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ANALYSIS OF METAL REMOVAL RATE AND SURFACE ROUGHNESS AND OVERCUT OF EN-31 IN WEDM

Shubham Upadhyay[1], Abhishek Srivastava[2],
Department of Mechanical Engineering
[1]M.Tech.(PE) Scholar, Mechanical Engineering department, S R Institute of Management & Technology, Lucknow
[2]Assistant Professor, Mechanical Engineering department, S R Institute of Management & Technology, Lucknow
Uttar Pradesh, India

***Abstract*— WEDM (Wire electrical discharge machining) has Amazon enhanced the deal with of modern and very rigid materials, specifically used for the medical industries, nuclear as well as aerospace. It is the most important Nontraditional machining procedure that is widely utilize for materials of machining difficult-to-machine like titanium, zirconium, etc., with complex aspect. Using numerical control WEDM, complicated profiles can be easily machined by electrically conductive materials of difficult-to- machine. The accuracy rate obtained along with the fine surface quality make the WEDM a much respected technology in the modern day manufacture.**

EN-31 alloy steel, widely used in automotive and lock industries, is electrically machined in order to study the effects of some important cutting parameters on MRR (Metal Removal Rate), Ra (Surface Roughness), and Overcut. Whereas the Metal Removal Rate determines the machining economics as well as production rate, the Surface Roughness (Ra) and Overcut denotes the quality of machining and degree of precision respectively. The experimental work during the study has been conducted on an ELECTRONICA SPRINTCUT WEDM machine and deals with the features of rough cutting regime of EN-31 alloy steel.

The present work also highlights the growth of mathematical models for correlating the inter-relationships of different WEDM machining factors like; Surface roughness, MRR, P (water pressure), T (wire tension), F (wire feed rate), Ip (pulse peak current), Ton (pulse on-time) and Overcut while machining EN-31 steel. A second-order polynomial, such as machining parameters, has been established for MRR, Ra and Overcut with use of RSM (Response Surface Methodology). These models are established by conducting a designed experiment which was based on the RCCD (Rotatable Central Composite Design). Mathematical models that was fitted to the experimental data basically will be contributing to the optimization of process parameters.

***Index Terms*— WEDM, EN-31, MRR, RSM, RCCD.**

I. INTRODUCTION

A. Introduction

From the past researches which was based on material science field have led to the development of high strength materials was used in advanced industries technology. These materials as well as alloys are categorized by their high hardness, high strength, along with high temperature resistance. Many of these materials are very difficult to machine or even un- Machinable by conventional means. However, EDM (Electrical Discharge Machining) is the Nontraditional machining procedure that utilize for basically machine electrically conductive materials.Controlled spark generation process is used to remove materials because EDM is basically a thermo-electric System and can also be utilize.EDM utilize in die making industry as well as in surgical components, nuclear, aerospace, automotive manufacturing. Due to absence of mechanical contact among work-piece as well as tool, fragile along with thin components can also be utilizein machine work with no damage as well as risk. Commercially EDM exists in two forms, Wire EDM (Wire Cutting machines as well as Die-sinking machines).

B. Wire Electric Discharge Machining Process

WEDM is a thermo electrical contend with where substance is corrode from the work piece by a number of secrete sparks among the work piece along with the electrode wire (tool) detached by a dielectric fluid thin film (deonized water) which is constantly given to the machining place to purge away the eroded contaminants. The wire movements is controlled numerically to get the accuracy for workpiece as well as desired three dimensional shape. The WEDM technology is developed considerably to meet up with the demands in several manufacturing fields, particularly in the precision die industry. In figure 1 the schematic WEDM picture is shown with control devices, working table, power distribute as well as dielectric flow.

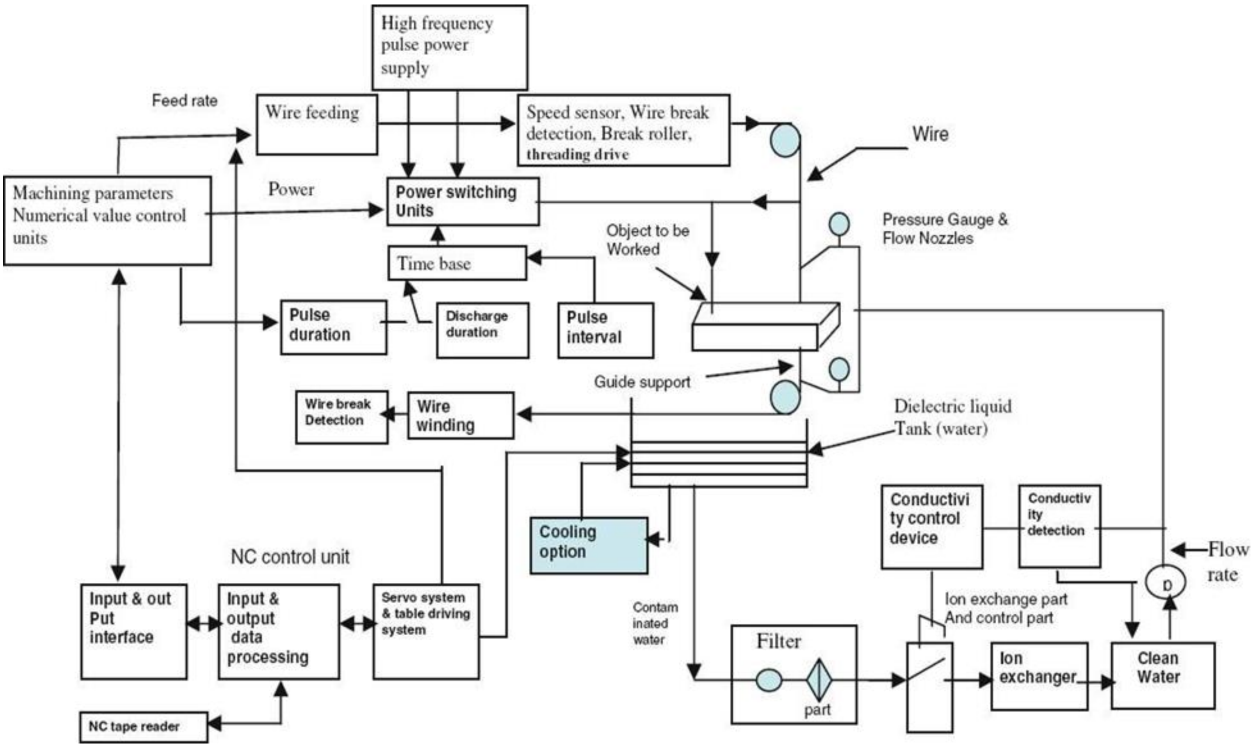

Figure 1.1: Schematic diagram of WEDM

In the WEDM, material was removed with use of electrically conductive substance through repetitive and rapid spark discharges among work gap as well as tool electrode attached in an electric circuit (WEDM manuals, 1999) along with the fluid dielectric medium is continually provided to the eroded particles as well as the cooling effect. (Kozak et al., 1994) 0.05 to 0.25 mm is the small diameter of wire which was used as a tool electrode. The wire is basicallydeliveredthrough the supply spool by the work-piece that is clamped on the table through the wire traction rollers. 0.025 to 0.05 mm is the gap applied among work piece as well as wire. (Spedding and Wang, 1997). Dielectric fluid is used as a Deionized water. Fire cannot be reused because its different dimension accuracy (Scott et al., 1991). The dielectric material is continually flashed from the gap across the wire, to the sparking place to eliminate the byproducts created throughout the erosion (Albert as well as Dauw, 1992). Wires made from copper, zinc coated brass, aluminum as well as Brass are used to make electrode tool. The content is eroded in front of the cable with a number of repeated sparks among electrodes, such that wire as well as workpiece.

II. LITERATURE REVIEW

Rao and Sarcar (2009) have experimentally investigated the influence of discharge current and job thickness on MRR, spark gap and cutting speed in WEDM process. Empirical relationships are established to evaluate the above parameters. The correlations was obtainedeffective with use of different cutting conditions as cutting time, cutting speed, spark gap, discharge current.

Patil and Brahmankar (2009) carried out an experimental investigation in to investigate the effect of non-electrical and electrical variables to check the performance of WEDM for (Al/Al2O3p). In the WEDM process many regression techniques has been established for several parameters like: kerf width, surface roughness and cutting speed. However, the optimum machine quality technique was used for kerf width, cutting speed and surface finish.

Gauri and Chakraborty (2009) presented amethod for the multi-response optimization of WEDM process variables based on the principal component analysis (PCA) technique. By using a modified PCA procedure, they analyzed 2kind of experimental data and determined the optimal machining conditions. However, as compared to techniques based on MRSN ratio and constrained optimization, it was found that optimization based on PCA provide the good result that could be possible pendant between the multiple feedbacks which is under the PCA- based conditions.

Saha et al. (2009) have studied about the wire electro-discharge machinability of 5vol% TiC/Fe in MMC. Average gap voltage, wire feed-rate, pulse off-time and pulse on-time variables was considered as input process variables whereas the performance measure parameters were kerf width, cutting speed. In their study, they have used NRBFNwith enhanced k-means clustering method for modeling of WEDM process. Under the given condition it was calculated that kerf and average gap was inversely proportional to cutting speed. Whereas kerf width and cutting speed was not so affected by the pulse on-time as comparing to the average gap voltage. Kerf width, cutting speed both increased with increase in pulseon-time rise.

In their study, Parashar et al. (2009) have proposed Taguchi's dynamic design of experiments to optimize surface roughness for WEDM operations. The effect of several machining variables like; flushing pressure, wire feed speed, pulse off time, gap voltage has been examined while SS 304L machining. WEDM process parameters. Pulse on time is regarded as the influencing machining variables for flushing pressure, pulse off time, gap voltage along with surface roughness. The wire feed contains the lowest impact on the surface roughness. The results shows that the validity of the old Taguchi technique for enhancing the machining efficiency as well as optimizing the machining variables within WEDM operations.

A. Aims and Objectives of Present Work

WEDM is discovered to be an incredibly capability electro thermal practice in the area of conductive content machining. Due to the better practice ability, WEDM is a crucial machining tool to create intricate and complex components shapes in parts like electronics and computer industries, nuclear, aerospace, automobile, die making as well as some other tools.

Choice of the perfect machining variables mixture for accomplishing increased operation efficiency for exampledimensional accuracy, cutting speed, surface roughness, process performance is a difficult job of WEDM procedure because of existence of big amount of procedure variables along with complex stochastic procedure mechanism. From the available literature it can be seen that a selection of experimental investigation functions is performed on various components to learn the impact of different procedure variables on WEDM activities and enhance the parametric ways. RSM is the most useful method for these types of problems. In a few recommendations, the RSM applicability in machining procedure is found (Sorkhel as well as Bhattacharyya, 1999; Ebeid et al., 2004; George et al., 2004).

The investigations on the influence of various cutting parameters in WEDM process have been made by a number of workers. Most of these investigations had been made to attain higher (MRR), to improve the surface roughness, to achieve the dimensional accuracy, etc. Researchers have been used different materials for their study; they have used different techniques for optimization along withmodeling of the WEDM process. As, EN-31 is one of the most widely used materials in the automotive and lock industry, there is a need to find out the effect of cuttingvariables on performance measures in WEDM while machining EN-31 material. This will help in resolving many problems faced by the local lock industry.

In the present work EN-31 alloy steel is used to study the effect of several cutting factors on Surface Roughness, MRR as well as Overcut in the WEDM process. Parametric analysis has been done by conducting a set of experiments using "Electronica Sprintcut" Wire EDM Machine. Mathematical models correlating the inter- relationships of differentWEDM machining parameters such as; peak current (Ip), pulse on-time (Ton), wire tension (T), wire feed rate (F) and water pressure (P) on metal removal rate (MRR), surface roughness (Ra) and Overcut have been obtained using the response surface methodology (RSM) approach. A Rotatable Central Composite Design (RCCD) has been used for the study. The effects of cutting parameters have been analyzed on MRR, Ra and Overcut by using analysis of variance (ANOVA). Mathematical models fitted to the experimental data will help towards the selection of the optimum machining conditions. The variations of metal removal rate, surface roughness and overcut with machining parameters are also presented in graphical forms.

III. THEORITICAL BACKGROUND

A. Mechanism of Metal Removal in EDM

When a suitable voltage is applied across the electrodes, potential intensity between the closest micro-irregularities builds up. Impurities increase field strength and electrons start leaving the cathode (field emission) and drift towards anode (fig. 3.1a). Collision ionization at this stage is not expected. However, the dielectric fluid gets heated and a bubble is formed. High pressure vapor (or gas) bubble expands. Within the bubble, Collision ionization takes place and after sometime, a narrow channel of continuous conductivity is formed (fig. 3.1b).

The plasma channel and the enveloping bubble expand continuously and there is considerable flow of electrons towards anode (fig. 3.1c). Due to increase in the field strength and impact of ions on the electrode surface, its temperature increases and the electron emission changes from field emission to thermal field emission. This increases the temperature further which melts and evaporates certain volume of material.

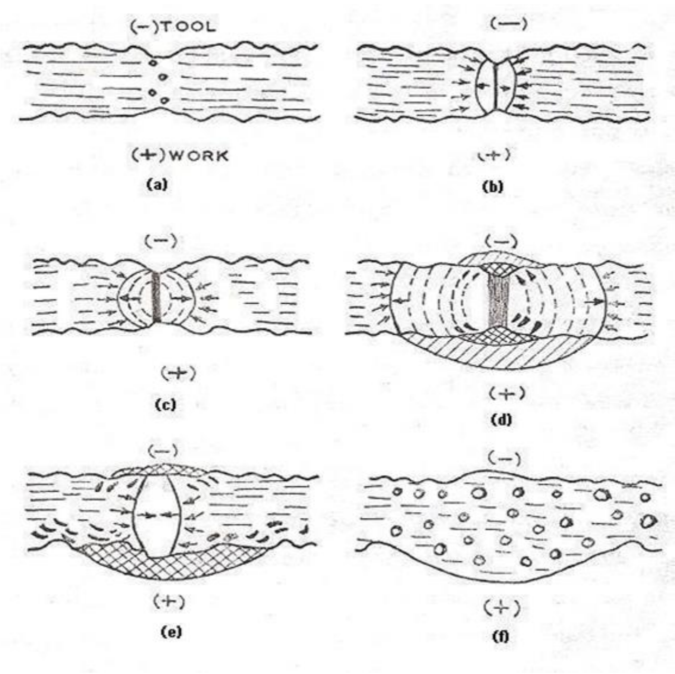

Figure 3.1: Successive stages of discharge

At this stage, some additional factors such as mechanical impact of particles, electrical forces, and pressure waves created due to high temperature gradient cause expulsion of the material from the molten pool (fig. 3.1d). A little (300 – 500 µs) after the discharge terminates, pressure inside the bubble drops abruptly due to its collapse, and some of the molten metal in the molten pool is ejected due to combined hydraulic and thermo- dynamical effects (fig. 3.1e).

Ejected metal is solidifies subsequently and is swept away by the flowing dielectric in the form of debris (fig. 3.1f). After the discharge is over, the dielectric within the gap de-ionizes completely and the channel of conductivity ceases to exist. A fresh discharge may initiate at some other point, where the tool-work gap is minimum.

B. Working principle of Wire-cut EDM

The basic working principle of wire-cut EDM is same as that of die-sinking EDM .In this system slowly moving wire moving along a prescribed path and removes material from the work piece. The material is removed by a series of discrete discharges between the wire electrode and the workpiece in the presence of dielectric fluid, which creates a path for all parole as the fluid becomes oozed in the gap. Every discharge leaves a crater in the work piece and the tool. The area where discharge takes place is heated to extremely high temperature, so that the surface is melted and evaporated. The eroded particles are flushed away by the flowing dielectric fluid. The mechanism involved in wire-cut EDM process is shown below in fig 3.2.

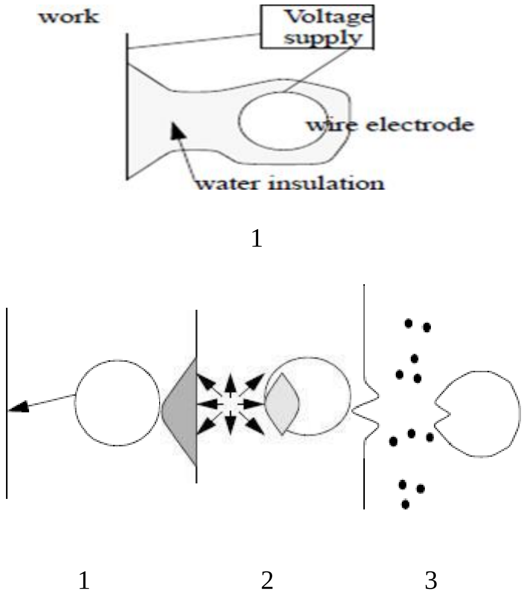

Figure 3.2: The mechanism involved in wire-cut EDM process

C. Design of Experiments (DOE)

DOE (Design of the Experiments) represent the experiments based on planning, analyzing as well as designing to obtain the efficient and effective results or conclusions. In executing a created test, modifications are designed on the enter variables as well as the corresponding modifications in the paper variables are found. The type in responses is widely known as feature as well as the results variables. Each aspect is able to capture many values throughout the experiment. Each such worth of the element is known as a quality. A operate or trial is a specific mixture of component quantities whose impact on the result is of interest. High value of parameter is represented by +1 as well as -1 is the value of low level parameters and [-1 1] is transforming all these parameters in same code. It's crucial to integrate statistical data evaluation techniques in the experiment to effort for statistically conclusions.

IV. EXPERIMENTAL PROCEDURE

A. Experimental Set-Up

All the experiments was conducted on a CNC (Computer Numerically Controlled) Wire-cut EDM Machine, ELEKTRA SPRINTCUT, manufactured by ELECTRONICA MACHINE TOOLS Ltd., India. The Elektra Wire-cut EDM comprises of a machine tool, a power supply unit (ELPULS) and a dielectric supply unit. The experimental set- up is shown in fig 4.1.

Figure 4.1: Experimental set-up of wire cut EDM [Courtesy NSIC, Aligarh (India)]

Table 4.1 shows the range along with least count of different electrical variables that are available on the machine.

Table 4.1: Range of values available on the Wire EDM machine on which experiments have been conducted

Parameters	*Range*	*In steps of*
Pulse on-time	00-31 μs	1 μs
Pulse off-time	00-63 μs	1 μs
Pulse peak current	10-230 A	5 A
Pulse peak voltage setting	0-2	1
Wire tension	300-1980 g	120 g
Wire feed	01-15 m/min	1 m/min
Water pressure	3-12 kg/cm^2	1 kg/cm^2
Servo voltage setting	0-99	1
Servo feed setting	0-999	1

B. Work-piece and Tool

Preparation of work-piece

Experiments has been done on EN-31 alloy steel work-piece with use of a brass wire tool. The work-piece is in the form of a small rectangular block of dimensions 25 mm x 10 mm x 9 mm. Work-pieces of this size were cut out from the rectangular strip of EN- 31alloy steel (Commercially available drawn strips). First of all these rectangular strips were ground on a surface grinder in order to remove the flaws and rust. Then small pieces of required size were cut by hand hacksaw. Again these small work-pieces are grinded over surface grinder in order to remove burrs and to achieve final shape and size. Table 4.2 shows the chemical composition of the work-piece. The small sized work pieces are used for ease of weight measurement on the balance and also economical. The work- pieces used for the experimental work are shown in the fig 4.2.

Table 4.2: Chemical Composition (wt. %) of EN-31 alloy steel

Elements	*Composition (wt. %)*
Carbon, C	1.05
Silicon, Si	0.3
Manganese, Mn	0.6
Chromium, Cr	1.0
Iron, Fe	Balance

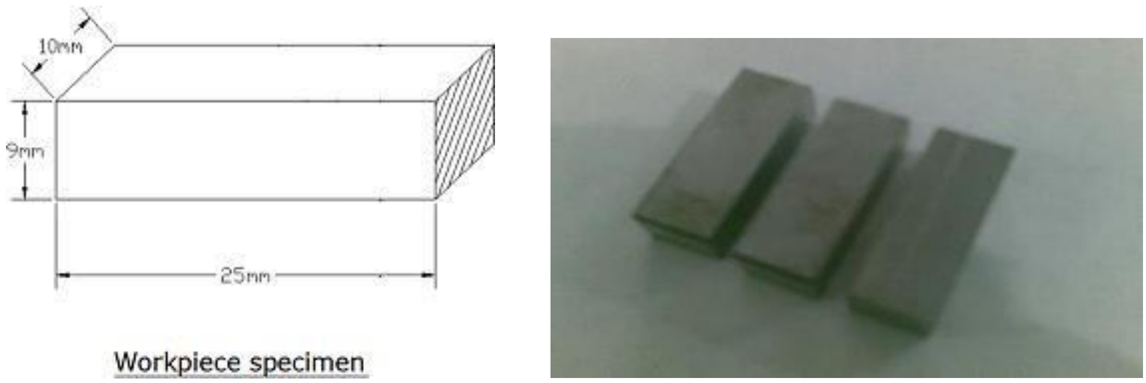

Figure 4.2: Workpiece specimens used for experimental work

C. General plan of the Experiments

The general plan of the experiments and range of the parameters used in the present study is given below in table 4.3.

Table 4.3: General Plan of the Experiments

Items	*Description*
Work material	EN-31 alloy steel (Commercially available drawn bars)
Size of the Work-piece	25mm X 10mm X 9mm
Tool material	Brass wire, 0.25 mm diameter (ELEKTRADURACUT)
Polarity	Work-piece (+); Tool (-)
Angle of cut	Vertical
Machined slot length	7 mm; along the 10 mm length of the Workpiece
Dielectric used	De-ionized water; Conductivity 20 mho
Flushing type	Both sides (top and bottom)
Input (test) parameters	Pulse on-time (μs); [10, 15, 20, 25, 30]
	Pulse peak current (A); [100, 125, 150, 175, 200]
	Wire tension (g); [540, 900, 1260, 1620, 1980]
	Wire feed rate (m/min); [5, 7, 9, 11, 13]
	Water pressure (kg/cm^2); [7, 8, 9, 10, 11]
	Pulse off-time; 63 μs

D. Experimental Procedure

The test specimens (work-pieces) were thoroughly washed in petrol, dried, and accurately weighed on an electronic balance ("ADAIR", AD-600B) to an accuracy of 0.01 g. These samples were then mounted on the work table in the work holding fixture one by one and properly aligned. Wire electrode is initially kept at the position 8 mm from the free end of the work -piece along its 25 mm length from where the machining starts. The placement of test specimen on the work table is shown in fig 4.3. A constant gap between the work-piece and the wire electrode was maintained during machining by the servo motor. The fixed parameters were set as per given values shown in the table

The input (or test) parameters were set for each run as per given design of experiments (DOE). All the parameters controlled and monitored during machining by the control panel of the machine unit. Water (dielectric) pressure was monitored by the gauge provided in the flow line of the dielectric. Both top and bottom flushing was used. Length of the machined slot was set to 7 mm. The machining time was recorded with the help of stop watch. Machined samples were cleaned, dried with the help of air blower so that dielectric particles were removed from the machined slot and again weighed for determining the weight of material eroded during the test. The experimental work was carried out at National Small Scale Industries Corp. (NSIC) Ltd., Aligarh, UP (India).

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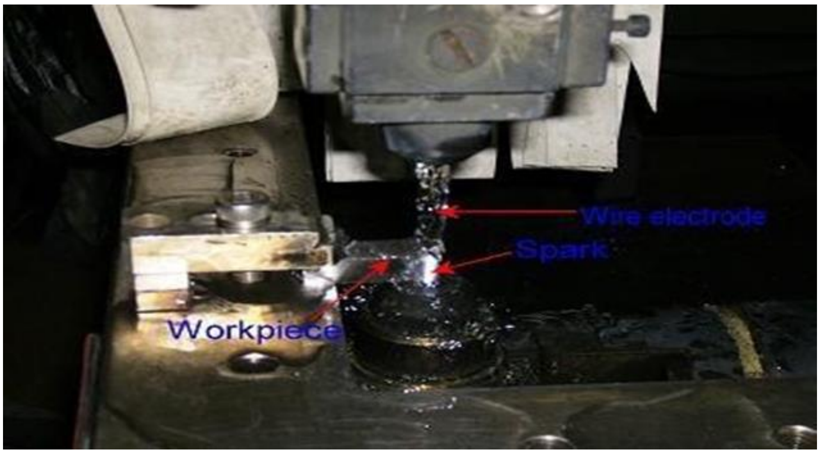

Figure 4.3: Picture showing the placement of test specimen on the work table

V. PLAN OF EXPERIMENTS

A. Plan of Experiments

Experiments that are based on Rotatable Central Composite Design (RCCD) was conducted to study the effect of various process parameters on MRR, Overcut and Ra. The data obtained from the RCCD utilized a model of MRR, Overcut and Ra in terms of input parameters.

- The overall experimentation falls within the following steps:
  - Data analysis
  - Design of experiments (DOE)
  - Conducting experiments

Parameter selection and range selection

Out of the several controllable parameters available on the control panel of the WEDM machine, Pulse on-time (Ton), Pulse peak current (Ip), Wire tension (T), Wire feed rate (F) and Water pressure (P) were chosen as the input parameters. The upper and lower limits of all the parameters are restricted by the machine capabilities. All the experiments were conducted with direct polarity. Table 5.1 shows the input parameters.

Table 5.1: Range of input parameters over which experiments were conducted

Input Parameter	*Minimum value*	*Maximum value*	*In steps of*
Pulse on-time, Ton (μs) [X_1]	10	30	5
Pulse peak current, Ip (A) [X_2]	100	200	25
Wire tension, T (g) [X_3]	540	1980	360
Wire feed rate, F (m/min) [X_4]	5	13	2
Water pressure, P (kg/cm^2) [X_5]	7	11	1

Table 5.2: Coding of input (or process) parameters

Coded Levels / *Input Parameters*	-2	-1	0	+1	+2
Pulse on-time, Ton (μs)	10	15	20	25	30
Pulse peak current, Ip (A)	100	125	150	175	200
Wire tension, T (g)	540	900	1260	1620	1980
Wire feed rate, F (m/min)	5	7	9	11	13
Water pressure, P (kg/cm^2)	7	8	9	10	11

B. Response Surface and RegressionAnalysis

Analysis of the experimental results has been done using the software, Minitab 15. The software was used for model fitting and for Analysis of Variance (ANOVA). The RCCD is capable of fitting a quadratic model. Hence, first a quadratic fitting of Metal Removal Rate, Surface Roughness and Overcut was carried out. Quadratic models with first-order interaction terms and square terms were fitted. Analysis of Variance (ANOVA) based statistical tests was performed to determine the suitability of the fitted model. Significance of each one of them was tested according to the F-test. Since, not all of the terms in the fitted unit might have considerable consequences. In such a situation, the fitting is usually raised by eliminating several of the terms (Montgomery along with myers, 2002). This was conducted by a phase smart fitting.

Backward elimination regression technique was used for model reduction (model reduction means removal of insignificant terms from the first model). Again, Analysis of Variance (ANOVA) based statistical tests was performed to determine the suitability of the fitted model. Finally both the models have been compared and variation of the responses with respect to the input parameters was shown graphically.

VI. RESULTS AND DISCUSSION

A. Parametric Analysis

In order to study the effect of the input parameters, a designed experiment was shown as in Section 5.2.1. Since, the aim is to fit a second order polynomial function using the DOE, hence, a Rotatable Central Composite design has been used which is capable of fitting a second order polynomial function.

B. Regression analysis and Model fitting

Regression analysis of the experimental results obtained from the RCCD runs has been done using the software, Minitab 15. Full second order models and reduced second order models (reduced models can be obtained by stepwise backward elimination regression) were obtained for MRR, Overcut and Ra. The regression analysis for each response is discussed below.

1) Regression Analysis for Metal Removal Rate (MRR)

Regression analysis is performed to find out the relationship between input parameters and the output response. In order to test the significance of each individual term in the model; a complete analysis of variance according to Student's t-test was performed. Table 6.2 presents the values of β coefficients of the model terms. The calculated t- values as well as corresponding p-values are listed in Table 6.2. It can be seen from Table 6.2 that factors (Ton, Ip, T, Ton*Ton, T*T, Ton*Ip, and Ton*T) having p-value less than 0.05 are significant for 95% confidence level and also some factors (F, P, Ip*Ip, F*F, P*P, Ton*F, Ton*P, Ip*T, Ip*F, Ip*P, T*F, T*P, and F*P) are insignificant or they have no significant effect in the regression model, due top-value is higher than

0.05. Results show that the response (MRR) is most affected by Pulse on-time (Ton), Pulse peak current (Ip), and wire tension(T).

Table 6.2: Table of regression model for MRR analysis

Term	Coef	SE Coef	T	P
Constant	11.1453	0.3840	29.027	0.000*
Ton	7.0872	0.1965	36.068	0.000*
Ip	3.3633	0.1965	17.116	0.000*
T	-1.9615	0.1965	-9.982	0.000*
F	-0.0737	0.1965	-0.375	0.715
P	-0.0348	0.1965	-0.177	0.863
Ton*Ton	0.9073	0.1777	5.105	0.000*
Ip*Ip	0.1548	0.1777	0.871	0.402
T*T	0.5433	0.1777	3.056	0.011*
F*F	-0.0092	0.1777	-0.052	0.960
P*P	-0.1017	0.1777	-0.572	0.579
Ton*Ip	1.6362	0.2407	6.799	0.000*
Ton*T	-1.1014	0.2407	-4.576	0.001*
Ton*F	-0.0834	0.2407	-0.347	0.735
Ton*P	-0.0343	0.2407	-0.143	0.889
Ip*T	-0.1413	0.2407	-0.587	0.569
Ip*F	-0.0922	0.2407	-0.383	0.709
Ip*P	0.2246	0.2407	0.933	0.371
T*F	0.4078	0.2407	1.694	0.118
T*P	0.0162	0.2407	0.067	0.947
F*P	-0.3994	0.2407	-1.660	0.125

A complete analysis of variance (ANOVA) was performed for the experimental results obtained from RCCD runs so as to study the significance of linear, square and interaction terms. Table 6.3 indicates that all terms of the regression model are significant for the confidence level of 95%. The exemplary implication can be checked either by analyze the F- value to a threshold F-value or by analyze the analogous p-value to the threshold p-value. The F-values can be converted into the p-value by using the F probability distribution curve. The threshold p-value depends on the chosen significance level which was set here to 5%.The model F-value of 90.15 implies that the model is significant at 95% confidence level. There is only a 0.0% chance that a "Exemplary F- Value" this large could occur due to noise. The "Lack of Fit F-value" of 4.04 implies the "Lack of Fit" is not significant which is desirable. The p-value for lack of fit is 0.073, suggesting that this model adequately fits the data.

Table 6.3: ANOVA table for regression model of MRR

Sources	d.f	Seq. SS	Adj . SS	Adj. MS	F	P
Regression	20	1670.74	1670.74	83.537	90.15	0.000*
Linear	5	1569.47	1569.47	313.893	338.73	0.000*
Square	5	32.42	32.42	6.485	7.00	0.004*
Interaction	10	68.85	68.85	6.885	7.43	0.001*
Residual Error	11	10.19	10.19	0.927		
Lack-of-Fit	6	8.45	8.45	1.409	4.04	0.073**
Pure Error	5	1.74	1.74	0.348		
Total	31	1680.94				

The fitted regression model for MRR in terms of coded parameters is shown below:

$$Y(MRR) = 11.1453 + 7.0872 X_1 + 3.3633 X_2 - 1.9615 X_3 - 0.0737 X_4 - 0.0348 X_5 + 0.9073 X_1^2 + 0.1548 X_2^2 + 0.5433 X_3^2 - 0.0092 X_4^2 - 0.1017 X_5^2 + 1.6362 X_1 X_2 - 1.1014 X_1X_3 - 0.0834 X_1X_4 - 0.0343 X_1X_5 - 0.1413 X_2X_3 - 0.0922 X_2X_4 + 0.2246 X_2X_5 + 0.4078 X_3X_4 + 0.0162 X_3X_5 - 0.3994 X_4X_5$$

The regression data for any installed design is displayed with Table 6.4. The R Squared (R-Sq) is described as the ratio of variability clarified by the product on the complete variability in the particular information and also can be used as a degree of the goodness of healthy. The greater R Sq methods unity, the greater the product healthy on the experimental data. For example, the gotten worth of 0.9939 for R Sq in the situation of MRR means the unit describes around 99.39 % of the variability within MRR. R Sq worth additionally confirms the connection in between the impartial reactions and elements may sufficiently be defined by styles.

Adjusted R-Sqis a measure of the amount of variation about the mean which is explained by the model. The values of adjusted R-Sq (98.29%) and error term (S = 0.9626) indicate the goodness of the model. A value of 0.9829 indicates that 98.29% of the observed variation in the response can be explained by the model. When there is a large difference in the values of predicted R-Sq andthe adjusted R-Sq, it indicates that some non-significant terms have been included in the model and the model would improve on excluding such terms. Backward step- wise fitting was used for model fitting with terms of p-value greater than 0.05 dropped.

Table 6.4: Table of regression statistics for MRR analysis

S	R-Sq	R-Sq (Adjusted)	R-Sq (Predicted)
0.9626	99.39%	98.29%	87.37%

The fitted regression model for MRR in terms of the actual parameter values is:

MRR = 7.132 - 1.09 Ton - 0.246 Ip - 0.00692 T + 1.53 F + 2.33 P + 0.0363 Ton*Ton + 0.000248 Ip*Ip + 0.000004 T*T - 0.0023 F*F - 0.102 P*P + 0.0131 Ton*Ip - 0.000612 Ton*T - 0.0083 Ton*F - 0.0069 Ton*P - 0.000016 Ip*T - 0.00184 Ip*F + 0.00898 Ip*P + 0.000566 T*F + 0.000045 T*P - 0.200 F*P

Where, MRR is in mg/min and Tonin µs, Ipin A, Tin g, F in m/min, and P in kg/cm^2.

After employing the backward elimination technique once again a total evaluation of variance based on Student's t test was performed. The estimated t values in addition to corresponding p values are mentioned with Table 6.5. As are visible in Table 6.5, all of the terms have a p value under 0.05, this means they're important for a confidence level of ninety five %.

Table 6.5: Table of reduced regression model for MRR analysis

Term	Coef	SE Coef	T	P
Constant	22.82	6.831	3.341	0.003
Ton	-1.220	0.355	-3.444	0.002
Ip	-0.181	0.038	-4.778	0.000
T	-0.010	0.004	-2.414	0.025
Ton*Ton	0.0362	0.006	6.354	0.000
T*T	0.0000042	0.000	3.800	0.001
Ton*Ip	0.0131	0.002	8.404	0.000
Ton*T	-0.0006	0.000	-5.654	0.000
Ip*P	0.006	0.002	2.613	0.016
T*F	0.0007	0.000	2.876	0.009
F*P	-0.103	0.035	-2.965	0.007

The ANOVA table for the reduced second order model is shown in Table 6.6. The model F- value of 275.448 implies that the model is significant at 95% Confidence level. There is only a 0.0% chance that a "Model F-Value" this large could occur due tonoise.

Table 6.6: ANOVA table for reduced regression model of MRR

Sources	Add of Squares	d.f	Mean Square	F.	P.
Regression	1667.988	10	166.799	275.448	0.000
Residual	12.717	21	0.606		
Total	1680.704	31			

The regression data for decreased subsequent design is displayed with Table 6.7. The expected R-Sq worth as well as the modified R-Sq great had been discovered to remain for good understanding. Modified R-Sq is a degree of the quantity of perturbation regarding the hostile that is clarified by the model. An importance of 0.9888 suggests that 98.88 % of the noticed perturbation in the reply may be clarified by the model. As are visible in Table 6.7, the big difference in between the expected R Sq worth as well as the modified R Sq great has reduced on shedding minor phrases.

Table 6.7: Comparison of regression statistics for the full and reduced second order MRR models

Model Statistics	Full Second Order	Reduced Second Order
S	0.9626	0.778
R-Sq	99.39%	99.24%
Adjusted R-Sq	98.29%	98.88%
Predicted R-Sq	87.37%	98.04%

The fitted reduced model after backward elimination for MRR is:

MRR = 22.82 - 1.22 Ton - 0.181 Ip - 0.010 T + 0.0362 Ton*Ton + 0.0000042 T*T + 0.0131 Ton*Ip - 0.0006 Ton*T+ 0.006 Ip*P + 0.0007 T*F - 0.103 F*P

Where, MRR is in mg/min and Tonin µs, Ipin A, Tin g, F in m/min, and P in kg/cm2.

2) Regression Analysis for Overcut

Table 6.8 presents the values of β coefficients of the model terms. The calculated t- values as well as corresponding p-values are listed in Table 6.8. It can be seen from Table 6.8 that only Pulse on-time (Ton) is the significant model term because it has p- value less than 0.05 at 95% confidence level and factors Ip, T, F, P, Ton*Ton, Ip*Ip, T*T, F*F, P*P, Ton*Ip, Ton*T, Ton*F, Ton*P, Ip*T, Ip*F, Ip*P, T*F, T*P, and F*Pare insignificant or they have no significant effect in the regression model, because their p-value is higher than 0.05. Results show that the response (Overcut) is most affected by the Pulse on-time (Ton).

Table 6.8: Table of regression model for Overcut analysis

Term	Coef	SE Coefe	T	P
Constant	38.9318	2.161	18.016	0.000*
Ton	-3.375	1.106	-3.052	0.011*
Ip	0.5417	1.106	0.49	0.634
T	-1.3333	1.106	-1.206	0.253
F	-1.2917	1.106	-1.168	0.267
P	0.875	1.106	0.791	0.446
Ton*Ton	1.0682	1.000	1.068	0.308
Ip*Ip	-0.5568	1.000	-0.557	0.589
T*T	0.0682	1.000	0.068	0.947
F*F	0.0682	1.000	0.068	0.947
P*P	1.1932	1.000	1.193	0.258
Ton*Ip	-0.25	1.354	-0.185	0.857
Ton*T	-0.0625	1.354	-0.046	0.964
Ton*F	0.375	1.354	0.277	0.787
Ton*P	-1.375	1.354	-1.015	0.332
Ip*T	-1.1875	1.354	-0.877	0.399
Ip*F	-0.375	1.354	-0.277	0.787
Ip*P	-1.00	1.354	-0.738	0.476
T*F	0.4375	1.354	0.323	0.753
T*P	-0.3125	1.354	-0.231	0.822
F*P	-0.25	1.354	-0.185	0.857

*significant

Analysis of variance (ANOVA) was performed for the experimental results obtained from RCCD runs so as to study the significance of linear, square and interaction terms. Table 6.9 shows that all the terms of the regression model are insignificant at 95% Confidence level. The model F-value of 0.93 implies that the model is insignificant at 95% Confidence level. The p-value for lack of fit is 0.347, suggesting that this model adequately fits the data. The regression statistics for the fitted model is also shown in Table 6.9. A value of 0.6288 for R-Sq in the case of Overcut implies that the model explains approximately 62.88% of the variability in Overcut. The values of adjusted R- Sq (0.00%) and error term (S = 5.4177) indicate that the fitted model is not good. Therefore backward elimination method was used for model fitting with terms of p-value greater than 0.05 dropped.

Table 6.9: ANOVA table for regression model of Overcut

Sources	Df.	Seq. SS	Adj. SS	Adj. MS	F	P
Regression	20	547.01	547.01	27.351	0.93	0.573**
Linear	5	381.5	381.5	76.3	2.60	0.087**
Square	5	85.51	85.51	17.102	0.58	0.713**
Interaction	10	80.00	80.00	8.0	0.27	0.975**
Residual Error	11	322.86	322.86	29.351		
Lack-of-Fit	6	205.53	205.53	34.255	1.46	0.347**
Pure Error	5	117.33	117.33	23.467		
Total	31	869.87				

S=5.4177	R-Sq=62.88%	Adj R-Sq=0.00%	Pred R-Sq=0.00%

**Insignificant

Table 6.10: Table of reduced regression model for Overcut analysis

Terms	Coefe	SE Coefe	T	P
Constant	42.914	4.484	9.570	0.000
P*P	0.138	0.054	2.558	0.016
Ton*P	-0.077	0.020	-3.914	0.001

The ANOVA table for the reduced second order model for Overcut is shown in Table 6.11. The model F-value of 8.23 implies that the model is significant at 95% confidence level. There is a single 0.1% incidental that a "Exemplary F-Value" this large could occur cause ofbuzz.

Table 6.11: ANOVA table for reduced regression model of Overcut

Sources	Sum of Squ	d.f	Mean Squ	F	P
Regression	314.966	2	157.483	8.230	0.001
Residual	554.909	29	19.135		
Total	869.875	31			

The regression data for decreased subsequent buy design is displayed with Table 6.12. The R Sq worth for the unit is discovered to be 0.3621which means the unit describes around 36.21 % of the variability in Overcut. Modified R Sq is a degree of the quantity of perturbation regarding the hostile that is clarified by the model. A importance of 0.3181 suggests that 31.81 % of the noticed perturbation in the reply may be clarified by the model.

Table 6.12: Comparison of regression statistics for the full and reduced second order Overcut models

Model Statistics	Full Second Order	Reduced Second Order
S	5.4177	4.370

The fitted reduced model after backward elimination for Overcut is: Overcut = 42.914 + 0.138 P*P - 0.077 Ton*P

Where, Overcut is in µm and Tonin µs, Ipin A, Tin g, F in m/min, and P in kg/cm2.

3) Regression Analysis for Surface Roughness (Ra)

Table 6.13 presents the values of β coefficients of the model terms. The calculated t- values as well as corresponding p-values are also listed in this table. It can be seen from Table 6.13 that factors (Ton and Ip) having p-value less than 0.05 are significant for 95% confidence level and that factors (T, F, P, Ton*Ton, Ip*Ip, T*T, F*F, P*P, Ton*Ip, Ton*T, Ton*F, Ton*P, Ip*T, Ip*F, Ip*P, T*F, T*P, and F*P) having p-value higher than 0.05 are insignificant or they have no significant effect in the regression model. Results show that the response (Ra) is most affected by Pulse on-time (Ton) and Pulse peak current (Ip).

Table 6.13: Table of regression model for Ra analysis

Term	Coef	SE Coef	T	P
Constant	2.30568	0.06674	34.545	0.000*
Ton	0.555	0.03416	16.248	0.000*
Ip	0.09583	0.03416	2.806	0.017*
T	-0.01833	0.03416	-0.537	0.602
F	-0.01667	0.03416	-0.488	0.635

P	-0.0225	0.03416	-0.659	0.524
Ton*Ton	0.02182	0.0309	0.706	0.495
Ip*Ip	-0.01943	0.0309	-0.629	0.542
T*T	0.02932	0.0309	0.949	0.363
F*F	0.00182	0.0309	0.059	0.954
P*P	-0.02068	0.0309	-0.669	0.517
Ton*Ip	0.0675	0.04183	1.614	0.135
Ton*T	-0.015	0.04183	-0.359	0.727
Ton*F	0.0375	0.04183	0.896	0.389
Ton*P	0.01375	0.04183	0.329	0.749
Ip*T	0.0425	0.04183	1.016	0.331
Ip*F	0.065	0.04183	1.554	0.149
Ip*P	0.00625	0.04183	0.149	0.884
T*F	0.01	0.04183	0.239	0.815
T*P	-0.00375	0.04183	-0.09	0.930
F*P	0.03875	0.04183	0.926	0.374

*significant

Analysis of variance (ANOVA) was performed for the experimental results obtained from RCCD runs so as to study the significance of linear, square and interaction terms. Table 6.14 indicates that linear terms of the regression model are significant for the confidence level of 95%. The model F-value of 14.17 implies that the model is significant at 95% confidence level. There is only a 0.0% chance that a "Model F-Value" this large could occur due to noise. The "Lack of Fit F-value" of 3.74 implies the "Lack of Fit" is not significant which is desirable. The p-value for lack of fit is 0.085, suggesting that this model adequately fits the data.

Table 6.14: ANOVA table for regression model of Ra

Sources	d.f	Sequ SS	Adj. SS	Adj. MS	F.	P.
Regression	20	7.93319	7.93319	0.39666	14.17	0.000*
Linear	5	7.6399	7.6399	1.52798	54.57	0.000*
Square	5	0.06829	0.06829	0.01366	0.49	0.779**
Interaction	10	0.225	0.225	0.0225	0.80	0.631**
Residual Error	11	0.30801	0.30801	0.028		
Lack-of-Fit	6	0.25186	0.25186	0.04198	3.74	0.085**
Pure Error	5	0.05615	0.05615	0.01123		
Total	31	8.2412				
S=0.1673	R-Sq=96.26%		Adj R-Sq=89.47%		Pred R-Sq=17.07%	

*significant; **Insignificant

The fitted regression model for Ra in terms of coded parameters is shown below:

$$Y\ (Ra) = 2.30568 + 0.555X_1 + 0.09583\ X_2 - 0.01833\ X_3 - 0.01667\ X_4 - 0.0225\ X_5 +$$

$$0.02182X_1^2 - 0.01943\ X_2^2 + 0.02932\ X_3^2 + 0.00182\ X_4^2 - 0.02068X_5^2 +$$

$$0.0675\ X_1X_2 - 0.015\ X_1X_3 + 0.0375\ X_1X_4 + 0.01375\ X_1X_5 + 0.0425\ X_2X_3 +$$

$$0.065\ X_2X_4 + 0.00625\ X_2X_5 + 0.01\ X_3X_4 - 0.00375\ X_3X_5 + 0.03875\ X_4X_5$$

The fitted regression model for Ra in terms of the actual parameter values is:

Ra= 5.40 - 0.053 Ton - 0.0175 Ip - 0.00119 T - 0.478 F + 0.096 P + 0.00087 Ton*Ton -

0.000031 Ip*Ip + 0.000000 T*T + 0.00045 F*F - 0.0207 P*P + 0.000540 Ton*Ip -

0.000008 Ton*T + 0.00375 Ton*F + 0.00275 Ton*P + 0.000005 Ip*T +

0.00130 Ip*F + 0.00025 Ip*P + 0.000014 T*F - 0.000010 T*P + 0.0194 F*P

Where, Ra is in µm and Tonin µs, Ipin A, Tin g, F in m/min, and P in kg/cm2.

After employing the backward elimination technique, again a complete analysis of variance according to Student's t-test was performed. The calculated t-values as well as corresponding p-values are listed in Table 6.15. As can be seen in Table 6.15, all the terms have a p-value less than 0.05, which means that they are significant for a confidence level of 95%.

Table 6.15: Table of reduced regression model for Ra analysis

Term	Coef	SE Coef	T	P
Constant	1.740	0.173	10.075	0.000
Ip	-0.011	0.001	-7.975	0.000
Ton*Ip	0.001	0.000	19.561	0.000

The ANOVA table for the reduced second order model is shown in Table 6.16. The model F- value of 196.963 implies that the model is significant for a confidence level of 95%. There is only a 0.0% chance that a "Model F-Value" this large could occur due to noise.

Table 6.16: ANOVA table for reduced regression model of Ra

Sources	Sum of Square	d.f	Mean Square	F.	P.
Regression	7.676	2	3.838	196.963	0.000
Residual	0.565	29	0.019		
Total	8.241	31			

Table 6.17: Comparison of regression statistics for the full and reduced second order Ra models

Model Statistics	Full Second Order	Reduced Second Order
S	0.1673	0.140
R-Sq	96.26%	93.14%
Adj. R-Sq	89.47%	92.67%
Pred. R-Sq	17.07%	91.04%

The fitted reduced model after backward elimination for Ra is: Ra = 1.740 – 0.011 Ip + 0.001 Ton*Ip

Where, Ra is in µm and Tonin µs, Ipin A, Tin g, F in m/min, and P in kg/cm2.

VII. CONCLUSION AND FUTURE WORK

A. Conclusions

In this particular experimental analysis, the result of WEDM variables including water pressure, wire feed rate, wire tension, pulse peak current, as well as pulse on-time on machining qualities of EN 31 steel was examined. Tests depending on the "Rotatable Central Composite Design" (RCCD) have been performed to create models versions of the procedure. To summarize the primary options that come with the result, the following conclusions might be drawn:

- WEDM process has proved its adequacy to machine EN-31 steel. The MRR lies in the range of 1.64 - 29.39 mg/min, Overcut lies in the range of 30.5 – 53.5 µm and Surface Roughness (Ra) lies in the range of 1.54 – 3.25 µm.
- From the designed set of teststhat is based on the Rotatable Central Composite Design (RCCD) it was found that the Wire tension, Pulse peak current as well asPulse on-time are the most dominating parameters for Metal removal rate (MRR). Whereas Pulse on-time is the most dominating variables for Overcut, Pulse peak current as well as Pulse on-time are the most dominating parameters for Surface Roughness (Ra).
- The evaluation of the result variables utilizing RSM method has got the benefit of detailing the outcome of every functioning parameter on the importance ofthe resulting effect parameter.
- The regression strategy is a crucial instrument for representing the relation among machining distinctive along with WEDM procedure enter details, as well as the acquired mathematical versions, signify the correlationcompletely.
- RCCD is an effective instrument for supplying experimental diagrams as well as statistical mathematical versions, to do the tests economically andappropriately.
- The variables affecting the Metal removal rate, Overcut and Surface roughness were identified using ANOVA technique. Statistical analysis is carried out and the model adequacy is also checked.
- The pulse on-time variables has immediate impact on the metallic removing rate as well as surface roughness, as we rise the pulse on time the metal removal rate and surface roughness grows. While Overcut decreases with increased heartbeat ontime.
- The pulse peak current variables has immediate impact on the metallic removing rate as well as surface roughness, as we rise the pulse on time the metal removal rate and surface roughness grows. While Overcut very first elevates then decreases with increased heartbeat on time.
- Metal removal rate, Overcut and Surface roughness decreases when the wire tension is increased.
- Wire feed rate does not have any impact on the MRR as well as surface roughness. While Overcut reduces once the wire feed rate is raised.
- MRR as well as Surface roughness initially rise then decreases with increased in water pressure. While Overcut at first reduces then raised with increased water pressure.
- The evolved engineering environment in field of wire electric discharge machining of EN 31 metal is going in the area of potentiality in contemporary manufacturing uses for effective production of accuracy tasks. Since EN 31 metal is popular in lock and automotive industries. Aside from the suggested modeling method may also be used for optimizing the machining parameters in WEDM.

C. Scope for Future Work

- Additional study may try to think about another functionality requirements, like surface waviness, wear ratio, dimensional shift, cutting speed, etc. as an output parameter (or maybe response). This particular strategy may additionally be offer for the different pretty traditional machining initiatives as well as for machining of complex materials as composites to elevate the functionality attribute concurrently.
- An effort may be put for considering more parameters, for example open circuit voltage, spark gap voltage,pulse off-time,duty factor,effective wire offset,dielectric flow rate,dielectric type as well as wire/work-piece materialis often utilized as input variables for additional studies. The methods provided in this particular research may additionally be performed for the finishing functioning of WEDM procedure.
- The experimental results obtained in this study may be optimized so that a technology table is developed, which will be very useful and may be used as a guideline for machining of EN-31 steel. Besides experimental work, adequate range prevails for theoretical modeling as well as system simulation in WEDM.

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