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Influence of Servo Voltage and Dielectric Fluid Pressure in Wire Electrical Discharge Machining of Titanium Alloy

Siva Prasad Arikatla
Research Scholar
IGNOU, New Delhi
Sr. Lecturer Govt. Polytechnic
Ongole

Dr K Tamil Mannan
Associate Professor
School of Engineering & Technology
IGNOU, New Delhi

Dr Arkanti Krishnaiah
Professor& Head
Osmania University College of Engineering
Hyderabad, Telangana

ABSTRACT:
Wire electrical discharge machining (WEDM) is extensively used for machining of complex shapes in the field of die and mould making, medical, aerospace and automobile industries. Improper selection of wire electrical discharge machining process parameters setting can affect the machining efficiency and surface roughness due to arcing phenomenon that lead by discharge point of focus. The present study has been made to study the influence of wire electrical discharge machining process parameters such as servo voltage and dielectric fluid pressure during machining of Ti-6Al-4V Titanium alloy by wire electrical discharge machining process and these parameters were optimized using response surface methodology (RSM). The analysis of variance (ANOVA) was carried out to study the effect of process parameters on process performances. The mathematical models are also developed for process performance such as kerf width, material removal rate (MRR), surface roughness, cutting rate and overcut and validated with the experimental results.

KEY WORDS: Wire EDM, Kerf width, MRR, Surface roughness, over cut, ANOVA

I. INTRODUCTION:

Wire electrical discharge machining (WEDM) technology has been widely used in tool and die-making industry, automotive, medical and practically any conductive materials. It is a non-traditional machining process which used the continuously circulating wire as electrode and cuts the work piece along a programmed path. In WEDM, a thin single-strand metal wire is fed through the work piece submerged in a tank of dielectric fluid. WEDM is typically used to make punches, tools, and dies from hard metals that are difficult to machine with other methods. WEDM is commonly used when low residual stresses are desired, because it does not require high cutting forces for removal of material. If the energy per pulse is relatively low, little change in the mechanical properties of a material is expected due to these low residual stresses, although material that has not been stress-relieved can distort in the machining process. The work piece may undergo a significant thermal cycle, its severity depending on the technological parameters used. Such thermal cycles may cause formation of a recast layer on the part and residual tensile stresses on the work piece.

Titanium alloys are hard metals which contain a mixture of titanium and other chemical elements. Ti-6Al-4V grade titanium alloy is the most popular titanium alloy and is used for a range of applications in the aerospace, marine, power generation and offshore industries. Titanium alloys have very high tensile strength, fatigue resistance, light in weight (highest strength-to-weight ratio), extraordinary corrosion resistance, toughness even at elevated temperatures and able to withstand high temperatures. However, the high cost of both raw materials and processing limit their use to military applications, aircraft, spacecraft, medical devices, connecting rods on expensive sports cars and some premium sports equipment and consumer electronics. Auto manufacturers Porsche and Ferrari also use titanium alloys in engine components due to its durable properties in these high stress engine environments.

Although "commercially pure" titanium has acceptable mechanical properties and has been used for orthopedic and dental implants, for most applications titanium is alloyed with small amounts of aluminum and vanadium. This mixture has a solid solubility which varies dramatically with temperature, allowing it to undergo precipitation strengthening. This heat treatment process is carried out after the alloy has been worked into its final shape but before it is put to use, allowing much easier fabrication of a high-strength product. Yang, X, Liu, CR et al., studied the machining of titanium and its alloys (1), Kuriakose, Sh, Shanmugan MS et at., studied the characteristics of wire electro discharge machined Ti 6Al 4V surface (2) and Rahman.M.M et al., have done the modeling of machining parameters of Ti 6Al 4V for electric discharge machining using a neural network approach (3). Titanium and its alloys are attractive and important materials in modern industry due to their unique properties. Titanium is a very strong and light metal. This property causes that titanium has the highest strength-to-weight ratio in comparison the other metal that are studied to medical use. Titanium is also incredibly durable and long-lasting. When titanium cages, rods, plates and pins are inserted into the body, they can last for upwards of 20 years. Titanium non-ferromagnetic property is another benefit, which allows patients with titanium implants to be safely examined with MRIs and NMRIs (4, 5). Titanium and its alloys are used in many different industries such as biomedical applications, automobile, aerospace, chemical field, electronic, gas and food industry (6). In recent decades, titanium is applied widely in biomedical and medical field because it is absolutely a proper joint with bone and other body tissue, immune from corrosion, strong, flexible and compatible with bone growth. Titanium is used in different medical applications such as dental implants, hip and knee replacement surgeries, external prostheses and surgical instruments (4, 7). Elias C.N et al., studied the Bio Medical applications of Titanium and its alloy (8) and Kumar A et al., has done the investigations into machining characteristics commercially pure titanium using CNC electric discharge machining (9). On the other hand, there is some limitation for titanium use because of its initial high cost, availability, inherent properties and manufacturability (9). Machining titanium and its alloys by conventional machining methods has some difficulties such as high cutting temperature and high tool wear ratio. Thus, titanium and its alloys are difficult-to-machine through conventional machining process. Therefore, unconventional machining processes are introduced for machining titanium and its alloys (2, 6). Gu.L, Rajukar K.P et al., studied the electric discharge machining of Ti-6Al-4V with a bundled electrode.

G.N. Levy (10) developed an environmentally friendly and high capacity dielectric regeneration for Wire EDM. In wire EDM the most frequently used dielectric is water and the use of water bears some risks and described a filtration unit based on membrane technology. Liao et. al. (11) identified the machining voltage, current-limiting resistance, type of pulse-generating circuit and capacitance are the significant parameters which affecting the surface roughness, also found that a low conductivity of dielectric should be incorporated for the discharge spark to take place. Manna and Bhattacharyya (12) conducted experiments on aluminium-reinforced silicon carbide metal matrix composite using Wire EDM and concluded that the open gap voltage and pulse on period are the most significant machining parameters, for controlling the MRR. The open gap voltage affected the cutting speed significantly. Tosun et. al. (13) investigated the effect and optimization of machining parameters on the kerf width MRR in WEDM operations and found that the highly effective parameters on both the kerf and the MRR were open circuit voltage and pulse duration, whereas wire speed and dielectric flushing pressure were less effective factors. It is found that the open circuit voltage was about three times more important than the pulse duration for controlling the kerf, whereas open circuit voltage for controlling the MRR was about six times more important than pulse duration. Y.S Liao et. al. (14) studied the feasibilities to achieve a fine surface finish in Wire EDM and identified that the machining voltage, current-limiting resistance, type of pulse-generating circuit and capacitance are the significant parameters affecting the surface roughness in finishing process. In addition, it is found that a low conductivity of dielectric should be incorporated for the discharge spark to take place. Sarkar et. al. (15) developed a feed forward back-propagation neural network to model WEDM machining process to predict the response parameters as a function of six different control parameters, i.e. pulse on time, pulse off time, peak current, wire tension, dielectric flow rate and servo reference voltage.

Pradhan et. al. (16) optimized micro-EDM process parameters for machining Ti-6Al-4V super alloy and examined the influence of machining process parameters such as peak current, pulse-on-time, dielectric flushing pressure and duty ratio on performance criteria like MRR, TWR, over cut and taper. A. Klink et. al. (17) evaluated the surface integrity of powder metallurgical tool steel by main cut and finishing trim cuts in Wire EDM and observed that the average surface finish was 0.1 µm and 0.2 µm for CH- and water-based dielectrics and CH based EDM produced much lower tensile residual stress than water based EDM. Neeraj Sharma et. al. (18) observed that the MRR and surface roughness decreases with increase in pulse off time and servo voltage. Gao et. al. (19) carried out a study on WEDM process optimization for PCD micro milling tool and found that for roughing operation, peak current and voltage pulse width are the dominant parameters; while for finishing operation, Peak current, peak voltage are the largest influence of parameters on cutting speed. Vikram Singh et. al (20) investigated the effects of various Wire EDM process parameters such as pulse on time, pulse off time, servo voltage and wire feed rate on the MRR, surface roughness and cutting rate for AISI D2 Steel. Rupesh Chalisgaonkar et. al. (21) analyzed and optimized the process capability in Wire EDM of commercially pure Titanium with the input parameters such as pulse on time, pulse off time, peak current, wire feed, wire tension and servo voltage has been selected for process capability investigation in WEDM process. Yanzhen Zhang et. al (22) investigated the volume of melted and removed material and removal efficiency with different dielectrics.

II. EXPERIMENTAL WORK:

The experiments were conducted on ULTRACUT S1 Four Axis Wire Cut EDM machine from Electronica India Pvt. Ltd. The titanium alloy of Ti-6Al-4V was used as work piece material for the present Investigations. The chemical composition of Ti-6Al-4V titanium alloy by % weight is given in Table I. A diffused brass wire of 0.3 mm diameter was used as the wire electrode due to its extreme properties like electric discharge performance, heat resistance, low clarification and heat release. The chemical composition of brass wire was 63% copper and 37% Zinc by weight and its tensile strength is 142000 PSI. The deionized water was used as dielectric because of its low viscosity and rapid cooling rate and its temperature was kept at 20ºC. The process parameters such as server voltage and dielectric fluid pressure has taken at three different levels as shown in Table II and experiments were conducted on ULTRACUT S1 Four Axis Wire EDM machine with brass electrode of diameter 0.3 mm. The selections of these factors were based on the suggestions from the handbook recommended by the machine manufacturer, preliminary research results and journals. The kerf width was measured with optical microscope with magnification of 100X. Ten readings at different ten spots were taken and their average has been considered as kerf width of the cutting slot. MRR is calculated by considering the kerf width, cutting speed and thickness of workpiece. The surface roughness was measured with S1500DX/SD2 model SURFCOM with sensitivity of ½ Max and at magnification of X10000. Cutting rate is directly noted from the display parameters of wire electric discharge machine. The over cut is calculated as difference of kerf width and wire diameter. The influence of wire electric discharge machining process parameters such as servo voltage and dielectric fluid pressure on process performance of kerf width, MRR, surface roughness, cutting rate and over cut have been investigated.

Table I. Chemical composition of Ti-6Al-4V Titanium alloy

C	Fe	Al	O_2	N_2	V	H_2	Ti
0.08	0.22	6.08	0.02	0.05	4.02	0.15	Balance

Table II. Test Conditions

Process Parameter	L1	L2	L3
Servo Voltage (V)	40	50	60
Dielectric fluid pressure (kgf/cm2)	10	11	12

III. RESULTS AND DISCUSSIONS:

A. KERF WIDTH:

Response surface methodology approach is the procedure for determining the relationship between various process parameters with various machining criteria and exploring the effects of these process parameters on the coupled responses [23/20]. Design of Experiments (Three level response surfaces) was used to predict the significant effects and their interactions of the two important Wire EDM machining parameters i.e. servo voltage and dielectric fluid pressure on various response variables such as kerf width, MRR, surface roughness, cutting rate and over cut and these responses were modelled using Design of Experiments (DOE) software (Design Expert 7) by taking two factors, servo voltage and dielectric fluid pressure at three levels i.e. 40, 50, and 60V and 5, 10 and 15 kgf/cm^2 respectively. The optimum values of selected variables were obtained by solving the regression equations and by analyzing the response surface contour plots. Analysis of variance (ANOVA) was used to analyze the experimental data and the relative significance of the machining parameters with respect to the measure of performance was investigated. The analysis of variance based on partial sum of squares is shown in table III.

Table. III Analysis of variance (ANOVA) for Kerf width

Source	Sum of Squares	df	Mean Square	F Value	p-value, Prob>F
Model	0.000293	5	5.85E-05	69.52541	< 0.0001
A-Servo Voltage	0.000181	1	0.000181	215.633	< 0.0001
B-Dielectric Pressure	4.82E-05	1	4.82E-05	57.22493	0.0001
AB	1E-06	1	1E-06	1.188061	0.3118
A^2	5.68E-05	1	5.68E-05	67.46879	< 0.0001
B^2	5.99E-07	1	5.99E-07	0.711081	0.4270

The Model F-value of 69.53 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case servo voltage, dielectric pressure and square of servo voltage are significant model terms. The "Pred R-Squared" of 0.8053 is in reasonable agreement with the "Adj R-Squared" of 0.9662. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 26.740 indicates an adequate signal. This model can be used to navigate the design space. After eliminating the non significant terms, the final response equation for kerf width is found as follows:

$$\text{Kerf Width} = 0.236057 + 0.004984 * SV - 0.00031 * WP + 1E\text{-}05 * SV * WP - 4.5E\text{-}05 * SV^2 + 1.86E\text{-}05 * WP^2$$

The experimental results revels that the kerf width increases as the servo voltage and dielectric fluid pressure increases. However for extended servo voltage and dielectric fluid pressure the kerf width reduced, as shown in Fig. 1 and we observed the same through design expert response surface plot, as shown in Fig. 2.

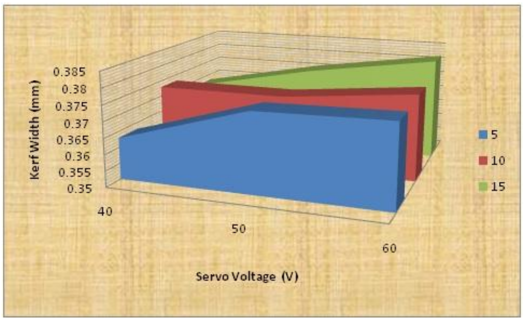

Fig. 1 Servo Voltage and Dielectric Pressure Vs. Kerf width

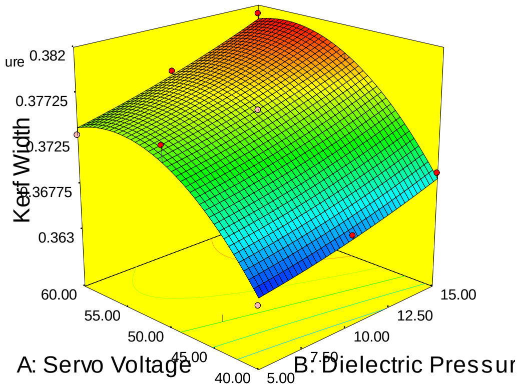

Fig. 2 Design Expert Response surface plot for Kerf width

B. MATERIAL REMOVAL RATE:

The material removal rate is calculated by taking the over cut into consideration as; Material Removal Rate (mm^3/min) = **CS x K_w x t**, Where 'CS' is the cutting speed in (mm/min), 'Kw' is the kerf width in (mm) and't' is the work piece thickness in (mm). Analysis of variance (ANOVA) was used to analyze the experimental data and the relative significance of the machining parameters with respect to the MRR was investigated. The analysis of variance based on partial sum of squares for material removal rate is shown in table IV.

Table. IV Analysis of variance (ANOVA) for MRR

Source	Sum of Squares	df	Mean Square	F Value	p-value, Prob>F
Model	0.238872	5	0.047774	5.708676	0.0205
A-Servo Voltage	0.080968	1	0.080968	9.675085	0.0171
B-Dielectric Pressure	0.070417	1	0.070417	8.41426	0.0230
AB	0.035532	1	0.035532	4.245836	0.0783
A^2	0.051825	1	0.051825	6.192713	0.0417
B^2	0.009458	1	0.009458	1.1301	0.3230

The Model F-value of 5.71 implies the model is significant. There is only a 2.05% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case servo voltage, dielectric pressure and square of servo voltage are significant model terms. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 9.076 indicates an adequate signal.

This model can be used to navigate the design space. After eliminating the non significant terms, the final response equation for material removal rate (MRR) is found as follows:

$$MRR = 6.045362 - 0.14422 * SV - 0.02577 * WP + 0.001885 * SV * WP + 0.00137 * SV^2 - 0.00234 * WP^2$$

The experimental results revels that the material removal rate is high at low and high values of servo voltage and dielectric fluid pressure and moderate at medium values of servo voltage and dielectric fluid pressure, as shown in Fig. 3 and we observed the same through design expert response surface plot for material removal rate as shown in Fig. 4.

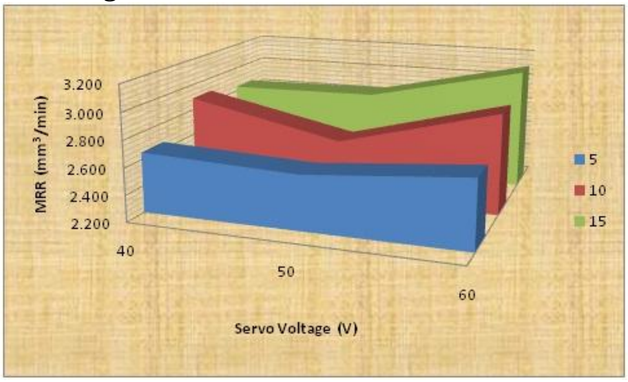

Fig. 3 Servo Voltage and Dielectric Pressure Vs. Material Removal Rate

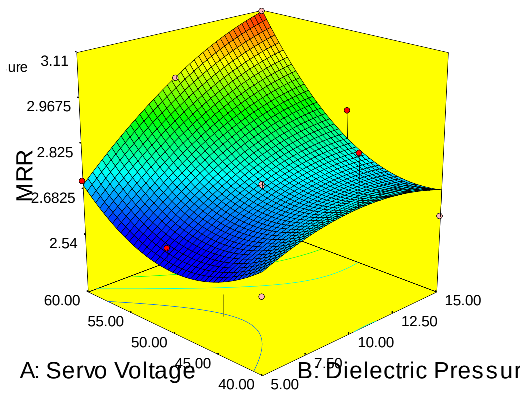

Fig. 4 Design Expert Response surface plot for Material Removal Rate

C. SURFACE ROUGHNESS:

The surface roughness was measured with S1500DX/SD2 model SURFCOM with sensitivity of ½ Max and at magnification of X10000. Analysis of variance (ANOVA) was used to analyze the experimental data and the relative significance of the machining parameters with respect to the surface roughness was investigated. The analysis of variance based on partial sum of squares for surface roughness is shown in table V.

Table. V Analysis of variance (ANOVA) for Surface roughness

Source	Sum of Squares	df	Mean Square	F Value	p-value, Prob>F
Model	0.764425	5	0.152885	4.791911	0.0319
A-Servo Voltage	0.0017	1	0.0017	0.053289	0.8240
B-Dielectric Pressure	0.00236	1	0.00236	0.073975	0.7935
AB	0.00483	1	0.00483	0.151396	0.7088
A^2	0.12565	1	0.12565	3.938275	0.0876
B^2	0.358526	1	0.358526	11.23736	0.0122

The Model F-value of 4.79 implies the model is significant. There is only a 3.19% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case servo voltage, dielectric pressure and square of dielectric pressure are significant model terms. A ratio greater than 4 is desirable. The ratio of 5.315 indicates an adequate signal. This model can be used to navigate the design space. After eliminating the non significant terms, the final response equation for Surface roughness is as follows:

Surface Roughness=9.894178-0.22193*SV-0.32695*WP+0.000695*SV*WP+0.002133*SV^2 +0.014412*WP^2

Form the experimental results, it is observed that the surface roughness is too high at low and high values of servo voltage and dielectric pressure and the surface roughness is moderate at medium values of servo voltage and dielectric pressure, as shown in Fig. 5 and we observed the same through design expert response surface plot for Surface roughness, as shown in Fig. 6.

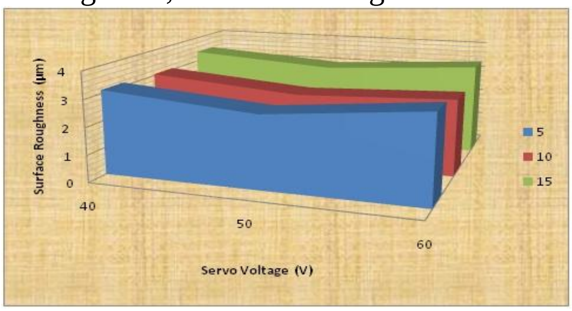

Fig. 5 Servo Voltage and Dielectric Pressure Vs. Surface roughness

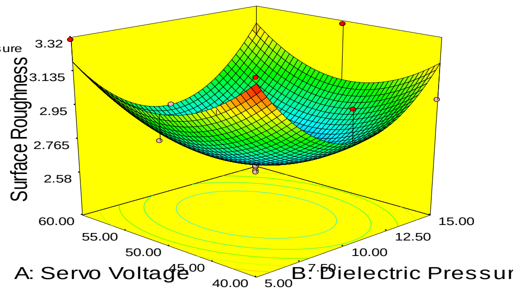

Fig. 6 Design Expert Response surface plot for Surface roughness

D. CUTTING RATE:

The cutting speed has been directly noted from the parameters display of Wire Electrical Discharge Machine. Analysis of variance (ANOVA) was used to analyze the experimental data and the relative significance of the machining parameters with respect to the cutting rate was investigated. The analysis of variance based on partial sum of squares for cutting rate is shown in table VI.

Table. VI Analysis of variance (ANOVA) for Cutting Rate

Source	Sum of Squares	df	Mean Square	F Value	p-value, Prob>F
Model	0.232413	5	0.046483	6.627607	0.0138
A-Servo Voltage	0.0024	1	0.0024	0.342198	0.5769
B-Dielectric Pressure	0.060601	1	0.060601	8.640717	0.0217
AB	0.017292	1	0.017292	2.465573	0.1604
A^2	0.142851	1	0.142851	20.36799	0.0028
B^2	0.003022	1	0.003022	0.430822	0.5326

The Model F-value of 6.63 implies the model is significant. There is only a 1.38% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case servo voltage, dielectric pressure and square of servo voltage are significant model terms. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 9.037 indicates an adequate signal.
This model can be used to navigate the design space. After eliminating the non significant terms, the final response equation for Cutting rate is found as follows:

$$\text{Cutting Rate} = 9.495093 - 0.23857*SV - 0.01919*WP + 0.001315*SV*WP + 0.002274*SV^2 - 0.00132*WP^2$$

From the experimental results it is observed that the cutting rate is high at lower and higher values of servo voltage and cutting rate is moderate at medium values of servo voltage. But the cutting speed increases as the dielectric pressure increases, as shown in Fig. 7 and we observed the same through design expert response surface plot for cutting rate, as shown in Fig. 8. Further, it is observed that the server voltage have more significant effect on cutting rate. Farnaz Nourbakhsh and K. P. Rajurkar et al., are also proved the same (24).

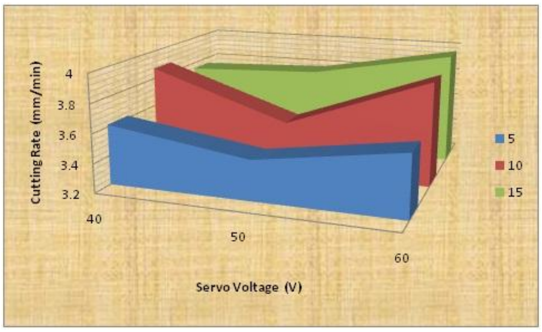

Fig. 7 Servo Voltage and Dielectric Pressure Vs. Cutting rate

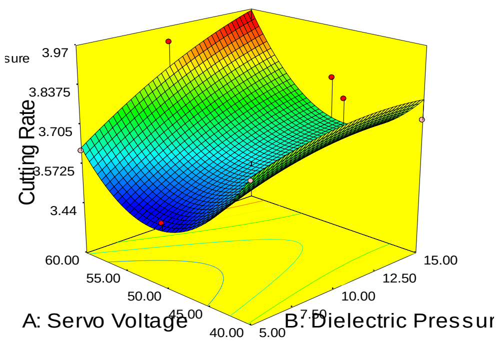

Fig. 8 Design Expert Response surface plot for Cutting rate

E. OVER CUT:

The difference between the kerf width and diameter of wire is termed as 'over cut'. Over cut has been determined with the difference of kerf width and wire diameter. Analysis of variance (ANOVA) was used to analyze the experimental data and the relative significance of the machining parameters with respect to the over cut was investigated. The analysis of variance based on partial sum of squares for over cut is shown in table VII.

Table VII Analysis of variance (ANOVA) for over cut

Source	Sum of Squares	df	Mean Square	F Value	p-value, Prob>F
Model	0.000293	5	5.85E-05	69.52541	< 0.0001
A-Servo Voltage	0.000182	1	0.000182	215.633	< 0.0001
B-Dielectric Pressure	4.82E-05	1	4.82E-05	57.22493	0.0001
AB	0.000001	1	0.000001	1.188061	0.3118
A^2	5.68E-05	1	5.68E-05	67.46879	< 0.0001
B^2	5.99E-07	1	5.99E-07	0.711081	0.4270

The Model F-value of 69.53 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case servo voltage, dielectric pressure and square of servo voltage are significant model terms. The "Pred R-Squared" of 0.8053 is in reasonable agreement with the "Adj R-Squared" of 0.9662. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 26.740 indicates an adequate signal. This model can be used to navigate the design space. After eliminating the non significant terms, the final response equation for over cut is found as follows:

$$\text{Over Cut} = -0.06394+0.004984*SV-0.00031*WP+0.00001*SV*WP-4.5E\text{-}05*SV^2 +1.86E\text{-}05*WP^2$$

The reason that the cutting width is greater than the width of the wire is because sparking occurs from the sides of the wire to the work piece, causing erosion. The experimental results reveal that the overcut increases as the servo voltage and dielectric pressure increases. However, for extended servo voltage the over cut decreases, as shown in Fig. 9. We observed the same through design expert response surface plot, as shown in Fig. 10.

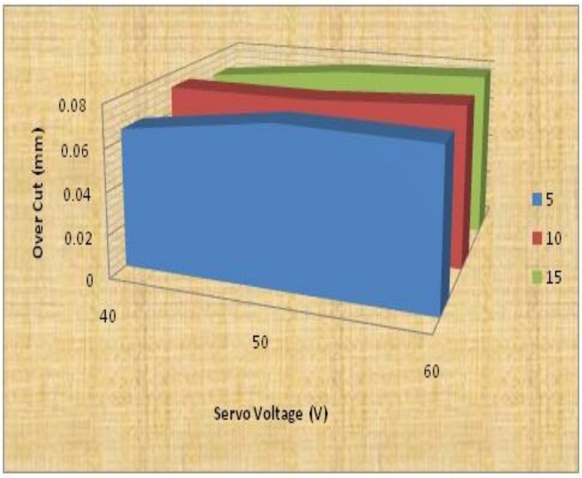

Fig.9 Servo Voltage and Dielectric Pressure Vs Over cut

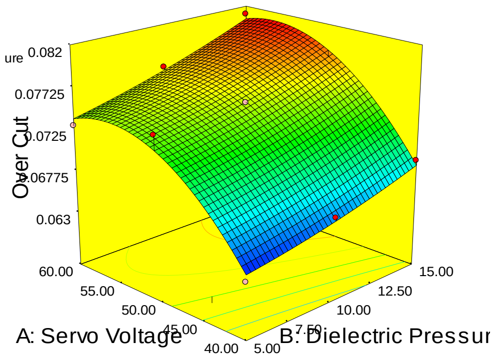

Fig. 10 Design Expert Response surface plot for over cut

IV. CONCLUSIONS:

In this study, the influence of wire EDM parameters such as servo voltage and dielectric pressure on kerf width, MRR, surface roughness, cutting rate and over cut has been studied. Based on the experimental results and design of experiments (RSM) the following conclusions were made:

1. It is observed that the kerf width increases as the servo voltage and dielectric fluid pressure increases. However for extended servo voltage and dielectric fluid pressure the kerf width reduced. The MRR and Surface roughness are high at low and high values of servo voltage and dielectric pressure and moderate at medium values of servo voltage and dielectric fluid pressure.
2. It is observed that the cutting rate is high at lower and higher values of servo voltage and moderate at medium values of servo voltage. But the cutting speed increases as the dielectric pressure increases. The overcut increases as the servo voltage and dielectric pressure increases. However, for extended servo voltage the over cut decreases.
3. The final response equations were found for kerf width, MRR, surface roughness, cutting rate and over cut and the experiment results were compared with the model equations.

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