Mechanics, Materials Science & Engineering, May 2017 – ISSN 2412-5954

Multi-Response Optimization and Regression Analysis of Process Parameters for Wire-EDMed HCHCr Steel Using Taguchi's Technique

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DOI **10.2412/mmse.59.23.582** provided by Seo4U.link

Keywords: wire EDM, HCHCr, copper, Taguchi, ANOVA, pulse-on, pulse-off, hardness.

ABSTRACT. In this study, effect of machining process parameters viz. pulse-on time, pulse-off time, current and servo-voltage for machining High Carbon High Chromium Steel (HCHCr) using copper electrode in wire EDM was investigated. High Carbon High Chromium Steel is a difficult to machine alloy, which has many applications in low temperature manufacturing, and copper is chosen as electrode as it has good electrical conductivity and most frequently used electrode all over the world. Tool making culture of copper has made many shops in Europe and Japan to used copper electrode. Experiments were conducted according to Taguchi's technique by varying the machining process parameters at three levels. Taguchi's method based on L_9 orthogonal array was followed and number of experiments was limited to 9. Experimental cost and time consumption was reduced by following this statistical technique. Targeted output parameters are Material Removal Rate (MRR), Vickers Hardness (HV) and Surface Roughness (SR). Analysis of Variance (ANOVA) and Regression Analysis was performed using Minitab 17 software to optimize the parameters and draw relationship between input and output process parameters. Regression models were developed relating input and output parameters. It was observed that most influential factor for MRR, Hardness and SR are T_{on}, T_{off} and SV.

Introduction. High Carbon High Chromium (HCHCr) steel is a type of tool steel which comes under one of the three series of cold work group. As the name of the group indicates, these steels are used for cutting or forming materials at low temperatures. Comparatively more alloying elements are used in this type of steels and surface hardness is also high. This has applications in thread rolling dies, punches, dies, reamers, finishing rolls for tire mills etc., This material has low machinability comparing to other steels and so this material was chosen in this study to machine using wire EDM [1-3].

Wire Electrical Discharge Machining (wEDM) is one of the indispensable machining techniques for making complicated shapes on difficult to machine metals with low residual stresses and good surface finish [4]. This is particularly used for die materials which require high strength and hardness as well as good wear resistance. It does not require any special tool or technique and the process time is also less comparing to conventional manufacturing process. A conductive wire acts as an electrode and material is eroded from the work piece by series of discrete sparks between the work piece and wire electrode separated by a thin film of dielectric fluid. Dielectric fluid flashes away the eroded material and it also acts as coolant [5]. Because of its less cutting forces, its application has been extended to machine metal foams used in heat exchangers and slicing silicon wafers used in solar cells and microelectronic components [6-9]. In this study, HCHCr was machined using wire EDM to study the process parameters for this material.

An important aspect while machining using wire EDM is the selection of electrode material. There are various conductive materials that can be used as electrodes but the more frequently used electrode material copper is used in this study. Copper became the metallic electrode material of choice with development of the transistorized and pulse-type power supplies. Shops in Europe and Japan prefer to use copper as electrode material due to its tool making culture [10].

The Taguchi method, a statistical and efficient technique for product design and optimization was used to achieve the off-line quality control [11-12]. As the most reliable step in the Taguchi approach, the parameter design emphasizes on obtaining the optimum combination of parameters to improve a quality characteristic with low variability [13-14]. Taguchi method was developed on orthogonal array (OA) concept and experiments were also designed using the same concept. Using Design of Experiments (DOE) in Minitab software, an L_9 standard Orthogonal Array was adopted in this study. In comparison with full factorial design method, Orthogonal Array is efficient and cost saving due to small number of experimental runs. Further regression analysis was conducted and regression equations were developed for the parameters.

Experimental Method.

The workpiece material, electrode wire and machine used to carry out the experiments are described below. Design factors and response variable as well as methodology implemented for the experimentation is also outlined.

Material and Equipment used.

The wire EDM used to carry out the experiments was CNC Sprint Cut 734 (Electranica Sprint Cut 734) from Electrionica Ltd., Pune (Fig 1). Dielectric fluid used in this machine is de-ionized water and copper wire of diameter 0.25 mm is taken as electrode material. HCHCr steel substrates of dimension 100 x 50 x 10 mm were considered for machining. Vickers Hardness Tester with diamond indenter and Surface-SJ 301 surface roughness tester made by Mitutoyo Company were used.

Fig. 1. Wire cut CNC.

Experimental Design.

Taguchi method based on orthogonal array was used to design experiments in this study. The process parameters were selected depending upon machine, cutting tool and work piece capability. The input process parameters taken in this experiment are pulse-on time (T_{on}), pulse-off time (T_{on}), current (I_p) and servo voltage (SV) as shown in Table 1.

Table 1. Input process parameters of Wired EDM.

S.NO.	PROCESS PARAMETERS	LEVEL 1	LEVEL 2	LEVEL 3
1	PULSE TIME ON (T_{ON})	100	105	110
2	PULSE TIME OFF (T_{OFF})	55	59	63
3	PEAK CURRENT (IP)	10	11	12
4	SERVO VOLTAGE (SV)	10	55	90

Experimental Procedure:

The number of experiments was limited to 9 according to L_9 orthogonal array using Taguchi's statistical technique. The experiments were carried out by varying process parameters at three levels. After conducting experiments, the substrates were taken out, dried and measured for Material Removal Rate (mm^3/min), Hardness (HV) and Surface Roughness (µm) were measured. Material Removal Rate (MRR) was calculated using the formula in equation (1).

$$MRR = \frac{V_R}{T_M} \tag{1}$$

where V_R – volume of material removed after machining;

T_M – machining time.

The surface roughness tester is used to measure the roughness on the work piece after machining. This observation helped in finding how the experiment conditions are affecting the surface roughness. Then hardness of the surface was tested using micro hardness tester having Vickers diamond indenter and indenter is pressed into the materials surface with a penetrator and a weight of 1000 gms. The result of applying the load with a penetrator is an indent or permanent deformation of material surface caused by the shape of the indentor. The values obtained for MRR, Surface Roughness and Hardness are shown in Table 2.

Table 2. Experimental readings.

		Actual values				Coded values			MRR	Hardness	Surface roughness
Exp no	T_{on}	T_{off}	I_p	SV	T_{on}	T_{off}	I_p	SV	(mm3/min)	HV	µm
1	100	55	10	10	-1	-1	-1	-1	0.0658	33	2.695
2	100	59	11	55	-1	0	0	0	0.1976	34	3.497
3	100	63	12	90	-1	1	1	1	0.2045	32	3.855
4	105	55	11	90	0	-1	0	1	0.2272	34	3.8
5	105	59	12	10	0	0	1	-1	0.0946	33	2.8
6	105	63	10	55	0	1	-1	0	0.3073	34	3.32
7	110	55	12	55	1	-1	1	0	0.3246	34	3.45
8	110	59	10	90	1	0	-1	1	0.3719	34	3.82
9	110	63	11	10	1	1	0	-1	0.1515	29	3.82

Process optimization.

Process optimization was done by optimizing parameters using MINITAB 17 software. This software optimizes both static and dynamic responses provided but the quality characteristic of static response is limited. This software optimizes by calculating signal to noise ratio which is one of the important parameter in Taguchi Method. The three important concepts under Signal to Noise ratio are Larger-The-Best, Smaller-The-Best and Nominal-The-Best. Among them, Larger the better is taken for MRR and Hardness whereas Smaller the better is taken for Surface Roughness. S/N ratios of MRR, Hardness and surface roughness are calculated using formulae in eqs. (2) and (3) using Minitab 17 software are tabulated in table 3.

(a) **Larger-the-Better**

$$n = -10\ \mathrm{Log}_{10}\ [\text{mean of sum squares of reciprocal of measured data}] \tag{2}$$

(b) **Smaller-the-Better**

$$n = -10\ \mathrm{Log}_{10}\ [\text{mean of sum of squares of measured data}] \tag{3}$$

The S/N ratios obtained by MINITAB 17 software for MRR, Surface Roughness and Hardness are shown in table 3.

Table 3. MRR, Hardness and Surface Roughness for S/N Ratio.

		Coded values			***MRR***		***Hardness***		***Surface roughness***	
Exp no	***T_{on}***	***T_{off}***	***I_p***	***SV***	***(mm3/min)***	S/N	***HV***	S/N	**µm**	S /N
1	*-1*	*-1*	*-1*	*-1*	*0.0658*	-23.6355	33	30.3703	2.695	-8.61118
2	*-1*	*0*	*0*	*0*	*0.1976*	-14.0843	34	30.6296	3.497	-10.8739
3	*-1*	*1*	*1*	*1*	*0.2045*	-13.7861	32	30.103	3.855	-11.7205
4	*0*	*-1*	*0*	*1*	*0.2272*	-12.8718	34	30.6296	3.8	-11.5957
5	*0*	*0*	*1*	*-1*	*0.0946*	-20.4822	33	30.3703	2.8	-8.94316
6	*0*	*1*	*-1*	*0*	*0.3073*	-10.2487	34	30.6296	3.32	-10.4228
7	*1*	*-1*	*1*	*0*	*0.3246*	-9.77303	34	30.6296	3.45	-10.7564
8	*1*	*0*	*-1*	*1*	*0.3719*	-8.59148	34	30.6296	3.82	-11.6413
9	*1*	*1*	*0*	*-1*	*0.1515*	-16.3917	29	29.248	3.82	-11.6413

S/N Ratio response for MRR, Hardness and Surface Roughness are shown in Table 4, 5 and 6.

Table 4. S/N Ratio Response for MRR.

Level	**T_{on}**	**T_{off}**	**I_p**	**SV**
1	-17.17	-15.43	-14.16	-20.17
2	-14.53	-14.39	-14.45	-11.37
3	-11.59	-13.48	-14.68	-11.75
Delta	5.58	1.95	0.52	8.8
Rank	2	3	4	1

Table 5. S/N Ratio Response for Hardness.

Level	**T_{on}**	**T_{off}**	**I_p**	**SV**
1	30.37	30.54	30.54	30
2	30.54	30.54	30.17	30.63
3	30.17	29.99	30.37	30.45
Delta	0.37	0.55	0.37	0.63
Rank	3.5	2	3.5	1

Table 6. S/N Ratio Response for Surface Roughness.

Level	**T_{on}**	**T_{off}**	**I_p**	**SV**
1	-10.402	-10.321	-10.225	-9.732
2	-10.321	-10.486	-11.37	-10.684
3	-11.346	-11.262	-10.473	-11.652
Delta	1.026	0.94	1.145	1.921
Rank	3	4	2	1

Mean of S/N ratios versus input parameters viz. T_{on}, T_{off}, I_p and SV for MRR, Hardness and Surface Roughness are shown in figs. 2, 3 and 4 respectively.

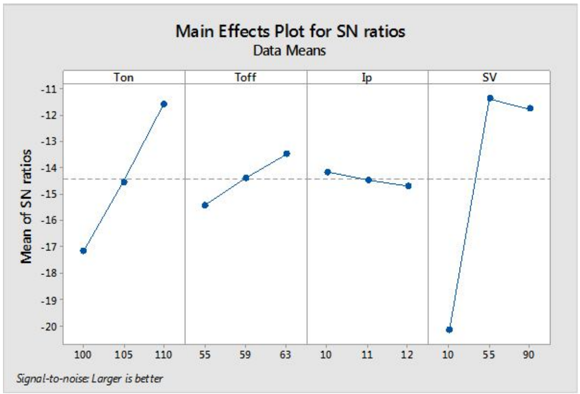

Fig. 2. S/N Plot for MRR.

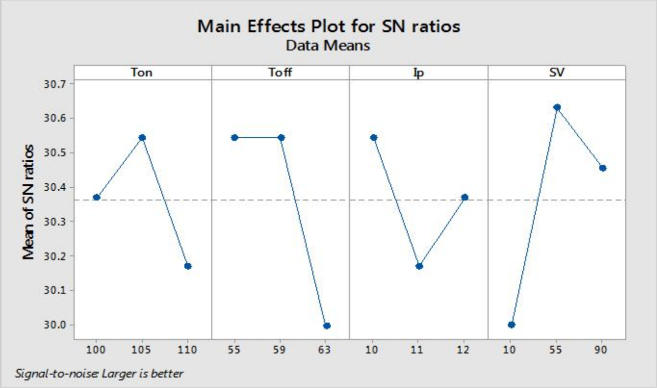

Fig. 3. S/N Plot for Hardness.

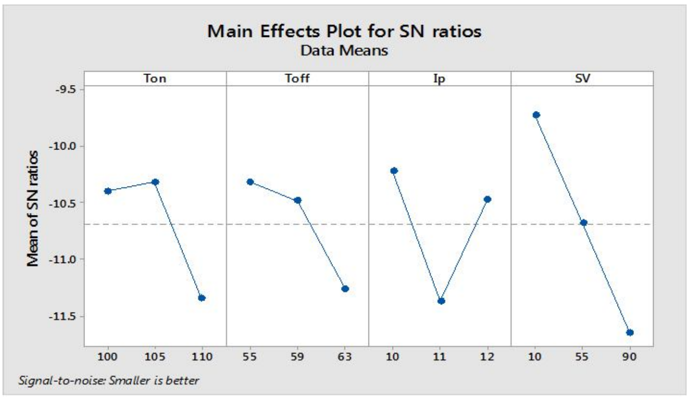

Fig. 4. S/N Plot for Surface Roughness.

ANOVA and Regression analysis.

The first and second order polynomial responses have been accomplished, consequently the analysis of variance are shown in tables 7, 8 and 9. Because of its adequacy, second order regression has been shown. Regression analysis was performed on the values of measured responses and the values of the different regression coefficients of second order polynomial mathematical equation have been estimated. The mathematical model has been developed by utilizing test results obtained through the entire set of experiments by using Minitab 17 software using multi-linear regression analysis method. The relation between EDM process parameters with a variety of machining criteria and output response were drawn as shown in eqns (4), (5) and (6) and residual plots for MRR, Hardness and Surface Roughness are shown in figs. 5, 6 and 7.

Table 7. ANOVA for MRR.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	7	0.109763	0.01568	4.97	0.333
T_{on}	1	0.005727	0.005727	1.81	0.407
T_{off}	1	0.001163	0.001163	0.37	0.653
I_p	1	0.004505	0.004505	1.43	0.444
SV	1	0.004419	0.004419	1.4	0.447
$T_{on} \cdot T_{off}$	1	0.003123	0.003123	0.99	0.502
$T_{on} \cdot I_p$	1	0.000273	0.000273	0.09	0.818
$T_{off} \cdot I_p$	1	0.002373	0.002373	0.75	0.545
Error	1	0.003158	0.003158	-	-
Total	8	0.112921	-	-	-

Regression Equation:

$$MRR^{0.5}\ (mm^3/min) = 0.4512 + 0.0467\ T_{on} + 0.0263\ T_{off} - 0.0518\ Ip+ \\ + 0.0718\ SV - 0.0732\ T_{on} \cdot T_{off} + 0.0217\ T_{on} \cdot I_p - 0.0451\ T_{off} \cdot I_p \tag{4}$$

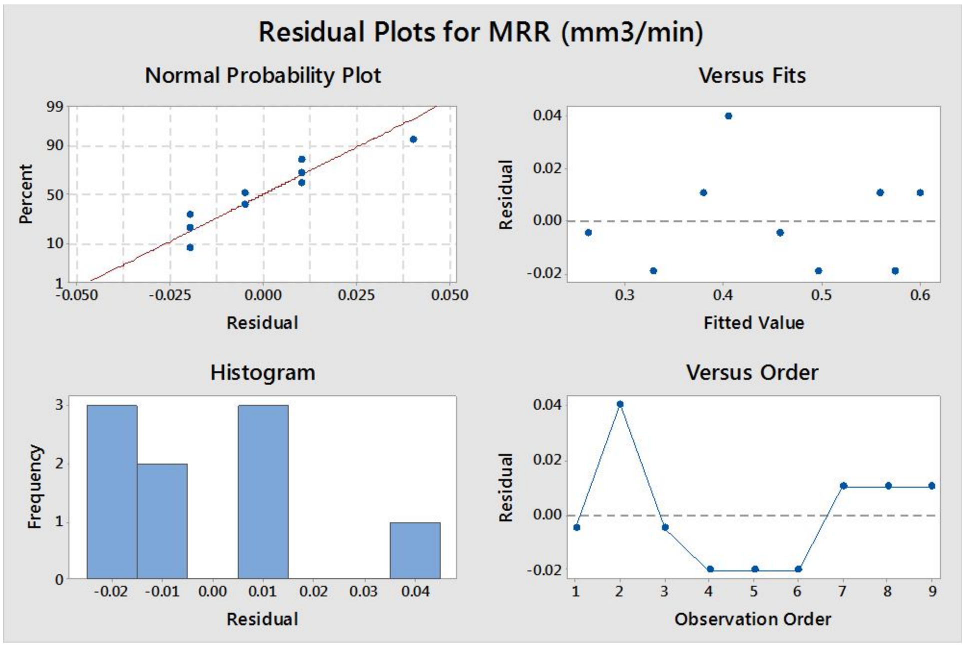

Fig. 5. Residual Plots for MRR.

Table 8. ANOVA for Hardness

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	7	0.173503	0.024786	38.31	0.124
T_{on}	1	0.029607	0.029607	45.76	0.093
T_{off}	1	0.057268	0.057268	88.51	0.067
I_p	1	0.021452	0.021452	33.15	0.109
SV	1	0.009562	0.009562	14.78	0.162
$T_{on} \cdot T_{off}$	1	0.016458	0.016458	25.44	0.125
$T_{on} \cdot I_p$	1	0.021376	0.021376	33.04	0.11
$T_{off} I_p$	1	0.026474	0.026474	40.92	0.099
Error	1	0.000647	0.000647	-	-
Total	8	0.17415	-	-	-

Regression Equation:

$$Hardness^{0.5} = 5.74288 - 0.1062\, T_{on} - 0.1846\, T_{off} - 0.1130\, Ip - 0.1056\, SV -- 0.1680\, T_{on} \cdot T_{off} - 0.1914\, T_{on} \cdot I_p - 0.1506\, T_{off} I_p \quad (5)$$

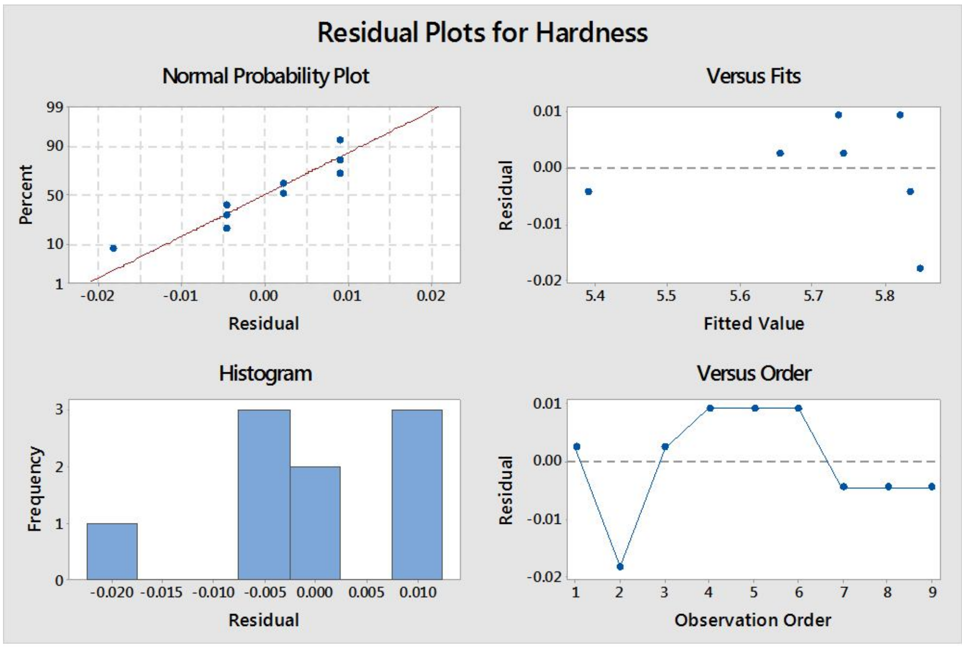

Fig. 6. Residual Plots for Hardness.

Table 9. ANOVA for Surface Roughness.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	7	0.11053	0.01579	1.62	0.542
T_{on}	1	0.00777	0.00777	0.8	0.536
T_{off}	1	0.01928	0.01928	1.98	0.394
I_p	1	0.01427	0.01427	1.46	0.44
SV	1	0.04841	0.04841	4.96	0.269
$T_{on} \cdot T_{off}$	1	0.01475	0.01475	1.51	0.435
$T_{on} \cdot I_p$	1	0.00799	0.00799	0.82	0.532
$T_{off} \cdot I_p$	1	0.00016	0.00016	0.02	0.919
Error	1	0.00976	0.00976	-	-
Total	8	0.12029	-	-	-

Regression Equation:

$$\begin{aligned} Surface\ roughness^{0.5} &= 1.8540 + 0.0544\ Ton + 0.1071\ Toff + 0.0921\ Ip + 0.238\ SV \\ &+ 0.159\ Ton{\cdot}Toff + 0.117\ Ton{\cdot}Ip + 0.0117\ Toff{\cdot}Ip \end{aligned} \tag{6}$$

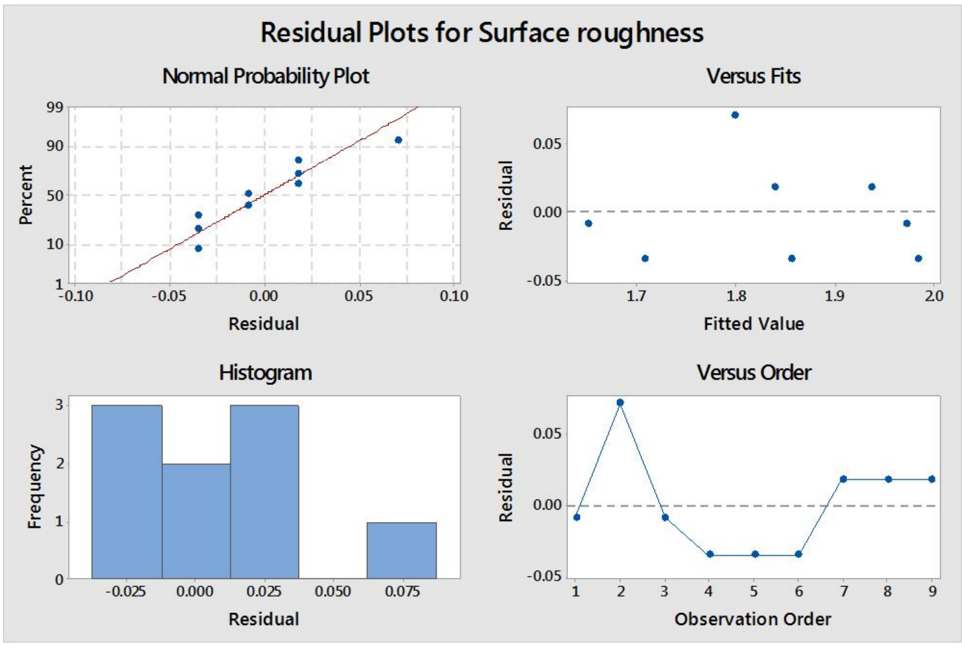

Fig. 7. Residual Plots for Surface Roughness.

Results and Discussions

Observations on MRR.

From S/N ratios graph in fig. 2, it is observed that MRR is linearly varying with T_{on}, T_{off} and I_p whereas non-linearly varying with SV. T_{on} has 30.19 % contribution to MRR. ANOVA (Table 7) and Regression equation (eq. 4) shows the significance of process parameters. Higher MRR (0.3719 mm^3/min) was obtained at T_{on} (110 µs), T_{off} (59 µs), I_p (10 amps) and SV (90 V). Adequacy of the regression model developed can be checked using values of S and R^2. R^2 value measures the amount of reduction in the variability of response obtained by using the variability of response obtained by using regression variables in the model [15]. R^2 of 97.00% and S of 0.056 indicates that it has good fit. More influencing factor from the regression model can be found by F value. Larger F value obtained at T_{on} (1.81).

Observations on Hardness.

Fig. 3 shows the S/N ratios obtained by MINITAB 17 software from the set of Hardness values. It is observed that Hardness does not linearly vary with any parameters. T_{off} has 37 % contribution to Hardness. Higher Hardness (34 HV) was obtained at same input parameters where higher MRR was obtained. Regression equation relating hardness with input parameters are shown in eq. (5) and values obtained by R^2 and S are 99.63% and 0.0254 respectively. This model also has good fit. Higher F value was obtained at T_{off} (88.51).

Observations on Surface Roughness.

S/N ratio plots calculated using set of surface roughness values are shown in fig. 4. It is observed that servo-voltage (SV) is varying linearly with surface roughness where other three input parameters T_{on}, T_{off} and Current I_p are non-linearly varying. SV (48.66 %) has higher contribution to Surface Roughness. Less surface roughness (2.695 µm) was obtained at T_{on} (100 µs), T_{off} (55 µs), I_p (10 amps) and SV (10V). R2 and S values are 91.89% and 0.098 respectively which indicates that model developed (eq. 6) has good fit. SV has higher F value of 4.96.

Summary. Higher MRR (0.3719 mm^3/min) and Hardness (34 HV) was achieved at T_{on} (110 µs), T_{off} (59 µs), I_p (10 amps) and SV (90 V). Lower Surface Roughness (2.695 µm) was obtained at T_{on} (100 µs), T_{off} (55 µs), I_p (10 amps) and SV (10V). Most influencing factor for MRR, Hardness and Surface Roughness are T_{on}, T_{off} and SV. Relation between input and output parameters was drawn using regression model developed by MINITAB 17 software.

Acknowledgement. All authors contributed equally.

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