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Investigating the Effects of Wire Electric Discharge Machining Parameters on MRR and Surface Integrity in Machining of Tungsten Carbide Cobalt (WC-24%Co) Composite Material

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Abstract: **Tungsten carbide composite (WC-24%Co) is a kind of difficult-to-cut material with poor machinability by traditional machining methods, while wire electrical discharge machining (WEDM) is suitable for machining of composite materials. In this paper, four input machining parameters including pulse on time, pulse off time, peak current and spark gap set voltage have been varied to investigate their effect on output responses. To investigate the output characteristics; material removal rate (MRR) and different aspects of surface integrity for WC-Co samples such as topography of machined surface, crack formation, craters (of variable size), pock marks, micro-cracks and recast layer were considered as performance criteria. The variations of MRR versus input machining parameters were investigated by means of main and interaction effect plots and also verified by ANOVA results. The effect of pulse energy based on pulse on time and pulse current variations against crack formation, craters (of variable size), pock marks and recast layer thickness were studied. The possibilities of carbides and oxides were formed either in free form and/or in compound form due to decomposition of de-ionized water; machined samples and wire material on the work surface after WEDM process were investigated by field Emission scanning electron microscope (Fe-SEM QUANTA 200 FEG) and Energy Dispersive X-Ray Analysis (EDX). The experimental results revealed that general aspects of surface integrity for machined samples are mostly affected by pulse current and pulse on time. The approximate density of cracks, craters (of variable size) and pock marks on the work surface is intensively dependent on pulse energy variations. Although increase of pulse energy improves the material removal efficiency.**

Keywords: **WEDM, WC-24%Co composite, MRR, Surface Integrity, Response Surface Methodology, Desirability Function**

1. INTRODUCTION

WEDM is a versatile thermo-electric process. The electrical circuit produces controlled tiny sparks between the wire electrode and work. These sparks create high temperature which melts and vaporizes the work material. The control parameters are spark exposure time (Pulse On-time), capacitor charging time (Pulse Off-time), current intensity (Peak-current) and spark gap set voltage which can classify as machine parameter, material parameter, electrical parameter, and mechanical parameter. Four important parameters of significance were selected in the present work. Better productivity and economy is attained when the interactions among variables are understood. Many works were undertaken for WEDM optimization process variation in parameter makes generalization difficult. Response- surface methodology (RSM) is one of the important techniques in statistics used to determine the relationship between the effects of process parameters on the coupled responses. A lot of work being done with other materials but with WC-24%Co composite works undertaken pre was few. Kanagarajan and Palanikumar, have used the RSM model to maximize MRR on WC-30%Co composites. In the present study, WC-CO with cobalt binder (24%) was machined by WEDM.

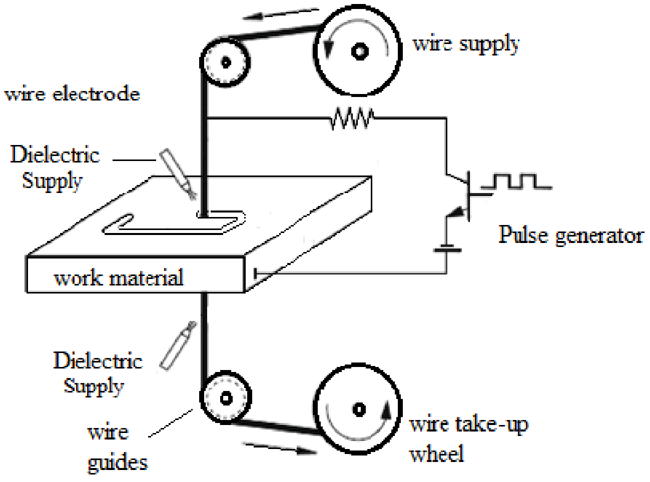

Fig. 1. Representation of WEDM process

Literature review states RSM is a combination of mathematical and statistical techniques and is used for developing improved and optimizing the parameter for the output response of material removal rate and surface roughness. Hewidy et al. has investigated the WEDM performance on Inconel 601 by using response surface methodology (RSM). They have confirmed that surface roughness increase with the increase of peak current and decrease with increase of duty factor and wire tension. Mahapatra and Patnaik; Kung and Chiang used coated wire electrode to investigate WEDM machining performance. Coated brass wire can perform at higher cutting speed as compared to brass wire electrode. Coated brass wire can also produce exceptional surface finish.

Liao et al. developed a mathematical model by means of regression analysis and then solved the optimization problem by a feasible direction method. Ramakrishnan and Karunamoorthy used multiresponse optimization method using Taguchi's robust design approach for WEDM. Each experiment had been performed under different cutting conditions of pulse on time, wire tension, delay time, wire feed speed and ignition current intensity.

Three responses, namely material removal rate, surface roughness, and wire wear ratio had been considered for each approach. It was observed that the Taguchi's parameter design is a simple, systematic, reliable and more efficient tool for optimization of the machining parameters. It was indentified that the pulse on time and ignition current had influenced more than the other parameters. Sarkar et al. modeling and optimization of wire electrical discharge machining of γ-TiAl in trim cutting operation. A second-order mathematical model, in terms of machining parameters, was developed for surface roughness, dimensional shift and cutting speed using RSM

2. EXPERIMENTAL METHODOLOGY

In the present work WC-CO metal matrix composite with 24% cobalt percentage was sliced to size of 70×50×20 mm rectangular bar by ELEKTRA SPRINTCUT 734 WEDM machine. A brass wire of 0.25 mm diameter was used as electrodes. The wires were supplied and spent wires were taken away by traction rollers made of ceramic material to reduce wire damage, friction and to enable high speed machining.

Used wires were collected in a separate tank. Distilled water was utilized as di-electric fluid to remove debris in order to keep the cutting zone clear and the work surface from heating up. An electrode gap up to 0.5 mm has been kept between wire and work. Dielectric after flushing and filtering will be recycled. The Experiments were planned on central composite design with 4 parameters at 3 levels and 30 experimental runs. The experimental plan, levels selected and their range is given in Table 1.

Table 1. Process variables and their levels

Symbol	Parameters	Levels	
		(-1)	(+1)
A	Pulse-on-time (MU)	106	116
B	Pulse-off-time (MU)	30	60
C	Current (Amp)	80	180
D	Voltage (Volt)	40	80

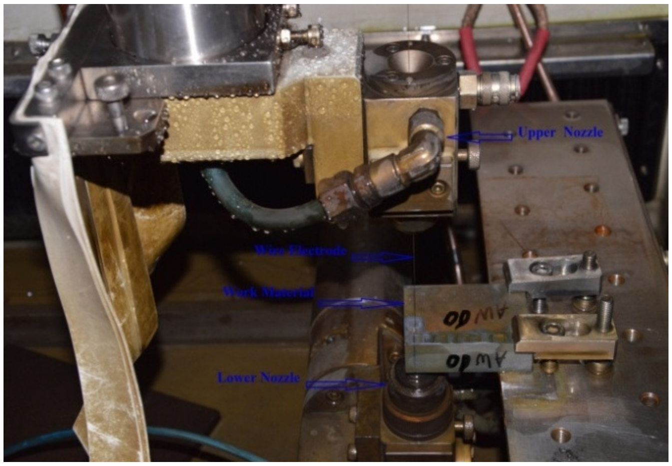

Fig. 2. Photograph shows the schematic diagram and the setup of WEDM process

3. RESULTS AND DISCUSSION

3.1. Response surface modeling of WEDM process

Response surface methodology is a collection of statistical and mathematical methods that is useful for modeling and analysis of engineering problems. In this technique, the main objective is to optimize the response surface that is influenced by various process parameters. The RSM has been applied for modeling and analysis of machining parameters in the WEDM process in order to obtain the relationship to the machining rate. In the RSM, the quantitative form of relationship between desired response and independent input variables is represented as follows:

$$Y = f(T_{on}, T_{off}, Ip \text{ and } SV)$$

Where, Y is the desired response and f is the response function (or response surface). For the purpose of analysis, the approximation of Y was proposed using the fitted second-order polynomial regression model which is called as the quadratic model. The quadratic model of Y is written as follows:

$$Y = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{i=1}^{k} b_{ii} X_i^2 + \sum_{i<j=2}^{2} b_{ij} X_i X_j \pm e_r$$

Where Y is the desired response and the x_i (1, 2, k) are the independent of k quantitative process variables. b_o is constant and b_i, b_{ii}, b_{ij} are the coefficients of linear, quadratic, and cross product terms.

3.2 Determination of main and interaction effects on metal removal rate

Based on the proposed second-order polynomial model, the effect of the process variable on the machining rate has been determined by computing the values using Design expert 9.0, software and the relevant data from Table 2. The mathematical relationship for correlating the machining rate and the considered process variables is obtained as follows:

$$\text{Metal Removal Rate} = -124.22029 + (1.56999 \times A) + (2.14733 \times B) - (0.35622 \times C) - (0.27341 \times D) -$$

$$(0.025582 \times A \times B) + (3.07534\text{E-}003 \times A \times C) -$$

$$(1.01011\text{E-}003 \times A \times D) + (1.09366\text{E-}005 \times B \times C) + (4.53964\text{E-}003 \times B \times D) + (5.33889\text{E-}004 \times C \times D)$$

It has been concluded from Eq. 1, there are three factor interactions between T_{on} and T_{off}, T_{on} and current, T_{on} and voltage, T_{off} and voltage, T_{off} and current, current and voltage.

When the values of probability (Prob>F) are less than 0.05, it means that the factor is significant. The estimated regression coefficients and analysis of variance for machining rate using 95 % of CI are shown in Table 3. The p value for lack of fit is 0.0946, F value of the model is 941.06 suggesting that this model adequately fits the data. The other important coefficient R^2, which is called determination coefficient in the resulting ANOVA table, is defined as the ratio of the explained variation to the total variation and is a measure of the degree of fit. When R^2 approaches unity, the response model fits better to the actual data and shows less difference between the predicted and actual values. The obtained values are predicted R^2 of 0.9920 is in reasonable agreement with the adjusted R^2 of 0.9969.

Based on the figure 3a, MRR is found to have an increasing trend with the increase of pulse on time. At the same time, it decreases with the increase of pulse off time. This establishes the fact that MRR is proportional to the energy consumed during machining and is dependent not only on the energy contained in a pulse determining the crater size, but also on the applied energy rate or power. It is observed from Figure 3b that MRR increases with increase in current but at slow rate and it also increases with increase in T_{on}. The higher is the current setting, the larger is the thermal effect during the on time. This leads to increase in MRR. But, the sensitivity of the current setting on the cutting performance is stronger than that of the pulse on time. While the peak current setting is too high, wire breakage occurs frequently. Figure 3c shows that MRR decreases with increase in the servo voltage.

From perturbation curve, as shown in figure 3d, it is clear that pulse on time and current are the factors of importance for MRR. Increased value of these two factors gives increased value of MRR.

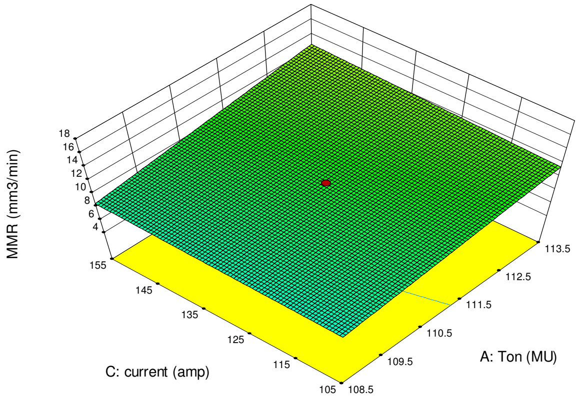

Fig. 3a. Interaction effect of Ton and T_{off} on MRR

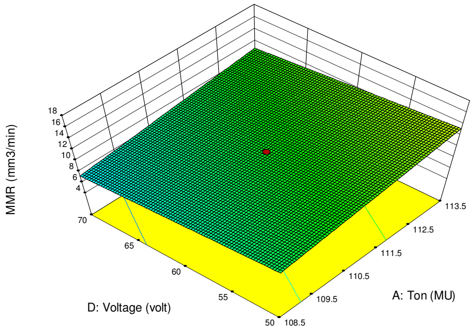

Fig. 3b. Interaction effect of Ton and Current on MRR

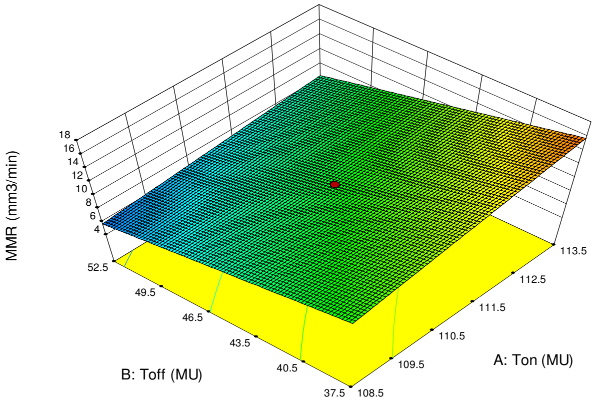

Fig. 3c. Interaction effect of Ton and Voltage on MRR

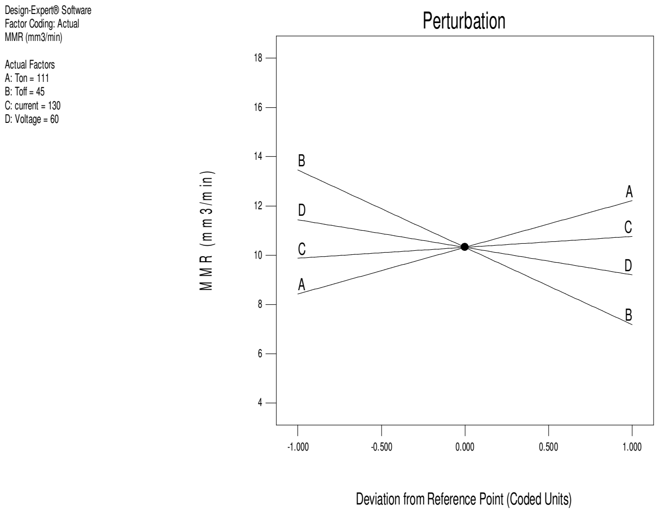

Fig. 3d. Perturbation curve for MRR

4. OPTIMIZATION THROUGH DESIRABILITY FUNCTION APPROACH

One of the useful approaches to optimization of multiple responses is to use the simultaneous optimization technique developed by Derringer and Suich. This approach includes the concept of desirability functions. The general approach is to first convert each response (y_i) into an individual desirability function (d_i) and varied over the range $\leq d_i \leq 1$. Where if the response y_i is at its goal or target, then ($d_i=1$). The response is outside an acceptable region ($d_i=0$). The weight of the desirability function for each response defines its shape. For each response, weights are assigned (r_i) to emphasize or de-emphasize the target. Finally, the individual desirability functions are combined to provide a measure of the overall desirability of the multiresponse system. This measure of composite desirability is the weighted geometric mean of the individual desirability for the responses. In the present investigation, the response parameter metal removal rate is chosen to maximize the overall desirability. The factor settings with maximum total desirability are considered to be the optimal parameter conditions.

TABLE 2: Test conditions in face-centered central composite design

Run	Factor 1 T_{on} MU	Factor 2 T_{off} MU	Factor 3 Current Amp.	Factor4 Voltage volt	Response MMR (mm^3/min)	Run	Factor 1 T_{on} MU	Factor 2 T_{off} MU	Factor 3 Current Amp.	Factor4 Voltage volt	MRR mm^3/min
1	113	52	150	70	8.10113	16	111	45	130	60	10.4628
2	113	37	150	70	14.8516	17	113	37	100	50	16.7458
3	111	45	80	60	9.449	18	106	45	130	60	6.4825
4	111	45	130	60	10.4896	19	108	37	100	50	12.1993
5	116	45	130	60	14.223	20	113	37	150	50	17.2504
6	111	45	180	60	11.369	21	108	37	150	50	12.1261
7	111	45	130	60	10.2495	22	113	37	100	70	12.9374
8	111	30	130	60	16.545	23	111	60	130	60	4.19008
9	113	52	150	50	9.5976	24	111	45	130	80	7.8365
10	108	52	100	70	4.5454	25	108	37	150	70	9.6923
11	113	52	100	70	7.025	26	108	37	100	70	8.98215
12	108	52	150	70	4.9673	27	111	45	130	60	10.4628
13	111	45	130	60	10.4896	28	111	45	130	60	10.2495
14	111	45	130	40	12.4904	29	108	52	150	50	6.6568
15	113	52	100	50	8.6097	30	108	52	100	50	6.1613

TABLE 3. The ANOVA table for MRR

ANOVA for Response surface 2FI model						
Source	**Sum of square**	**Df**	**Mean Square**	**F-Value**	**p-Value Prob>F**	
Model	355	10	35.55	941.06	<0.0001	Significant
A-Ton	84.80	1	84.80	2244.92	<0.0001	Significant
B-Toff	255.05	1	225.05	5957.96	<0.0001	Significant
C-current	4.61	1	4.61	121.98	<0.0001	Significant
V-Voltage	28.46	1	28.46	753.58	<0.0001	Significant
AB	3.74	1	3.74	98.88	<0.0001	Significant
AC	0.61	1	0.61	16.07	0.0008	
AD	0.010	1	0.010	0.27	0.6069	
BC	6.826E-005	1	6.826E-005	1.807E-003	0.9665	
BD	1.86	1	1.86	49.17	<0.0001	Significant
CD	0.29	1	0.29	7.65	0.0123	
Residual	0.72	0.038	0.038			
Lack of Fit	0.65	0.046	0.046	3.34	0.0946	Not significant
Pure Error	0.069	0.014	0.014			
Cor Total	356.18					

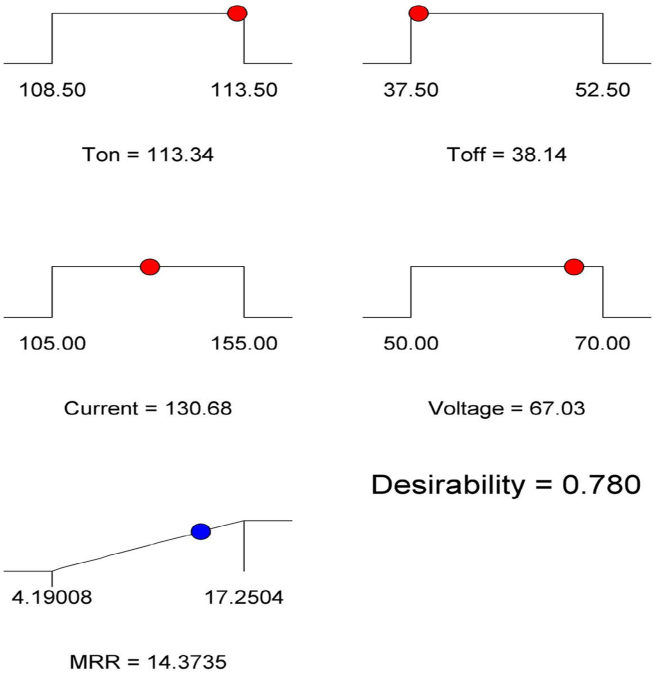

Fig. 4. Ramp graph for Max. Desirability (0.780)

5. SURFACE INTEGRITY ANALYSIS

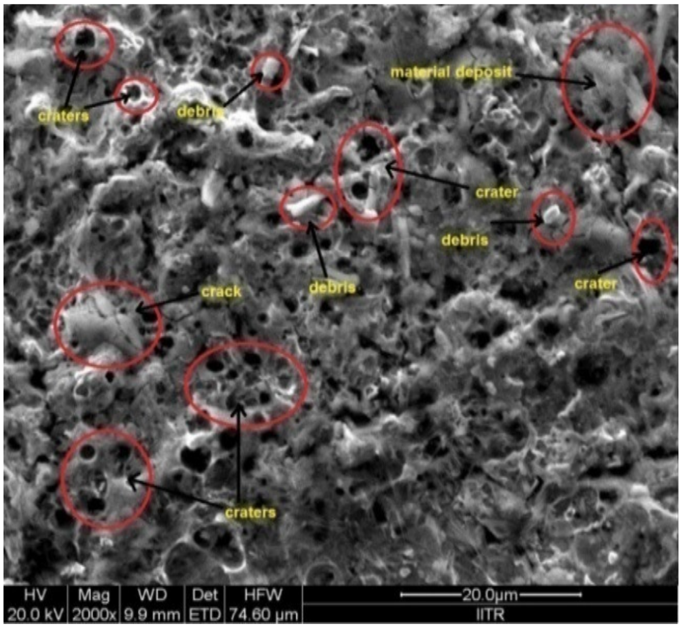

Fig. 5a. Fe-SEM of machined surface of WC-24%Co composite material (for 1st sample)

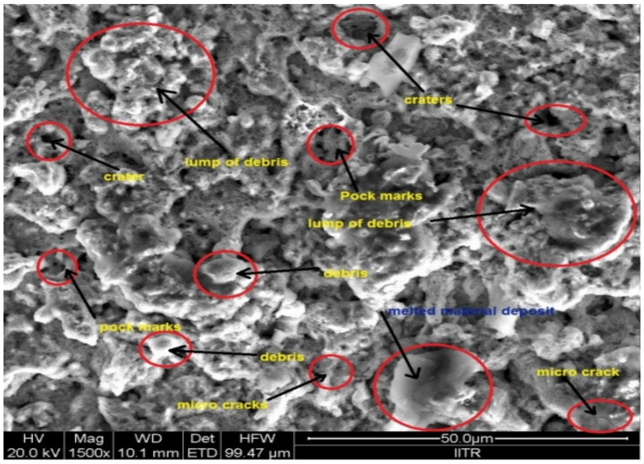

Fig. 5b. Fe-SEM of machined surface of WC-24%Co composite material (For 2nd sample)

To examine the surface integrity of the machined surface, Fe-SEM analysis was conducted on the machined surface of WC-24%Co composite material. Figure 5a shows the microstructure of the machined surfaces at different input parameters settings. Figure 5a shows the Fe-SEM micrograph of machined surface at lowest range values of input process parameters (i.e. T_{on}=0.75µs, T_{off}=12.5µs, current=100A and voltage=50V). This micrograph shows that surface can be characterized with craters, lump of debris, pocks marks and micro cracks. Figure 5b shows the Fe-SEM image of the cut surface at highest range values of the input parameters (i.e. T_{on}=0.75µs, T_{off}=12.5µs, current=150A and voltage=50V). It is found that, surface characterized with craters, debris, metal deposited and cracks. It can be observed from these figures that surface is full of craters and cracks arise at highest range of input process parameters. These craters were formed on the machined surface due to non- conductive particles pullout and presence of ceramic particles protruding on the machined surface and cracks are formed due to the entrance of carbon, the melted material contracts more than the unaffected parent part during the cooling process, and when the stress in the surface exceeds the material's ultimate tensile strength.

6. EDX ANALYSIS

The specimens were also subjected to energy dispersive X-Ray (EDX) to investigate how the structure and composition got altered during WEDM process. Figure 6. shows the Fe-SEM-energy dispersive X-ray (EDX) of affected surfaces, which are obtained by accelerating voltage of 20 kV. Through EDX analysis, the residuals of copper (Cu) and zinc (Zn) were detected in the (WC-24%Co) composite sample. This may be due to the melting and re-solidification of the brass wire electrode during WEDM spark erosion. The presence of oxygen in the WC-24%Co composite sample probably was due to oxidation as a result of high temperature involved in the process. Although EDX result showed that carbon (C) and oxygen (O) existed in the (WC-24%Co) composite sample; these elements were observed due to the fact that dielectric fluid normally contains carbon (C) and oxygen (O).

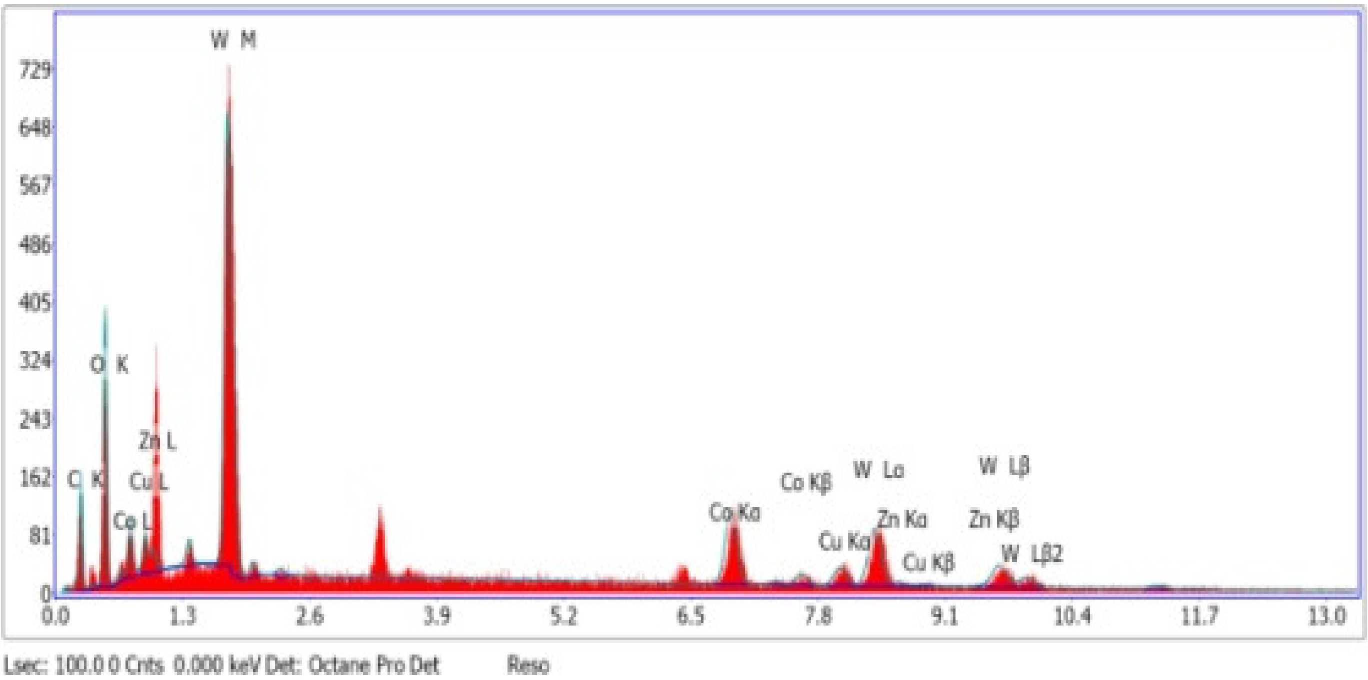

Fig. 6. EDX analysis result of WC-24%Co composite sample after WEDM

7. CONCLUSIONS

In the present research work, the 2FI model for metal removal rate has been developed to correlate the dominant machining parameters: pulse on time, pulse off time, peak current and spark gap voltage in the WEDM process of tungsten carbide cobalt composite (WC-24%Co) material. An experimental plan of the central composite design based on the RSM has been applied to perform the experimentation work. The machinability evaluation in the WEDM process has been analyzed according to the developed mathematical model to obtain the following conclusions:

1. For material removal rate, Pulse on time (A), pulse off time (B), peak current (C), spark gap set voltage (D) and some of the interactions (AB, BD) have been found to be significant (at 95% confidence level) for MRR. P value (0.0001) is same for all the four factors. The higher is the current setting, higher the MRR.

2. But, the sensitivity of the current setting on the cutting performance is stronger than that of pulse on time. The residuals of copper, carbon and zinc were detected in the machined samples using EDX analysis. This may be due to the melting, evaporation and resolidification of the brass wire electrode and are transferred to the work material.

3. It was observed that pulse on time and peak current deteriorated the integrity of machined samples resulting in formation of deep and wide craters, pock marks, globules of debris and micro cracks. The cracks were observed due to high pulse on time and peak current.

4. Wire rupturing was observed due to high peak current and more spark frequency. The formation of craters and residuals of debris adhered to surface of wire electrode was observed using the EDX analysis.

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