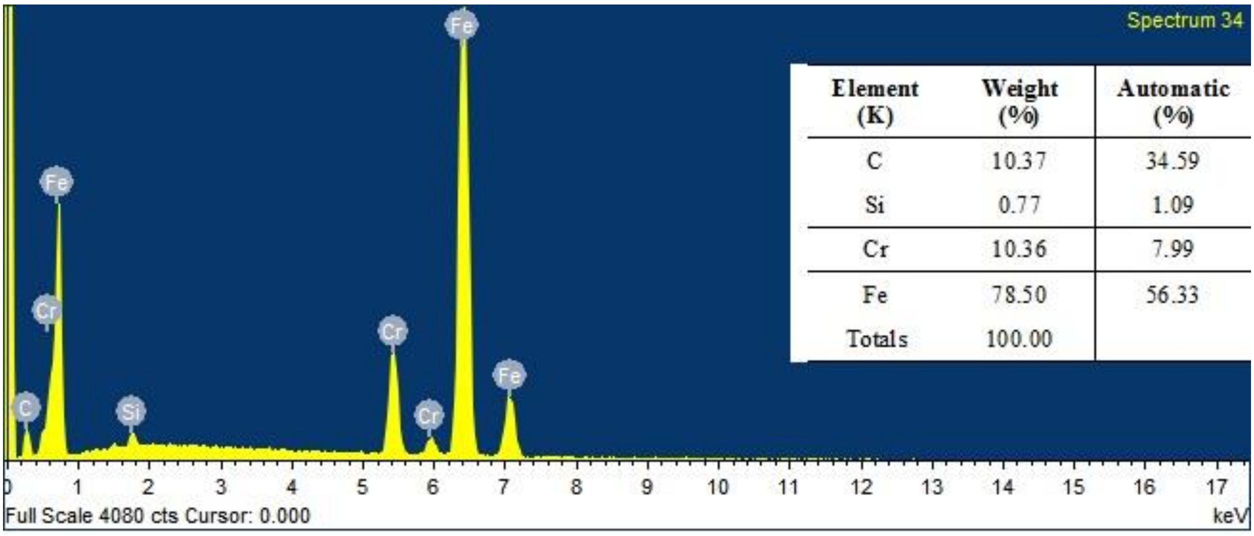


Figure 5. EDAX analysis of machined surface for nickel powder mixed in the dielectric.

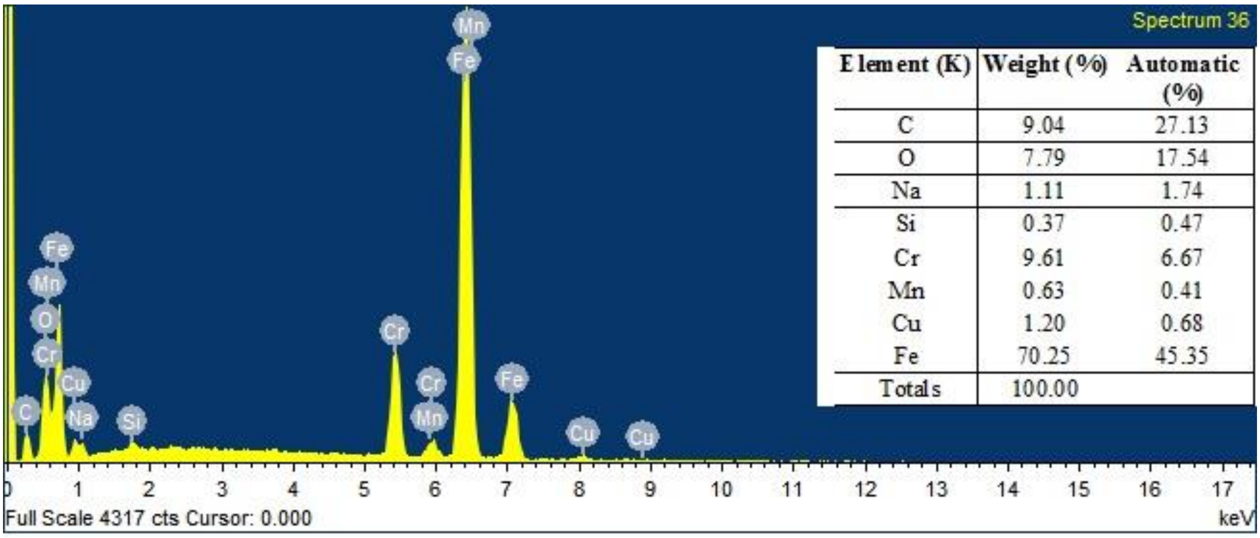


Figure 6. EDAX analysis of machined surface for combined zirconium and nickel powder mixed in the dielectric.

CONCLUSION

Present work was performed to study the effect of dielectric fluid and optimizing machining parameters on machining HCHCr die steel. For improving MRR, $(P)_2$ $(I_P)_2$ $(T_{on})_1$ $(T_{off})_1$, was identified as an optimal condition with respect to the single-objective optimization. For Ra, $(P)_3$ $(I_P)_1$ $(T_{on})_3$ $(T_{off})_3$ was identified as the optimal condition based on single objective optimization. TOPSIS study reveals that the optimal conditions for the third level of powder dielectric fluid are (Ni+Zr), 7 A peak current, 9 µs pulse on time, and 2 µs pulse off time. SEM study ensures a minimum level of micro cracks and craters are noted in Ni+Zr mixed dielectric fluid during optimal machining conditions. The confirmation experiment reveals that MRR improved from 8.931 mm^3/min to 28.608 mm^3/min, and Ra was enhanced from 5.756 µm to 4.845 µm. Improvement of CC on MRR and Ra by 35% and inclusion of material was ensured by the EDAX analysis.

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NAUČNI RAD

OPTIMIZACIJA I EFEKAT DIELEKTRIČNE TEČNOSTI SA Zr I Ni NA MAŠINSKU OBRADU ČELIČNOG MATERIJALA ELEKTRIČNIM PRAZNJENJEM

Ovaj rad ima za cilj optimizaciju parametara obrade i proučavanje uticaja dielektrične tečnosti pomešane sa prahom na proces obrade električnim pražnjenjem (EDM). TOPSIS metoda optimizacije je usvojena za identifikaciju optimalnih parametara obrade. HCHCr čelik je poželjniji kao materijal za mašinsku obradu. Zbog svoje tvrde i duktilne prirode, Ni, Zr i Ni+Zr su odabrani kao inkluzioni prahovi u dielektričnoj tečnosti. L9 niz Taguchi plan je poželjniji za izvođenje eksperimenata sa parametrima, kao što su vreme vršnog isključenja, vreme isključenja impulsa i impulsna struja. Studija TOPSIS je otkrila da su treća vrsta praškastog dielektričnog fluida (Ni+Zr), vršna struja od 7 A, vreme uključenog impulsa od 9 µs i vreme isključenog impulsa od 2 µs optimalni uslovi. Impuls vremena značajno je uticao na brzinu uklanjanja metala i hrapavost površine tokom mašinske operacije na HCHCr čeliku. SEM analiza je urađena da bi se utvrdio efekat praha mešanog dielektričnog fluida, dok je EDAX analiza urađena da bi se osiguralo prisustvo inkluzije praha.

Ključne reči: optimizacija, obrada sa električnim pražnjenjem, dielektrični fluid, nikl, cirkonijum, brzina uklanjanja metala, hrapavost površine.