Modelling of Surface Roughness for AISI 52100 Steel in WEDM by Design of Experiments

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***Abstract*— Wire electrical discharge machining (WEDM) is well known process for machining hard materials, Development of empirical model has been a major activity in metal cutting research. This paper presents an application of central composite face centered design for developing surface roughness model in WEDM of AISI 52100 steel. Four process parameters namely Pulse on time, Pulse off time, Water pressure and Wire feed are considered as input parameters. Each parameter was set at three levels. Based on the experimental data, a mathematical model in terms of process parameters was developed for surface roughness using multiple linear regression. Confirmation tests were performed to verify the predictability of the developed model.**

***Keywords*— WEDM, central composite, cutting speed, multiple regression.**

I. INTRODUCTION

In modern manufacturing industry, machining process play a vital role where cost and quality are the two prime factors. Wire Electric Discharge Machining (WEDM) is most widely used manufacturing process due to its capability of producing intricate shapes irrespective of hardness and toughness of material. This process is extensively used in mould and die making industries, aerospace industries, automotive industries etc.

WEDM is an electro thermal process which is used to produce complex two and three dimensional shapes through electrically conductive materials. In WEDM, removal of the material takes place by a series of discrete sparks occurring between the work piece and the wire which act as an electrode. The gap between the work piece and the wire is flooded with a stream of dielectric fluid which is directed to the working zone by a series of nozzle. The process uses a thin wire of diameter 0.1-0.3mm as the electrode and the work piece is mounted on a Computer Numerically Controlled (CNC) work table. The gap between work piece and the wire is usually ranges from 0.025-0.05mm and is maintained constant by computer-controlled positioning system. The wire is continuously fed through the work piece by microprocessor which enables machining of complex shape parts. With increasing demand for quality product as well as for higher productivity, WEDM needs to be performed more efficiently. Therefore, one of the most investigating areas is the modeling and optimization of process parameters to achieve a high quality product with the reduction of manufacturing cost. Material removal rate and Surface roughness are the most significant performance measure in WEDM process.

Abinesh et.al [1] investigated and optimized the process parameters influencing the MRR, SR and Electrode Wear by machining Titanium alloys using WEDM process .This involves the study of various input process parameters like pulse on time(T_{on}), Pulse off time(T_{off}), Peak Current (IP), Wire material, Work piece material and L_{16} Orthogonal array is selected to optimize the best suited values for machining the material. Hascalyk et al., [2] investigated the effect of WEDM parameters such as open circuit voltage, pulse duration, wire speed and dielectric fluid pressure on the surface roughness and metallurgical structure of AISI D5 steel. Optical and scanning electron microscopy, surface roughness and microhardness tests were used to study the characteristics of the machined specimens. Taking into consideration the experimental results, it is found that the intensity of the process energy does affect the amount of recast and surface roughness as well as micro cracking, the wire speed and dielectric fluid pressure not seeming to have much of an influence.

The models for co-relating the inter-relationships of various WEDM machining parameters of Inconel 601 material was established using Response Surface Methodology [3]. Results showed that the volumetric material removal rate generally increases with the increase of the peak current value and flushing pressure. Wear ratio increases with increase of peak current. Surface Roughness increases with the increase of peak current and decreases with increase of duty factor and wire tension. Yuan et al., [4] used a predictive approach based on Gaussian Process Regression in order to develop a reliable multi-objective optimization to optimize the HS-WEDM process. The authors used mean current, on time and off time as process parameters and MRR and SR were chosen as machining performance parameters. Singh and Garg [5] conducted studies on Electronica Sprint cut WEDM machine. They investigated the effect of pulse on time, pulse off time, gap voltage, peak current, wire feed, wire tension on material removal rate of hot die steel (H-11) using one variable at a time approach. The optimum parameters were predicted to maximize the material removal rate. Rao et al., [6] studied the effect of WEDM conditions on surface roughness for a parametric optimization using Taguchi Method. The minimum SR was obtained at low values of peak current, pulse on time, spark gap voltage and high value of wire tension. The proposed regression model (with high correlation co-efficient) successfully predicted the parametric values in the machining of Aluminum BIS-24345 alloy.

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Prohaszka et al.[7] investigated the use of electrode material for improving the WEDM performance. A non-alloyed steel work-piece with low carbon contents and negative polarity wire electrodes of magnesium, tin and zinc were used. It was found that the cutting efficiency of magnesium electrode was greater than zinc electrode. It is possible to increase the cutting speed of the WEDM process by using electrode with sharp edges (triangular, rectangular etc.). it was also concluded that, machinability on WEDM increases with the proper combination of electrical, mechanical, physical and geometrical properties of wire electrode. Bhattacharyya [8] investigated the variation of the geometrical inaccuracy caused by cutting speed and wire lag with various machine control parameters on die steel on WEDM using Taguchi method. It was observed that, for the minimum geometrical inaccuracy, the difference between the offset values for the rough cut and the trim cut should be as high as possible. The average cutting speed is affected by pulse-on time, pulse-off time and pulse-peak current for rough cutting; and pulse-on time and constant cutting speed during trim cutting. The surface roughness is influenced by pulse-peak voltage during rough cutting and pulse-on time, pulse-peak voltage, servo spark gap set voltage, dielectric flow rate, wire offset and constant cutting speed during trim cutting. The factors for geometrical inaccuracy for wire lag are pulse-on time, pulse-off time and pulse-peak current during rough cutting; and pulse-peak voltage, wire tension, wire offset, servo spark gap set voltage and constant cutting speed during trim cut.

Puertas et al. [9] reported the influence of machining parameters on surface roughness; material removal rate and electrode wear on cobalt-bonded cemented carbide (WC-Co) on Die-sinking EDM. It was found that the electrode wear decreases with the increase in intensity. The surface roughness increased with increase in intensity or pulse time. Material removal rate increased with increase in intensity and duty cycle while decreased with increase in pulse time. Chiang and Chang [10] optimized the WEDM for multiple performance characteristics. Al_2O_3 particle reinforced material (6061 alloy) and thin copper wire (Ø20mm) were used as work material and electrode material respectively. Eight machining parameters were included in the study. Taguchi method with grey relation analysis was used to analyze the results obtained. The maximum surface roughness was reduced from 3.214 to 2.051µm and cutting rate was improved from 7.504 to 15.02mm^2 /min under optimum condition. By considering both performance characteristics simultaneously, the optimum surface roughness and surface removal rate were observed to be 2.107µm and 14.827mm^2/min. Ramakrishnan et.al [11] describes the development of artificial neural network (ANN) models and multi response optimization technique to predict and select the best cutting parameters of wire electro-discharge machining (WEDM) process. To predict the performance characteristics namely material removal rate and surface roughness, artificial neural network models were developed using back-propagation algorithms. Inconel 718 was selected as work material to conduct experiments.

The main objective of this paper is to perform an experimental study on AISI 52100 steel to investigate the effect of various process parameters of Wire EDM on surface roughness. Experiments are conducted as per the Central Composite face centered (CCF) design and multiple linear regression is used to develop the empirical model.

II. PROCEDURES AND METHODS

A. *Materials and processes*

The work piece material is AISI 52100 steel with dimensions of 30 mm X 30 mm X 10 mm for experimentation. Initially the work pieces are cleaned and surface grinding is performed before conducting experiments. The Brass wire with 0.25 mm diameter is used as electrode. Dielectric solution is a mixture of hydrocarbon oil and distilled water in the ratio of 1:40. Table. I presents the properties of work piece material.

Table. I Material and their properties

Material	Electrical conductivity	Thermal conductivity	Melting point
AISI 52100 steel	$4.6X10^6$ s/m	46.6 w/(m K)	1424^0C

Commercial type of WEDM machine (with 5 - axis) is used in this investigation. Once wire is wound on the wire drum, the particular amount of wire is used for all the experiments. Work material is tightly clamped on the working table so as to avoid any relative motion between wire and the work piece and constant dielectric flow is ensured during the entire experimentation. The figure I and II shows the actual working zone during experimentation.

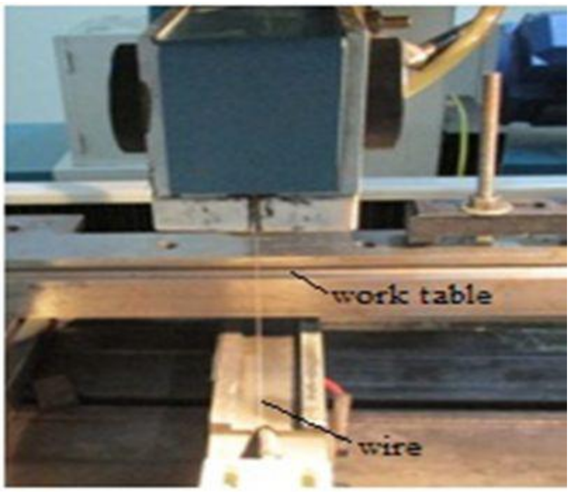

Fig .1 Working zone of wire EDM

B. *Experimental design*

Design of experimental technique was used for execution of the plan of experiments for four variables at three levels, whereby the levels are the values taken by the factors. The factors to be studied and the level of each factor are given in Table 2.Experiments are conducted as per central composite face centered design[X]. For four factors, the CCF design consists of 25 runs, which includes a 2^4 factorial portion (16 experiments), 8 axial points and a central point. The

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Fig .II Working zone of wire EDM

experimental layout along with the response (surface roughness) is shown in Table III.

Table. II Machining parameters and their levels

Factor symbol	Factor	Level 1 (-1)	Level 2 (0)	Level 3 (+1)
A	Pulse on time(μsec)	100	105	110
B	Pulse off time(μsec)	50	55	60
C	Water pressure (Kg/cm^2)	3	5	7
D	Wire feed rate(m/mm)	6	9	12

Table. III The Experimental layout: CCF (4) design

S.No	A(T_{on})	B(T_{off})	C(w.p)	D(w.f)	Surface roughness(μm)
1	-1 [100]	-1 [50]	-1 [3]	-1 [6]	1.36
2	-1 [100]	-1 [50]	-1 [3]	+1 [12]	1.07
3	-1 [100]	-1 [50]	+1 [7]	-1 [6]	1.62
4	-1 [100]	-1 [50]	+1 [7]	+1 [12]	1.5
5	-1 [100]	+1 [60]	-1 [3]	-1 [6]	2.72
6	-1 [100]	+1 [60]	-1 [3]	+1 [12]	1.46
7	-1 [100]	+1 60]	+1 [7]	-1 [6]	1.86
8	-1 [100]	+1 [60]	+1 [7]	+1 [12]	1.57
9	+1 [110]	-1 [50]	-1 [3]	-1 [6]	3.15
10	+1 [110]	-1 [50]	-1 [3]	+1 [12]	2.65
11	+1 [110]	-1 [50]	+1 [7]	-1 [6]	3.04
12	+1 [110]	-1 [50]	+1 [7]	+1 [12]	2.99
13	+1 [110]	+1 [60]	-1 [3]	-1 [6]	3.76
14	+1 [110]	+1 [60]	-1 [3]	+1 [12]	2.65
15	+1 [110]	+1 [60]	+1 [7]	-1 [6]	2.21
16	+1 [110]	+1 [60]	+1 [7]	+1 [12]	1.90
17	-1 [100]	0 [55]	0 [5]	0 [9]	1.63
18	+1 [110]	0 [55]	0 [5]	0 [9]	2.68
19	0 [105]	-1 [50]	0 [5]	0 [9]	2.17
20	0 [105]	+1 [60]	0 [5]	0 [9]	2.28
21	0 [105]	0 [55]	-1 [3]	0 [9]	2.11
22	0 [105]	0 [55]	+1 [7]	0 [9]	2.06
23	0 [105]	0 [55]	0 [5]	-1 [6]	2.35
24	0 [105]	0 [55]	0 [5]	+1 [12]	1.92
25	0 [105]	0 [55]	0 [5]	0 [9]	2.26
25	0 [105]	0 [55]	0 [5]	0 [9]	2.34

III. DATA ANALYSIS AND DISCUSSION OF RESULTS

The plan of tests was developed aiming at determining the relation between the process parameters with the surface roughness. The analysis of experiments was made into two phases. The first one concerned the analysis of factor and interaction effects. Model for surface roughness in terms of process parameters has been developed in second phase.

A. Analysis of the Factors and Interactions

From the factorial portion of CCF design, both factor and interaction effects (at two levels) can be obtained. It can be observed from axial and central portion of CCF design, considering experiments from 17 to 25, factor effects (at three levels) of each factor can be obtained when all other factors are at 0 levels. Using the experimental data, level means have been calculated. The level means obtained from factorial portion of CCF design, axial portion of CCF design for surface roughness is given in Tables IV & V. The influence of each control factor can be more clearly presented in response graph which are presented in Figures I & II.

From the tables of level mean analysis, it can be observed that the pulse on time, pulse off time and wire feed have been showing consistent behavior. As the pulse on time increases from '-1' level to '+1' level the surface roughness increases, pulse off time and wire feed increases from '-1' level to '+1' level the surface roughness decreases, whereas the other factor water pressure do not show the same consistency i.e. means the surface roughness increases from level '-1' to level '+1' from factorial portion of experiment but from one –factor- at-a time analysis, it can be observed that the surface roughness increases from '-1' level to '0' level and later decreases from '0' level to '+1' level (Table 6). Perhaps, the reason might have been the presence of interaction effects. The analysis of the interactions gives the additional information about the process. Interaction effects can be obtained by calculating all combinations of control factors. The interaction matrix enables the construction of interaction graphs, which indicate the existence or non-existence of interaction between two control factors. If the lines in the interaction graph are parallel, it indicates non-existence of interaction. The interaction matrix and interaction graphs for surface roughness are shown in Table VI and Figure III.

Table. IV Average Response of Surface Roughness for Factorial Portion of CCF Design

	A	B	C	D
Level -1	1.64	2.17	2.35	2.46
Level +1	2.79	2.27	2.09	1.97

Table. V Average Response of Surface Roughness for One Factor at a Time Analysis

	A	B	C	D
Level -1	1.63	2.17	2.11	2.35
Level 0	2.30	2.30	2.30	2.30
Level +1	2.68	2.28	2.06	1.92

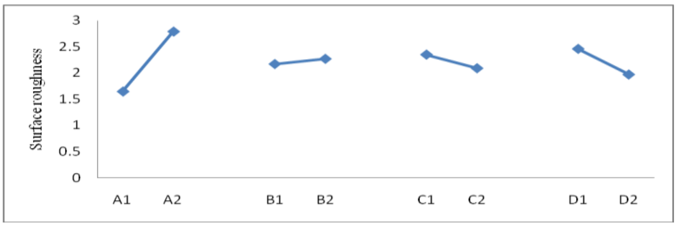

Figure I. Response Plot of Surface Roughness for Factorial Portion of CCF Design

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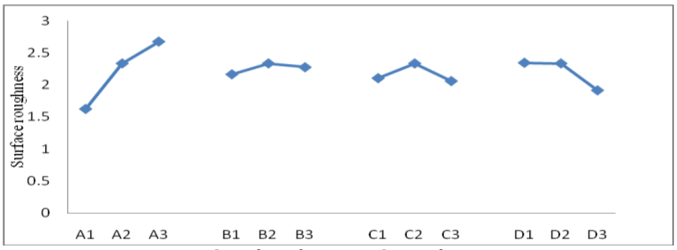
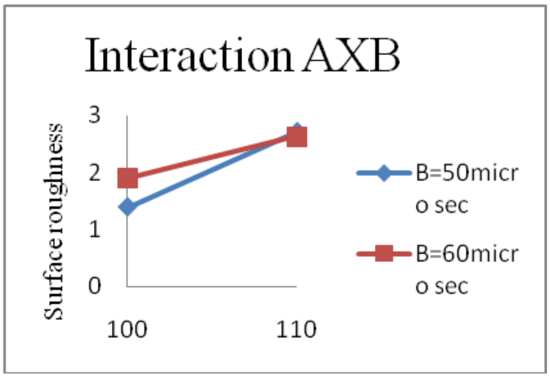
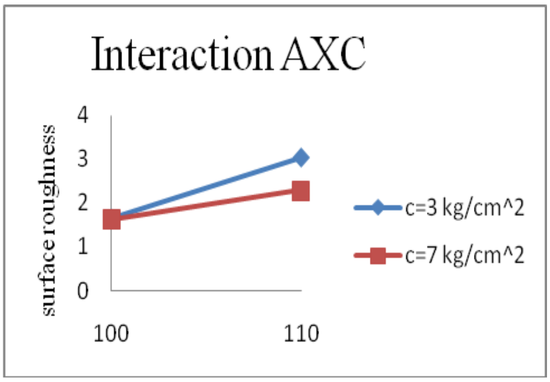


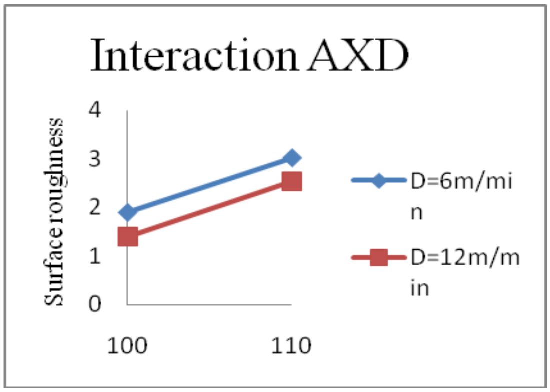
Figure II. Response Plot of Surface Roughness for One Factor at a Time Analysis

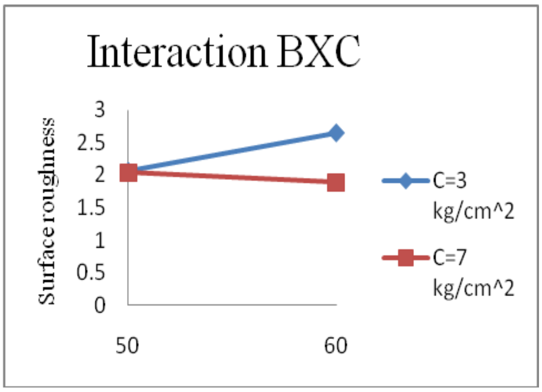
Table. VII Interaction Matrices for the Surface Roughness

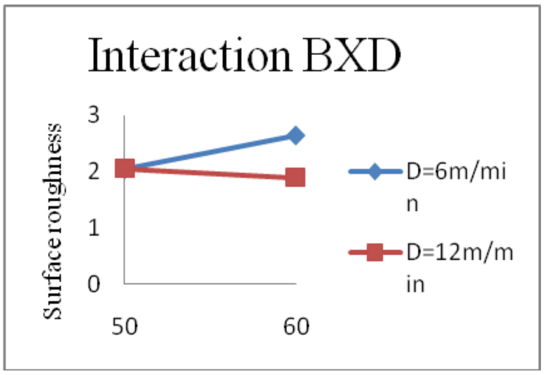
AXB	B1	B2	AXC	C1	C2	AXD	D1	D2
A1	1.39	1.90	A1	1.65	1.63	A1	1.89	1.40
A2	2.71	2.63	A2	3.03	2.28	A2	3.02	2.54
BXC	C1	C2	BXD	D1	D2	CXD	D1	D2
B1	2.05	2.03	B1	2.04	2.05	C1	2.74	1.95
B2	2.64	1.88	B2	2.63	1.89	C2	1.93	1.99











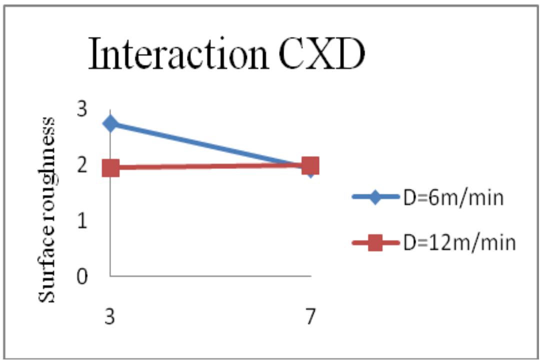


Figure III. Interactions Graphs of Parameters for Surface Roughness

From the interaction graphs, it can be observed that the interactions between the pulse on time and pulse off time, pulse on time and water pressure, pulse off time and water pressure, pulse off time and wire feed ,water pressure and wire feed are quite prominent for surface roughness.

B. Model for Surface roughness

Central composite designs are best for fitting a second order model, and accordingly CCF data is used to fit a second order model. The input data to SPSS software is provided in coded form of factors i.e. -1 to +1. To be precise, value of the factor in coded scale is = (actual value of factor – central value in the range)/ (difference between the maximum value and central value in the range). The parameter estimates obtained from SPSS software are shown in the below Table VII.

Table VII. Parameter Estimates

Variable	Parameter estimate	Standard error	T	Sig.
Constant	2.199	0.027	81.320	0.000
A	0.569	0.032	17.851	0.000
C	-0.121	0.032	-3.792	0.002
D	-0.242	0.032	-7.601	0.000
AB	-0.211	0.034	-6.231	0.000
AC	-0.126	0.034	-3.717	0.002
BC	-0.248	0.034	-7.341	0.000
BD	-0.126	0.034	-3.717	0.002
CD	0.149	0.034	4.419	0.000

Table VIII. Analysis of Variance for the Model

Source of variation	df	Sum of squares	Mean square	F-value	Sig.
Model	8	9.7.1	1.213	66.334	0.000
Error	16	0.292	0.018		
Total	24	9.994			

The surface roughness (SR) model developed using CCF design was given by:

SR=2.199+0.569A-0.121C-0.242D–0.211(AxB)-0.126(AxC)–0.248(BxC)-0.126(BxD)+0.149(CxD)

(R-square=0.971)

Surface roughness model in terms of actual factors can be expressed as:

Surface roughness = 2.199+0.569 pulse on time-0.121 water pressure-0.242wire feed-0.211 (pulse on time x pulse off time)-0.126 (pulse on time x water pressure)-0.248 (pulse off time x water pressure) - 0.126 (pulse off time x wire feed) +0.149 (water pressure x wire feed)

The R-square value of 0.971 indicates that 97.1% of the variability in surface roughness was explained by the model. The significance of individual parameters Pulse on time, Water pressure, Wire feed and interactions of pulse on time with pulse off time, pulse on time with water pressure, pulse off time with water pressure, pulse off time with wire feed, water pressure with wire feed have been identified on the surface roughness. The pulse off time has no significant effect individually on surface roughness, but its interaction with pulse on time, water pressure and wire feed has significant effect on surface roughness).

C. Confirmation Tests

Conducting confirmation experiments has been the final step of the design of experimental (DOE) process. The confirmation is performed by conducting tests using combinations of the factors and levels that are not previously evaluated. The below given table 8 shows the conditions used in the confirmation tests and the results obtained where a comparison was done between the foreseen values from the model developed in the present work with the values obtained experimentally.

Table 8.Cutting Conditions for Confirmation Tests and results

Test	A	B	C	D	Experimental value	Model value	Error %
1	106	54	6	10	2.3199	2.2158	4.49
2	109	58	3	8	3.0775	2.9857	2.98
3	102	50	4	7	1.7573	1.8662	6.20

It can be observed that the error percentage associated with the model is within the limits. Therefore, we can consider the empirical model which correlates the surface roughness with the process parameters, with a reasonable degree of approximation within the given working conditions.

IV. CONCLUSIONS

In this work, the surface roughness model in terms of Pulse on time, Pulse off time, Water pressure and Wire feed has developed using central composite design. Based on the work, the following conclusions may be drawn:

1. The significance of individual parameters Pulse on time, Water pressure, Wire feed and interactions of pulse on time with pulse off time, pulse on time with water pressure, pulse off time with water pressure, pulse off time with wire feed, water pressure with wire feed has been identified on the surface roughness.
2. The parameter pulse on time is identified as more dominating factor on surface roughness followed by wire feed and water pressure.
3. The surface roughness is increasing with pulse on time and decreases with water pressure and wire feed.
4. The pulse off time has no significant effect on surface roughness, but its interaction with pulse on time, water pressure and wire feed has significant effect on surface roughness.
5. By explicit incorporation of the interaction terms, the CCF design model gives better insight into the process. So, CCF design model developed for surface roughness serves as a good alternative to the popular multiplicative model.

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