International Journal of Scientific Research and Engineering Development-– Volume 4 Issue 1, Jan-Feb 2021

Available at www.ijsred.com

RESEARCH ARTICLE OPEN ACCESS

Experimental Investigation and Development of Mathematical Correlations of Cutting Parameters for Machining Titanium with CNC WEDM

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Abstract

Wire Cut EDM process material Titanium different parameters of machining current, cutting speed, spark gap and Material removal rate will be investigated and best suited values for stable and controlled machining with least wire breakage.In the present work aimed at Experimental Investigation to determining optimal values of machining parameters in the machining of Titanium material of different Thickness using wire cut electric discharge machine. It also aimed at development of mathematical correlations to determine the effect of machining parameters on Current, Cutting speed, Spark gap, and Material Removal Rate investigated and best suited values for stable and controlled machining with least wire breakage. The experiments are conducted on the Titanium material by cutting L and U shapes by varying machining current from a lower value to a higher value in 5 steps. The cutting speed is noted down from machine display and surface finish is measured on using Tally surf.The spark gap is calculated from cutting width. The optimum values of machining current, cutting speed, spark gap, surface roughness and MRR are used for plotting the curves and best fit curve is selected using the Origin 8.0,software.The mathematical relation is for best fit curve and statistically analysis is performed to find fitness of the curve. The maximum error obtained from calculated values and experimental values are found to be less than 4 %.From these we, conclude that Regression Statistical analysis gives better prediction values with less error%.

Keywords*:* WEDM, Cutting speed, MRR, Spark gap, surface roughness, Mathematical correlations, Regression Analysis

1.Introduction to WEDM

Wire Electrical Discharge Machining (Wire EDM), is a machining process in which a wire carrying electrical charge is used to cut the hard materials. The two major components required for the wire EDM machine the wire electrode and the degree of precision and the amount of material that can be removed. In order to cut complicated or intricate designs with greater precision and 3D profiles, Wire EDM machines requires not only the traditional X and Y axis but also the U and V axis for a standard 4-axis tooling but can also have a 5th axis.

In Wire EDM the material being machined is commonly inserted in a fixture and pumped with dielectric fluid, typically a deionized water of rated conductivity. Electrical currents passing through metals increase internal temperatures and metal tooled in higher heat environments becomes less rigid and have a loss of tensile strength. Tooling in water is to remove the chips and debris from the work area, in turn decreasing the amount of scoring of the finished product, to decrease the overall heat affected zone and to extend the life of the wire electrode.

1.1Operational features of WEDM system:

Wire EDM system involve various machining components and sub-components which actuate the various stages of operation of the system commencing from the initial stage of spark gap generation, through the variousparametric settings leading to the final stage of finishing the products. Thus, the system reflects the technology of process control to be somewhat complex and critically intricate. Hence, a through study of the operational technology of the process is highly needed for a better understanding of the different machining parameters and related control terminologies which play vital role in the integration of the system components.

The WEDM system comprises of a main work-table called X-Y table on which the work piece is clamped, an auxiliary table called U-V table and the wire feed drive subsystem. The main table moves along the X and Y axes, in steps of usually 1µm by means of pulse motor set on the X and Y axes where as the U-V table moves, in steps of usually 1µm by means of pulse motor set along U and V axes which are parallel to X and Y axes respectively. To achieve high dimensional accuracy of product WEDM uses a low friction slide drive. The slides for movement of X and Y axes are mounted on precision needle-cages in pre tensioned hardened guide ways. The guide ways are suitably protected from dust by using bellows and the slide drive is obtained by either a closed loop DC motor drive or a DC stepper motor drive. The DC stepper motor of low inertia and high resolution driven by a specially controlled translator provides the step sizes of 1µm accurately. The DC servo motor drives, using SCR control or pulse width modulation control with the high resolution encoder feedback, provide accurate positioning repeatability of usually 2µm.

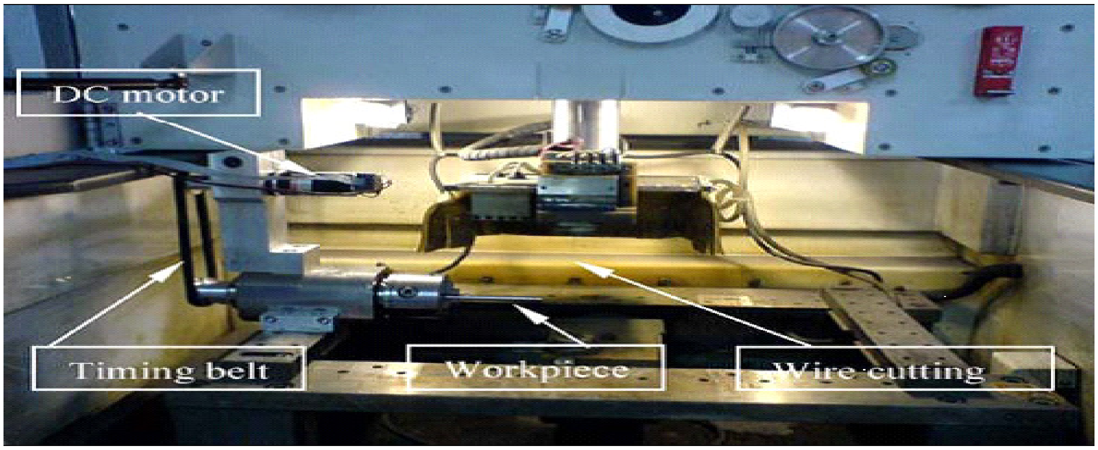


Figure: Wire-cut EDM machine table

2.Review of Past Research:

Liao and Yu [1] performed experiments to determine the specific discharge energy (SDE) i.e. the energy required to remove a unit volume of material. It is reported that SDE is constant for a specific material. A quantitative relationship between machining characteristics- MRR, efficiency of MRR and machining parameters is derived. The results can be applied for determining the settings of machining parameters of different materials.

Han et al. [2] analyzed the effect of discharge current on machined surface morphology. The surface morphology is studied under various pulse durations, caused by pulse energy generated through discharge current. The short pulses and long pulses having 0.67 and 0.60 mJ of pulse energy caused similar size craters giving rise to similar surface. The authors concluded that the surface morphology depends on pulse energy in turn discharge current only.*Sanchez et al.* [3] studied the errors occurred in cornerswhile machining AISI D2 steel of 50mm and 100mm thickness with WEDM using 0.25mm diameter brass wire. The authors analyzed the reasons for errors in corner cutting as the friction between wire guides, dielectric flushing, wire deformation and work piece thickness. The authors optimized the parameters for better accuracy and suggested multiple trim cuts.

Han et al.[4] aimed to simulate the relative motion between the wire electrode path and NC path of the rough cutting in the WEDM. The experimental results and simulation results are compared and found to have consistency. The authors suggested finding the corner value prediction by simulation and accordingly path program can be developed. *Puri and Bhattacharyya* [5] employed L27 orthogonal array based on Taguchi method to evaluate the main influencing factors that affect the cutting speed, surface roughness and geometrical accuracy due to wire lag. The authors machined hardened and annealed M2 type die steel of 28mm thickness with 0.25mm wire on Supercut 734 model machine and developed a model to minimize wire tool vibration.

Mu-Tian Yan, Pin-Hsum Huang (6) developed a closed-loop wire tension control system for a wire-EDM machine is presented to improve the machining accuracy. Dynamic models of the wire feed control apparatus and wire tension control apparatus are derived to analyze and design the control system. PI controller and one-step-ahead adaptive controller are employed to investigate the dynamic performance of the closed-loop wire tension control system. In order to reduce the vibration of wire tension during wire feeding, dynamic absorbers are added to the idle rollers of wire transportation mechanism. Experimental results not only demonstrate that the developed control system with dynamic absorbers can obtain fast transient response and small steady-state error than an open-loop control system, they also indicate that the geometrical contour error of corner cutting is reduced with approximately 50% and the vertical straightness of a work piece can be improved significantly.

Kanlayasiri and Boonmung[7] optimized the parameters effecting surface finish, for machining DC53 tool steel of 27mm thick with Sodick A280 model machine using 0.25mm diameter wire by designing the experiments with Taguchi method. The authors developed mathematical model for optimization to predict surface roughness values and error analysis is applied. The developed model is showing a maximum error of 30%.

Levy and Maggi [8] compared the machinability of ten different steel grades with WEDM, considering the heat affected zone and micro hardness. It was observed that the steel manufacturing method had great influence on final accuracy than chemical composition. The authors recommended the trim cut technique to avoid heat affected zone.*ShajanKuriakose and Shunmugam* [9] designed the experiments using Taguchi L18 array and conducted on Ti6A14V material with 0.25mm diameter brass coated wire under preset conditions, 80 V, 8-12 A machining current, 4-8μs pulse time. The authors observed the formation of oxides due to high temperature generation, macro and micro level stresses induced during the process. The authors revealed that when the time between two pulses is larger, non uniform cooling and heating occurs. The authors suggested coated wire as electrode from metallurgical point of view.

3.EXPERIMENTATION

3.1 Methodology:

It is proposed to study the electrical properties like discharge current gap, voltage and power required and their effects on cutting criterion such as cutting speed, spark gap and MRR for hard materials like titanium, to cut/remove material or obtain desired shape to optimize the cutting parameters. Analysis is based on various thicknesses of titanium material. The process parameters like current, cutting speed, spark gap, MRR, surface roughness power etc. The table as shown and prepared as per data obtained for different thickness material experimental conducted. It is hoped that the results will be useful in setting the machine for quality cutting as well as to program the cutter off set and to estimate the machining time in turn cost.The design experiment the machining parameters are adjusted for optimize process parameters for efficient metal removal/cut from material the machining parameters to adjusted a given below.

Figure: 3.1 Ultra cut CNC wire cut EDM machine

4.Measurements: Surface roughness values of work piece/job was measured by tally surf instrument is used the exact values of surface roughness valves taken the stylus is passing through over work piece through which reading to be taken from display screen

Figure: 4.1 Tally surf surface roughness measuring instrument

- **Results and Discussions:**

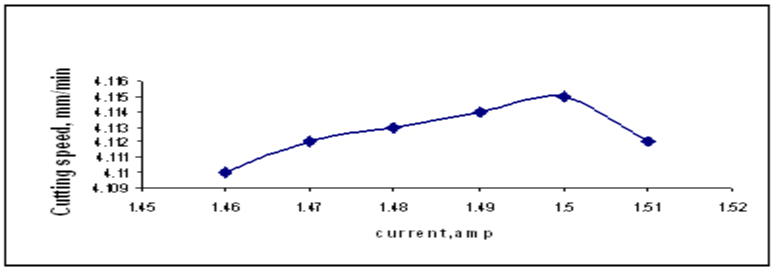
- The Titanium specimens of 20mm x 40mm size on thicknesses 5, 7.5, 10, 12.5, 15, 17.5,20,25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75 and 80, 85,90mm are prepared. The experiments are conducted on the work piece of every thickness by cutting L shape and U shape by varying the machining current from a lower value to a value where the machining is in consistent in 5 steps. At every machining current, I value the machining criteria is measured. The machining current, I value at which the machining is consistent with continuous cutting, better finish with least wire rupture is selected as optimal. The cutting speed is noted from the machine display, surface finish is measured on cut using Talysurf.The spark gap is calculated from cutting width.The Cutting width **Cw= d+2 x Sg**, where d is the wire diameter and Sg is the Spark gap. The MRR is calculated as**, MRR = T x Cw x Cs** where Cs is the cutting speed, mm/min and T is work piece thickness, mm. The optimum values of machining current, cutting speed, spark gap surface roughness and MRR for every thickness are used for plotting the curves and best fit curve is selected using the software. The mathematical relation is generated for this best fit curve and statistical analysis is performed to find the fitness of the curve. Regression analysis done for Effect of current on cutting speed, spark gap surface roughness, MRR and Effect of thickness on current, cutting speed, spark gap, MRR. As the current increases 1.5amp to 2.20amp and cutting speed increases maximum to 4.12amp regression analysis done for experimental data R-Sq-99.8%.error is 0.2%.The Regression values always equal to 1 then the curve becomes best fit curve. As the current increases 1.5amp to 2.20amp and spark gap increases 42.00µm to 60µm.from Regression analysis R-Sq-98.8% error is 1.2%.As the current increases surface roughness increases to 0.50µm to 0.75µm from regression analysis R-Sq-97.6% error is 2.4%.As the current increases MRR increase to 6.864 mm^3/min to 94.29 mm^3/min for experimental data regression analysis is R-sq-99.0% error is 1%.The validation of discharge current on job thickness, on the machining criteria such as cutting speed, spark gap, material removal rate Regression analysis done for experimental data.The maximum error obtained from calculated values and experimental values are found to be less than 4%.

5.Parametric analysis based on experimental data:

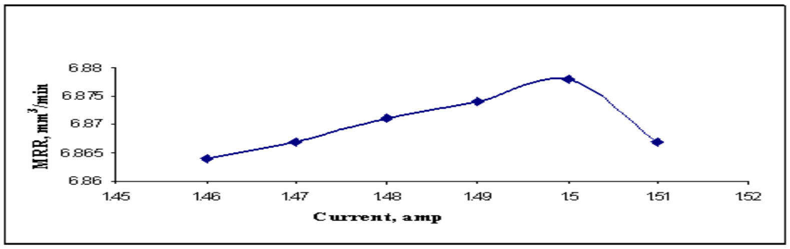
Table 5.1 Parameters obtained for 5mmthickness

S.No	Current Amp	Cutting speed,mm/min	Spark gapµm	Ra, µm	MRR,mm^3/min
1	1.46	4.110	42.00	0.50	6.864
2	1.47	4.112	42.00	0.50	6.867
3	1.48	4.113	42.05	0.49	6.871
4	1.49	4.114	42.10	0.47	6.878
5	1.50	4.115	42.15	0.46	6.875
6	1.51	4.112	42.00	0.50	6.867

The experiment is performed for **5mm** thickness current varies **1.46 Amp to 1.50Amp** and **cutting speed varies4.110 mm/min to 4.112mm/min** Graph 5.1 gives the effect of machining current on cutting speed for machining 5mm thick Titanium work piece. The plot shows an increasing trend in cutting speed with increase in current. As the current increases, energy input increases, causing raise in cutting speed. But beyond 1.5 amp current, the machining is observed to be erratic and wire getting ruptured causing decrement in cutting speed. The maximum cutting speed of 4.115mm/min is obtained with minimum wire rupture. The current at this cutting speed is considered as optimum value.



Graph: 5.1 Effect of machining current on cutting speed for 5 mm thickness



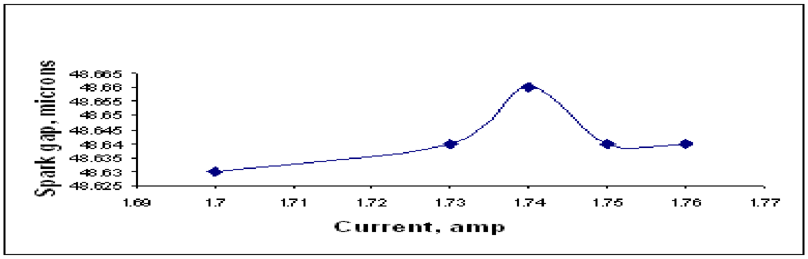
Graph:5.2Effect of Current on MRR for 5 mm thickness

Graph 5.5 gives the variation of machining current on cutting speed. The machining current has been varied from 1.7amp to 1.76amp in 0.01amp steps. The plot shows an increasing trend in cutting speed with increase in machining current till 1.75amp then suddenly fall. At 1.76amp current the machining is getting interrupted with large toll wear and wire brake edge. This may be due to avalanche of high energy sparks striking back the wire, breaking it. So 1.75amp is considered to be the optimum current value with highest cutting speed for machining 30mm thick titanium work piece. The cutting speed for 30mm thick job is lower than that of 5mm thick.

Compare with 5mm thickness Cutting Speed 4.112mm/min decreases to 3.75mm/min for 30mm thickness.

5.Effect of machining current on Spark gap for 30 mm thickness:

The experiment is conducted for **30mm** thickness **current** varies **1.70 Amp to 1.77Amp**and **spark gap** varies **48.63µm to 48.65µm.**Graph 5.6 shows the variation of spark gap with current. The spark gap is observed to be increasing with a small variation. The profile of the plot is similar to that of the plot obtained for 5mm thick job. The spark gap value is to be adopted which is obtained at the optimum current value 1.75amps.Compare with 5mm thickness 42µm spark gap increases to 48.65µm for 30mm thickness.



Graph: 5.3 Effect of machining current on Spark gap for 30 mm thickness

6.Mathematical Modeling:

Mathematical model was developed in the regression analysis using MINITAB Statistical. The statistic toolbox provides us four models in regression analysis.

- Linear: $Y = \beta0 + \beta1x1 + \beta2x2$ (5)
- Interactions: $Y = \beta0 + \beta1x1 + \beta2x2 + \beta3x1x2$ (6)
- Pure quadratic: $Y = \beta0 + \beta1x1 + \beta2x2 + \beta3x1^2 + \beta4x2^2$ (7)
- Full quadratic: $Y = \beta0 + \beta1x1 + \beta2x2 + \beta3x1x2 + \beta4x1^2 + \beta5x2^2$ (8)
- Here a response variable Y is modeled as a combination of constant, linear, interaction and quadratic terms formed from two predictor variables x1& x2.

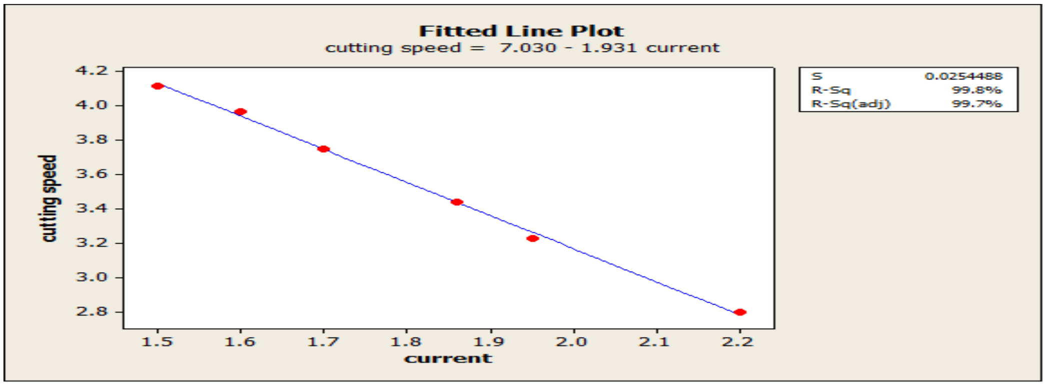
- Given data on x1, x2 and Y, regression estimates the model parameters.

6.1Regression analysis results for 5, 15, 30, 45, 60, 90mm thickness:

S.No	Thickenss, mm	Current, amp	Cutting speed, mm/min	Surface roughness, Ra	Spark gap mm/1000	MRR, mm3/ min
1	5	1.50	4.12	0.50	42.00	6.860
2	15	1.60	3.97	0.55	44.20	20.50
3	30	1.70	3.75	0.61	48.66	39.10
4	45	1.86	3.44	0.64	51.10	54.83
5	60	1.95	3.23	0.67	54.51	69.58
6	90	2.20	2.80	0.75	60.00	94.29

Table 6.1: Experimental data for 5mm, 15mm, 30mm, 45mm, 60mm, 90mm Machining Titanium

6.1.1 Effect of current on cutting speed 5,15,30,45,60,90mm thickness:



6.1 Effect of current on cutting speed

The regression equation is
cutting speed = 7.030 - 1.931 current
S = 0.0254488 R-Sq = 99.8% R-Sq(adj) = 99.7%

Analysis of Variance ANOVA:

Source	DF	SS	MS	F	P
Regression	1	1.21569	1.21569	1877.10	0.000
Error	4	0.00259	0.00065		
Total	5	1.21828			

The Graph 6.1 Cutting Speed values are required the experimental data is compared with statistical analysis. As the current increases, energy input increases causing raise in cutting speed. According to Regression Analysis the above graph is drawn between current cutting speed for the data R-sq-99.8%.The Regression values always equal to 1 then the curve becomes best fit curve.

6.2Equations Formed from Regression Analysis:

Statistical Analysis, Study on effect of WEDM parameters on machining criteria and development of Regression Equations.

6.2 Optimized parameters for 5 to 90 mm thickness

S.No	Thickness, mm	Currentamp	Cuttingspeed, mm/min	Surface roughness, Raμm	Spark gap mm/1000	MRR mm^3/min
1	5	1.50	4.12	0.50	42.00	6.860
2	7.5	1.53	4.05	0.52	42.70	10.180
3	10	1.57	4.01	0.54	43.48	13.923
4	15	1.60	3.97	0.55	44.20	20.150
5	20	1.65	3.91	0.58	45.57	23.43
6	30	1.74	3.75	0.61	48.66	39.10
7	40	1.83	3.54	0.64	51.20	49.80
8	45	1.86	3.44	0.64	51.10	54.830
9	55	1.92	3.28	0.66	53.70	64.475
10	60	1.95	3.23	0.67	54.51	69.58
11	70	2.00	3.14	0.68	56.00	79.62
12	75	2.05	3.05	0.69	57.03	83.28
13	80	2.11	2.97	0.71	58.04	86.98
14	85	2.15	2.89	0.73	58.98	90.39
15	90	2.20	2.83	0.75	60.00	94.29

6.2.1 Effect of Discharge Current on Thickness:

The variation in the discharge current with the increase in work piece thickness is obtained and shown in Graph.6.5 shows For a specified set of machining conditions it is observed that with increase, for **5mmm Thickness, Current 1.50amp** the required machining current also increases for **90mm Thickness, Current 2.20amp.** This is attributed to the high amount of energy required for high thickness job in which machining is possible only by increasing the current. This plot is useful to extract suitable minimum discharge current required for machining of any thickness Titanium work piece with in the machine working range

Polynomial Regression Analysis:

The regression equation is

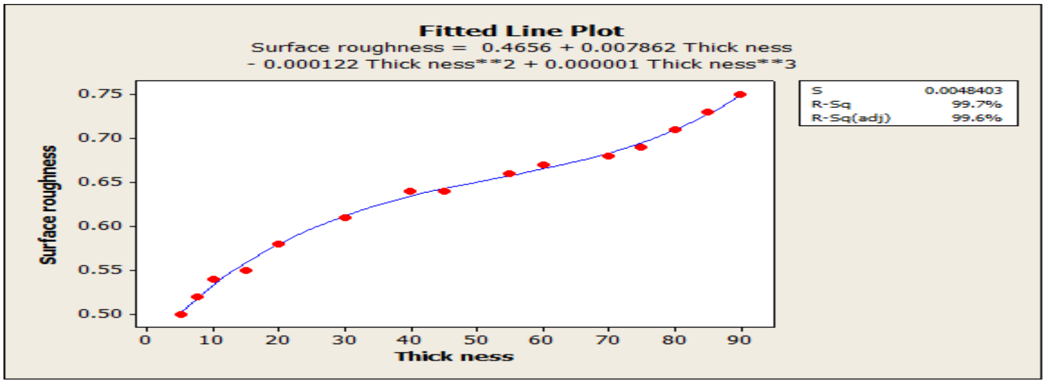
Cutting speed = 4.183 - 0.01443 Thick ness - 0.000054 Thick ness**2
+ 0.000001 Thick ness**3

S = 0.0290821 R-Sq = 99.7% R-Sq(adj) = 99.6%

```
Analysis of Variance
Source      DF     SS        MS        F     P
Regression   3  2.94287  0.980957  1159.84  0.000
Error       11  0.00930  0.000846
Total       14  2.95217
```

6.2.3 Effect of surface roughness on Thickness:

The Graph 6.7 shows Surface Roughness values are required the experimental data is compared with statistical analysis. The Surface Roughness Increases in current, energy input increases, number of high energy sparks increases, causing material removal with more craters of lower depth, gives rises to smooth finish.



6.3 Effect of surface roughness on Thickness

Polynomial Regression Analysis:

```
The regression equation is
Surface roughness = 0.4656 + 0.007862 Thick ness - 0.000122 Thick ness**2
                    + 0.000001 Thick ness**3
S = 0.00484032   R-Sq = 99.7%   R-Sq(adj) = 99.6%
Analysis of Variance
Source      DF      SS          MS        F      P
Regression   3  0.0857156  0.0285719  1219.53  0.000
Error       11  0.0002577  0.0000234
Total       14  0.0859733
```

Polynomial Regression Analysis:

```
The regression equation is
MRR = 0.479 + 1.299 Thick ness - 0.001280 Thick ness**2 - 0.000018 Thick ness**3
S = 0.919984   R-Sq = 99.9%   R-Sq(adj) = 99.9%
Analysis of Variance
Source      DF     SS       MS        F        P
Regression   3   13925.7   4641.89   5484.46   0.000
Error       11     9.3       0.85
Total       14   13935.0
```

6.4 Validation using Regression analysis:

The experimental results are compared with the regression analysis for the validation and the error percentage is calculated.

Table 6.3: Validation of Regression Results with the Experimental Results

	Thickness (t)	Current		Cutting speed		Surface roughness		Spark gap		Metal Removal Rate	
		Regression	Experiment value	Regression	Experiment	Regression	Experiment	Regression	Experiment	Regression	Experiment
	12.5	1.584249703	1.6	3.996140625	3.98	0.546765625	0.55	44.00445313	44	16.48134375	16.815
	17.5	1.632249185	1.62	3.919296875	3.94	0.571181875	0.56	45.34220938	44.9	22.72303125	23.43
	25	1.689997625	1.7	3.804125	3.85	0.601525	0.6	47.215625	47	31.87275	33.16
	35	1.740393483	1.8	3.654675	3.66	0.634195	0.62	49.500275	50.5	43.60425	44.903
	50	1.758981	1.9	3.4515	3.35	0.6787	0.65	52.58	53	59.979	59.63
	65	1.709158257	1.98	3.291525	3.17	0.735805	0.68	55.405025	55.3	74.56275	74.31

- Comparison of predicted current, cutting speed, surface roughness, spark gap, MRR with experimental results in all tested cases indicate that the error is less than 4% for regression model.
- The average error percentage for all the predicted values in the regression model is in the is 0.67%,

7.1Conclusions:

The influence of parameters, like discharge current, job thickness, on the machining criteria such as cutting speed, spark gap, surface finish, material removal rate are determined. Titanium material of different thicknesses is machined for determining the optimum values of machining parameters have been studied the effect of parameters on current, cutting speed, spark gap and Material removal rate investigated and best suited values for stable and controlled machining with least wire breakage. Variations and effect of cutting speed, Spark gap, surface roughness, MRR with respect to machining current. Regression Analysis are used for predicting current, cutting speed, spark gap, Surface roughness, MRR.

- The Mathematical correlations are developed for Regression Analysis.
- The developed prediction system is found to be capable of accurate process parameters prediction.
- A regression model is also developed by using the experimental data. The experimental results are compared to the regression models.
- As it has been anticipated, the regression models provided better prediction capabilities . because they generally offer the ability to model more complex non-linearities
- Comparison of predicted current, cutting speed, spark gap, surface roughness and MRR with experimental results in all testing cases indicate that the error is less than 4% for regression model.
- The average error percentage for all the predicted values in the regression model is 0.67%.

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