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EXPERIMENTAL BASED MODELLING AND ANALYSIS FOR WIRE-EDM OF WC-4.79%CO COMPOSITE

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Abstract-Among various material removal processes, Wire-EDM is considered as an effective process for the machining of modern composite materials. Its inherent capability for automation is another feature which fulfils the expectations of modern manufacturing industries. Wire-EDM is a complex machining process controlled by a large number of process parameters. In the present study an attempt has been made to find the effect of process parameters such as peak current, pulse on time, pulse off time, workpiece thickness and wire feed rate over different machining performance characteristics such as cutting rate, surface roughness and wire wear ratio. Taguchi based L_{27} orthogonal array has been used for conducting experiments. Analysis of variance (ANOVA) technique was used to find out the variables affecting the performance characteristics. A mathematical model has been developed for each machining performance using reweighted least square method to create relationships between process factors and responses. Results from the analysis show that the workpiece thickness, pulse on time and peak current are the most effective parameters affecting the cutting rate, surface roughness and wire wear ratio respectively.

Keywords–Wire EDM, Tungsten carbide, Orthogonal array, Taguchi, Robust regression

I. INTRODUCTION

Cemented tungsten carbide is a composite of tungsten carbide and cobalt metal. The use of WC-Co composite is very diverse. There are three major categories of its applications: metal cutting, wear parts and construction. Metal cutting involves WC tools. Wear parts involves metal forming dies, powder forming dies, wire drawing dies etc. Construction works involve drilling on geotechnical works, coal and ore mining by use of cutter or bits of tungsten carbide.[1] However machining of WC-Co composite is not an easy task with conventional machining process due to presence of high hardness, high fracture toughness and high impact strength. Among the different machining processes Wire EDM has proved to be an effective and economical tool for composite materials. The material removal mechanism of Wire EDM involves the erosion effect produced by the electrical discharges. As Wire EDM is controlled by several control factors which directly or indirectly affects the machining performance such as material removal rate, surface roughness, wire breakage etc. For getting the better machining performance the effect of variation of control factors on machining performance should be known. Several experimental investigations have been performed in the past for finding the effect of Wire EDM control factors on machining performance characteristics.

An experimental investigation for Wire EDM of Al_2O_3 particle reinforced material (6061 alloy) has been performed by Z.N.Guo et al.[2] It was concluded that In operation, a large pulse duration, a high voltage, a large machining current and a proper pulse interval should be selected for getting high machining efficiency.An experimental investigation have been performed by P. SrinivasaRao et al.[3] for finding machining accuracy on wire cut electrical discharge machining of Inconel 75 material of thickness 5mm to 90mm in different sizes.A series of experiments have been performed for finding the effects of cutting parameters on surface roughness in the WEDM process by Mustafa IlhanGokler et al.[4] on 1040 steel material of thicknesses 30, 60 and 80 mm, and on 2379 and 2738 steel materials of thicknesses 30 and 60 mm. Aqueel Shah et al. [5] investigated the effect of work piece thickness, open voltage, pulse on time, pulse off time, servo voltage, wire feed velocity, wire tension, dielectric pressure on the material removal rate, kerf, and surface roughness for wire EDM of WC-10%Co composite, it was expected that this factor was a significant one while according to this research work piece thickness is not a significant factor for material removal rate.S. Sivanaga et al. [6] investigated the effect of workpiece thickness on current, spark gap, cutting speed, material removal rate for machining Die-Steel with wire electrical discharge machining.S. Sivanaga et al. [7] investigated the effect of workpiece thickness ranging 5 mmto 80 mm on power, material removal rate and surface roughness.

Literature survey reveals that very less research work is available for investigating the effect of control factors on machining performance during Wire EDM of WC-Co composite. Hence experimental investigation has been performed in this work.Three levels of each input parameter have been selected for experimentation. On the basis of five input parameters and their three levels L_{27} OA has been used as design of experiment for performing the experimentation. Not only the main effect of workpiece thickness, but also the interaction effect of workpiece thickness with all other four machining parameters has been considered. Mathematical modelling has been performed using robust regression method so that machining performance characteristics could be correlated with control factors.

II. EXPERIMENTAL DETAILS

The experiments were carried out on a wire-cut EDM machine (ELECTRONICA ELPULS 40A DLX SPRINTCUT) with deionized water as dielectric. The composition of WC-Co composite used as workpiece material is given in Table 1. Brass wire with 0.25 mm diameter was used in the experiments. The performance characteristics in wire EDM process were considered as cutting rate, surface roughness and wire wear ratio. Based on the influence over the performance characteristics and literature survey four most effective parameters have been selected as: peak current, pulse on time, pulse off time and wire feed rate shown in Table 2 with their selected levels. Workpiece thickness is also considered as input parameter. The length of cut during machining was kept 8 mm. Photographic view of workpiece after experimentation shown in Fig. 1.

In this work cutting rate was calculated using the following mathematical formula

$$\text{Cutting Rate} = \frac{\text{Length of cut} \times \text{Workpiece thickness}}{\text{Machining Time}}$$

The surface roughness was measured with Talysurf surface roughness profilometer at 0.8 μm cut-off value after machining of workpiece.

Using weighing balance with 0.001 gm accuracy 15 m length of the eroded wire obtained from each experiment was weighed to get the final weight of eroded wire. Using the same weighing balance 15 m length of fresh wire was weighed to get the initial weight of wire. Then using the given mathematical formula wire wear ratio was calculated

$$\text{WWR} = \frac{\text{initial weight of wire} - \text{final weight of wire}}{\text{initial weight of wire}}$$

Table 1 Chemical composition of WC-Co composite used in experimentation

Material	W	Ti	Co	Fe	P	S	Mo	C
WC-Co	78.66	16.23	4.79	0.18	0.042	0.039	0.031	0.028

Table 2 Input Process parameters and their levels

Input parameters	Unit	Level 1	Level 2	Level 3
Workpiece thickness	mm	5	20	35
Peak current	A	170	200	230
Pulse on time	μs	11	18	25
Pulse off time	μs	30	40	50
Wire feed rate	m/min	3	5	7

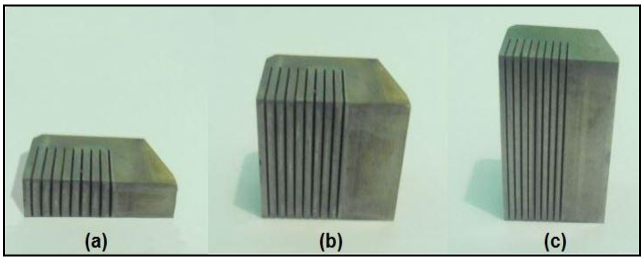

Fig.1. Photographic view of workpiece after machining
(a) 5 mm thickness (b) 20 mm thickness (c) 35 mm thickness

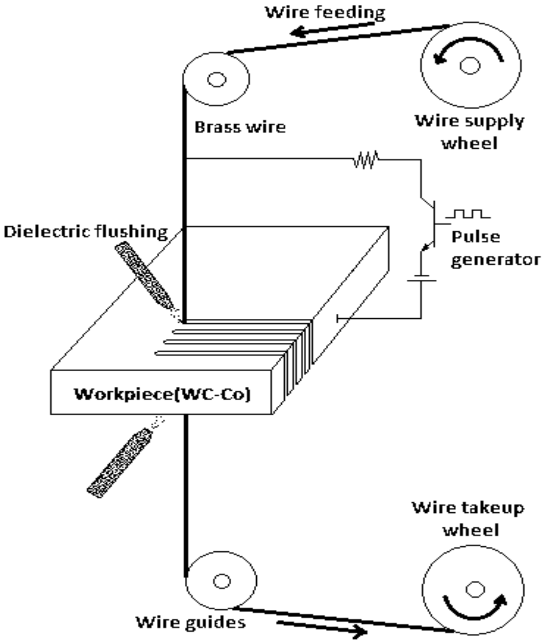

Fig.2. Schematic diagram of wire EDM

III. ROBUST DESIGN OF EXPERIMENTS USING TAGUCHI APPROACH

The fundamental principle of robust design is to improve the quality of a product by minimizing the effect of the cause of variation without eliminating the causes. The two major tools used in robust design are:

(1) Signal to noise ratio, which measure quality
(2) Orthogonal arrays, which are used to study many design parameters simultaneously

The S/N ratio combines both the parameters (the mean level of the quality and variance around this mean) into a single metric. The equation for calculating S/N ratios for “smaller is better” (LB) and “larger is better” (HB) types of characteristics are as follows:

$$\frac{S}{N} = -10\text{Log}_{10}(\text{MSD})$$

Where MSD = Mean squared deviation from the target value of the quality characteristic.

For cutting rate (larger the better)

$$\text{MSD} = \left(\frac{1}{y_1^2} + \frac{1}{y_2^2} + \frac{1}{y_3^2} + \cdots\cdots\cdots\cdots\cdots\right)/n$$

For surface roughness (smaller the better)

$$\text{MSD} = \left(y_1^2 + y_2^2 + y_3^2 + \cdots\cdots\cdots\cdots\cdots\right)/n$$

Where y_1, y_2, etc. = Results of experiments, observations or quality characteristics

n = number of repetitions

Conducting matrix experiments using special matrices called orthogonal arrays allows the effects of several parameters to be determined efficiently and is an important technique in robust design. In selecting an appropriate OA, the pre-requisites are:

1. Selection of process parameters and/or interactions to be evaluated
2. Selection of number of levels for the selected parameters

The determination of which parameters to investigate depends upon the product or process performance characteristics or responses of interest. When a particular OA is selected for an experiment, the following inequality must be satisfied:

$f_{L_N} \geq$ Total degree of freedom required for parameters and interactions

DOF of a parameter = number of levels-1

DOF of interaction = (DOF of Ist parameter) x (DOF of IInd parameter)

Where,

$$f_{L_N} = N - 1$$

Where,

f_{L_N} = Total degrees of freedom of an OA

L_N = OA designation

N=Number of trials

Depending on the number of levels of the parameters and total DOF required for the experiment, a suitable OA is selected. For performing the experiments 5 factors and 4 interaction factors with 3 levels have been selected. Hence

DOF of 5 factors = 5x2 = 10

DOF of 4 interaction factors = 4x2x2 = 16

Hence total DOF = 10+16 =26

Hence number of trials = Total DOF + 1 = 26+1 = 27

Hence L_{27} orthogonal array is most appropriate for this experimentation.

The experimental results based on L_{27} orthogonal array have been summarized in Table 3

Table 3 Experimental Results of Cutting rate, Surface roughness and Wire wear ratio

Trial No.	A	B	C	D	E	Cutting rate (mm^2/min)	S/N ratio (dB)	Surface roughness (µm)	S/N ratio (dB)	Wire wear ratio	S/N ratio (dB)
1	1	1	1	1	1	3.187	10.0676	1.56	-3.8625	0.034	29.3704
2	1	1	2	2	2	4.210	12.4856	2.60	-8.2995	0.051	25.8486
3	1	1	3	3	3	5.457	14.7391	3.48	-10.8316	0.048	26.3752
4	1	2	1	2	3	5.673	15.0763	1.79	-5.0571	0.035	29.1186
5	1	2	2	3	1	5.174	14.2765	2.63	-8.3991	0.057	24.8825
6	1	2	3	1	2	4.206	12.4774	3.54	-10.9801	0.067	23.4785
7	1	3	1	3	2	5.333	14.5394	1.67	-4.4543	0.042	27.5350
8	1	3	2	1	3	3.921	11.8679	2.92	-9.3077	0.051	25.8486
9	1	3	3	2	1	5.517	14.8341	4.06	-12.1705	0.070	23.0980
10	2	1	1	1	1	5.724	15.1540	1.04	-0.3407	0.038	28.4043
11	2	1	2	2	2	6.791	16.6387	1.27	-2.0761	0.032	29.8970
12	2	1	3	3	3	8.121	18.1922	2.54	-8.0967	0.047	26.5580
13	2	2	1	2	3	9.858	19.8758	1.91	-5.6207	0.048	26.3752
14	2	2	2	3	1	12.139	21.6837	4.02	-12.0845	0.090	20.9151
15	2	2	3	1	2	11.976	21.5662	3.81	-11.6185	0.067	23.4785
16	2	3	1	3	2	7.579	17.5922	2.97	-9.4551	0.055	25.1927
17	2	3	2	1	3	10.554	20.4683	3.68	-11.3170	0.060	24.4370
18	2	3	3	2	1	11.569	21.2659	4.20	-12.4650	0.094	20.5374
19	3	1	1	1	1	6.542	16.3142	1.02	-0.1720	0.029	30.7520
20	3	1	2	2	2	8.076	18.1439	1.93	-5.7111	0.049	26.1961
21	3	1	3	3	3	8.300	18.3816	2.93	-9.3374	0.064	23.8764
22	3	2	1	2	3	12.65	22.0418	2.02	-6.1070	0.069	23.2230

23	3	2	2	3	1	14.532	23.2465	3.38	-10.5783	0.123	18.2019
24	3	2	3	1	2	16.457	24.3270	3.98	-11.9970	0.123	18.2019
25	3	3	1	3	2	9.868	19.8846	1.55	-3.8066	0.063	24.0132
26	3	3	2	1	3	16.627	24.4163	2.76	-8.8182	0.073	22.7335
27	3	3	3	2	1	20.628	26.2891	4.01	-12.0629	0.119	18.4891

IV. RESULTS AND DISCUSSION

From the main effect plot of cutting rate it is clear that cutting rate is increasing by increasing the thickness of workpiecethe reason of this effect may be explained as there is a longer length of wire electrode in a thicker work piece, it provides for more of an opportunity for the occurrence of the spark. Plot of cutting rate shows that increase in the peak current leads to the increase of the cutting rate. Increase in peak current leads to increase in the rate of heat energy and hence in the rate of melting and evaporation. Increase in the peak current higher over a certain limit, leads to arcing which decreases discharge number and the machining efficiency and subsequently decrease in cutting rate.

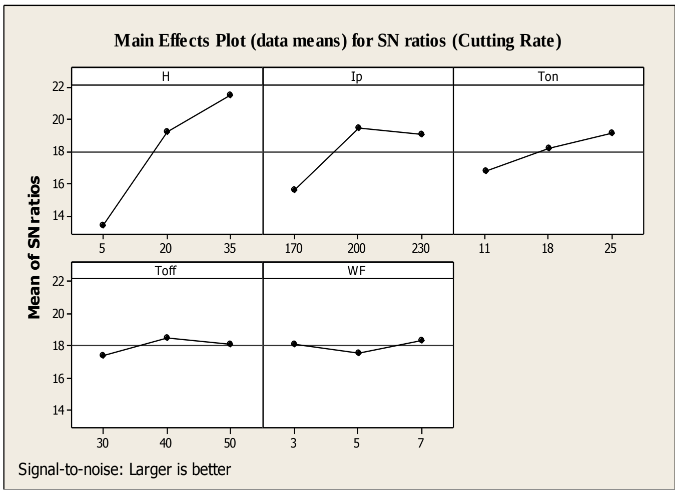

Fig.3. Effects of Process Parameters on Cutting Rate (S/N Data)

Plot of cutting rate also shows that cutting rate increases with increase in pulse on time. The increase in pulse on time means applying the same heating temperature for longer time. This will cause an increase in the evaporation rate and gas bubbles number, which explode with high ejecting force when the discharge ceases causing of bigger volume of molten metal.Pulse off time and wire feed rate do not have any significant effect on cutting rate.

In order to study parameter significance ANOVA was performed. The pooled version of ANOVA at 95% confidence level (α = 0.05) for cutting rate shows that workpiece thickness, peak current and pulse ON time has significant effect having 65.16%, 16.22% and 4.81% contribution on cutting rate whereas pulse off time and wire feed rate did not affect the cutting rate. Among interactions no interactions showed significant effect on cutting rate.

Table 4 Pooled Analysis of Variance for SN ratios for cutting rate

Source	DOF	SS	Variance	F ratio	Percentage contribution
H*	2	311.809	155.904	96.197	65.163
Ip*	2	80.085	40.042	24.707	16.228
Ton*	2	26.017	13.008	8.026	4.81
Toff	Pooled	--	--	--	--
WF	Pooled	--	--	--	--
H ×Ip	4	20.844	5.211	3.215	3.033
H × Ton	Pooled	--	--	--	--
H × Toff	4	15.326	3.832	2.364	1.867
H × WF	Pooled	--	--	--	--
Error	12	19.448	1.6206	--	8.899
Total	26	473.528	--	--	100%

$F_{0.05;\,2;\,12}$=3.8853, $F_{0.05;\,4;\,12}$=3.2592,*significant parameters

From the main effect plot of surface roughness it is clear that workpiece thickness does not have any significant effect on surface roughness. Plot of surface roughness shows that surface roughness has an increasing trend with the peak current over the range investigated. The surface roughness depends upon the size of the crater and also the amount of loosely bound WC grains placed over the machined surface. As the peak current increases the energy per pulse also increases, which produces deeper crater and a large volume of loosely bound WC grains resulting in higher surface roughness. Surface roughness has an increasing trend with increase in pulse on time. The increase in pulse on time means applying the same heating temperature for longer time. This will cause an increase in the evaporation rate and gas bubbles number, which explode with high ejecting force when the discharge ceases causing deeper crater on the surface. Pulse off time and wire feed rate do not have any significant effect on surface roughness.

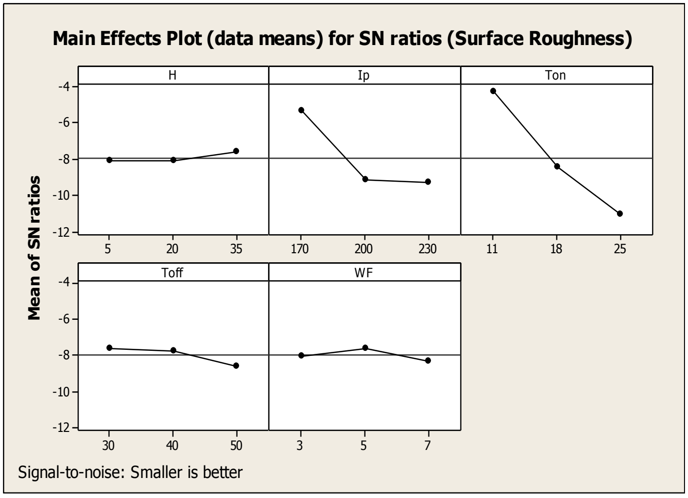

Fig.4. Effects of Process Parameters on Surface Roughness (S/N Data)

The pooled version of ANOVA at 95% confidence level (α = 0.05) for surface roughness shows that peak current and pulse ON time has significant effect having 23.64% and 56.62% contribution on surface roughness whereas workpiece thickness, pulse off time and wire feed rate did not affect the surface roughness of EDMed surface. Among interactions workpiece thickness and peak current, workpiece thickness and pulse OFF time showed significant effect on surface roughness.

Table 5 Pooled Analysis of Variance for SN ratios for surface roughness

Source	DOF	SS	Variance	F ratio	Percentage contribution
H	Pooled	1.59	--	--	--
Ip*	2	87.883	43.941	67	23.6464
Ton*	2	208.615	104.307	159.0449	56.6237
Toff	2	4.876	2.438	3.717	0.97357
WF	Pooled	2.098	--	--	--
H ×Ip*	4	43.816	10.954	16.7024	11.2515
H × Ton	Pooled	3.931	--	--	--
H × Toff*	4	13.046	3.261	4.9722	2.8468
H × WF	Pooled	0.251	--	--	--
Error	12	7.87	0.65583	--	4.66%
Total	26	366.107	--	--	100%

$F_{0.05;\,2;\,12}$=3.8853, $F_{0.05;\,4;\,12}$=3.2592, *significant parameters

From the main effect plot of the wire wear ratio it is clear that on increasing workpiece thickness wire wear ratio is also increasing, this is due to the fact that on increasing workpiece thickness same wire surface remains in front of workpiece surface for longer time hence more number of craters are generated on the wire surface causing an increased wire wear ratio. Plot of wire wear ratio shows that increase in the peak current leads to the increase of the wire wear ratio. Increase in peak current leads to increase in the rate of heat energy and hence in the rate of melting and evaporation form the wire surface. Increase in the peak current higher over a certain limit, leads to arcing which decreases discharge number and the machining efficiency and subsequently decrease in wire wear.

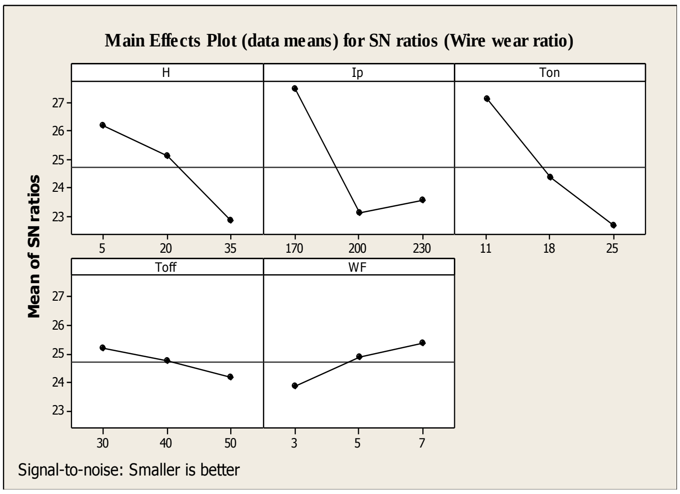

Fig.5. Effects of Process Parameters on Wire wear ratio (S/N Data)

Wire wear ratio has an increasing trend with increase in pulse on time. The increase in pulse on time means applying the same heating temperature for longer time. This will cause an increase in the evaporation rate and gas bubbles number, which explode with high ejecting force when the discharge ceases causing deeper crater on the surface of wire also.On increasing the wire feed wire wear ratio decreases this is due to the fact that the same wire surface remains in front of workpiece surface for shorter time hence less time is available for wire wear.

The pooled version of ANOVA at 95% confidence level (α = 0.05) for wire wear ratio shows that workpiece thickness, peak current and pulse ON time has significant effect having 15.59%, 32.76% and 28.16% contribution on wire wear ratiowhereas pulse off time and wire feed rate did not affect the wire wear ratio. Among interactions workpiece thickness and peak current showed significant effect on wire wear ratio.

Table 6 Pooled Analysis of Variance for SN ratios for wire wear ratio

Source	DOF	SS	Variance	F ratio	Percentage contribution
H*	2	51.545	25.7726	14.984	15.5959
Ip*	2	104.495	52.2473	30.3763	32.7626
Ton*	2	90.318	45.1589	26.2551	28.1663
Toff	Pooled	4.688	--	--	--
WF	2	11.098	5.5492	3.2262	2.4827
H ×Ip*	4	26.91	6.7275	3.9113	6.4938
H × Ton	Pooled	6.369	--	--	--
H × Toff	Pooled	4.267	--	--	--
H × WF	Pooled	8.756	--	--	--
Error	14	24.08	1.72	--	14.50%
Total	26	308.446	--	--	100%

$F_{0.05;\,2;\,14}$=3.7389, $F_{0.05;\,4;\,14}$=3.1122,*significant parameters

V. STATISTICAL MODELING

New statistical techniques have been developed that are not so easily affected by outliers. These are the robust methods, the results of which remain trustworthy even if a certain amount of data is contaminated. Robust regression works by assigning a weight to each data point. Weighting is done automatically and iteratively using a process called iteratively reweighted least squares. In the first iteration, each point is assigned equal weight and model coefficients are estimated using ordinary least squares. At subsequent iterations, weights are recomputed so that points farther from model predictions in the previous iteration are given lower weight. Model coefficients are then recomputed using weighted least squares. The process continues until values of coefficient estimates converge within a specified tolerance.

5.1 Modelling of cutting rate

$$CR = -\ 99.1506 - (0.3397\times H) + (0.9195\times Ip) + (0.2136\times Ton) + (0.7485\times Toff) - (2.3277\times WF) - (0.0030\times H^2) - (0.0023\times Ip^2) - (0.0069\times Ton^2) - (0.0079\times Toff^2) + (0.2495\times WF^2) + (0.0042\times H\times Ip) + (0.0121\times H\times Ton) - (0.0064\times H\times Toff) - (0.0142\times H\times WF)$$

R^2 describes the amount of variation in the observed response values that is explained by the predictors. The value of R^2 for regression model of cutting rate is 0.9668348, which shows that the obtained regression model for cutting rate describes 96.68% variation of cutting rate data. Table 7 shows the ANOVA table for regression analysis the model estimated by regression procedure is significant at an α-level of 0.05.

Table 7 ANOVA table for Regression model for cutting rate

Source	DOF	SS	variance	F ratio	Percentage contribution
Regression	14	499.91943	35.70853	24.987565	96.6834
Residual Error	12	17.14862	1.429052	--	3.3165
Total	26	517.06806	--	--	100%

R^2=0.9668348

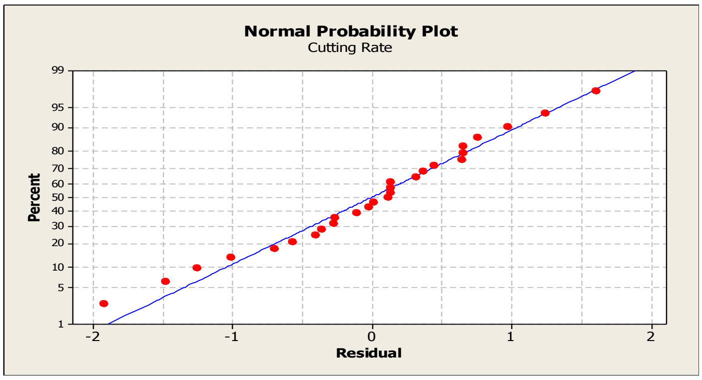

Fig.6. Normal probability plot for residuals of cutting rate model

One of the assumptions of regression is that the residuals should be normally distributed. In the normal probability plot of residuals each residual is plotted against its expected value under normality. If the residual distribution is normal this plot will be straight line. From Fig.6 it can be observed that the points fall reasonably close to the reference line, which indicates that the residuals follow a normal distribution.

5.2 Modelling of surface roughness

$$SR = -\ 19.8251 - (0.0286\times H) + (0.2096\times Ip) + (0.2309\times Ton) - (0.0798\times Toff) - (0.4814\times WF) - (7.383\times10^{-4}\times H^2) - (4.9374\times10^{-4}\times Ip^2) - (0.0028\times Ton^2) + (0.0010\times Toff^2) + (0.0461\times WF^2) + (2.6354\times10^{-4}\times H\times Ip) + (1.9886\times10^{-4}\times H\times Ton) + (1.9011\times10^{-4}\times H\times Toff) - (0.001623\times H\times WF)$$

The value of R^2 for regression model of surface roughness is 0.85518885, which shows that the obtained regression model for surface roughness describes 85.51% variation of surface roughness data. Table 8 shows the ANOVA table for regression analysis the model estimated by regression procedure is significant at an α-level of 0.05.

Table 8 ANOVA table for Regression model for surface roughness

Source	DOF	SS	variance	F ratio	Percentage contribution
Regression	14	23.25432	1.66102	5.06188	85.5188
Residual Error	12	3.937709	0.32814	--	14.4810
Total	26	27.19202	--	--	100%

R^2= 0.85518885

From Fig.7 it can be observed that the points fall reasonably close to the reference line, which indicates that the data follow a normal distribution. Hence the residuals of surface roughness model follow the normality assumption.

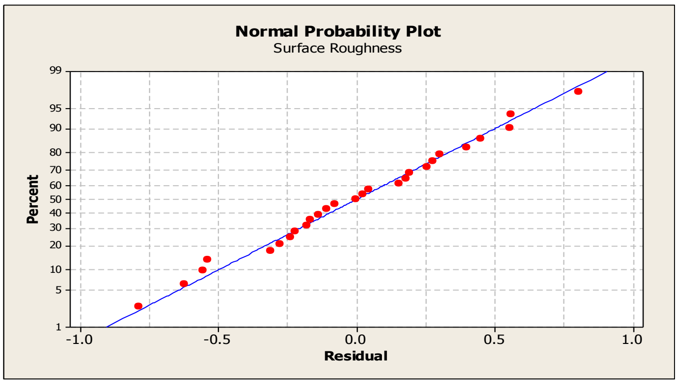

Fig.7. Normal probability plot for residuals of surface roughness model

5.3 Modelling of wire wear ratio

$$WWR = -0.8092 - (0.004286\times H) + (0.00847\times Ip) + (0.00365\times Ton) + (6.05\times10^{-5}\times Toff) - (0.00997\times WF) + (2.54\times10^{-5}\times H^2) - (2.09\times10^{-5}\times Ip^2) - (6.95\times10^{-5}\times Ton^2) - (1.6\times10^{-6}\times Toff^2) + (0.000763\times WF^2) + (1.53\times10^{-5}\times H\times Ip) + (5.52\times10^{-5}\times H\times Ton) + (1.7\times10^{-5}\times H\times Toff) - (0.000105\times H\times WF)$$

The value of R^2 for regression model of wire wear ratio is 0.8961, which shows that the obtained regression model for cutting rate describes 89.61% variation of wire wear ratio data. Table 9 shows the ANOVA table for regression analysis the model estimated by regression procedure is significant at an α-level of 0.05.

Table 9 ANOVA table for Regression model for wire wear ratio

Source	DOF	SS	variance	F ratio	Percentage contribution
Regression	14	0.01644403	0.001174457	7.391829	89.61
Residual Error	12	0.00190663	0.00015888	--	10.39
Total	26	0.01835067	--	--	100%

R^2= 0.8961

From Fig.8 it can be observed that the points fall reasonably close to the reference line, which indicates that the data follow a normal distribution. Hence the residuals of wire wear ratio model follow the normality assumption.

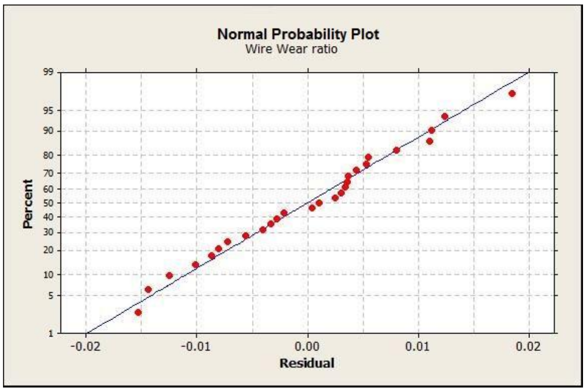

Fig.8. Normal probability plot for residuals of wire wear ratio model

VI. CONCLUSIONS

From the experimental data analysis it can be clearly observed that the workpiece thickness is the most significant parameter affecting the cutting rate, pulse on time is the most significant parameter affecting the surface roughness and peak current is the most significant parameter affecting the wire wear ratio.Finally, a mathematical model was developed using robust regression method to formulatethe control factors to the performance characteristics. The developed model showed high prediction accuracywithin the experimental region. These results will be useful for Wire EDM of WC-Co composite in the industrial applications.

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