

# Multi responses optimization of wire EDM process parameters using Taguchi approach coupled with principal component analysis methodology

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## Abstract

The wire EDM was known as for its better efficiency to machining hardest material and give precise and accurate result comparing to other machining process. The intent of this experimental paper is to optimize the machining parameters of Wire Electrical Discharge Machining (WEDM) on En45A Alloy Steel with the approach of Principal component Analysis (PCA). Three control variables Open Voltage (OV), Servo Voltage (SV), & Wire Feed (WF) are considered in this study to see their effect on three responses ie. Metal Removal Rate (MRR), Machining Time (MT) and Gap voltage (GV). The experiment has been conducted as per Taguchi's L<sub>9</sub> Orthogonal Array (OA). The Total principal component index (TPCI) is find out by using PCA methodology. There after ANOVA is applied to find out the percentage contribution of the process variables. It has been found that the open voltage (OV) is the most effecting variable on multiple responses.

*Keywords:* En45A alloy steel, wire electrical discharge machining (WEDM), Taguchi's orthogonal array (OA), Principal component analysis (PCA), ANOVA

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## 1. Introduction

Today's age is an industrial age. Now-a-days, many industries are using soft and hard materials to manufacture the product. To cut those hardest materials with precise dimension in minimum time, for this Wire Electrical Discharge Machine is used as Hotelling (1933). Globally, wire EDM is use as a machine tool for harder material which requires high strength and hardness, while the traditional manufacturing process needs some special tool or modern technique with a longer working time. WEDM is non-traditional, non-conventional, thermoelectric machining process which erodes material from work piece with the help of spark, which is generated between work piece and wire (tool electrode) immersed in liquid dielectric medium (distilled water). In this electric discharge melt and vaporize the material which is ejected and flushed out by the fluid is in Pearson paper (1901). WEDM is also capable to perform operation on taper angle by applying a relative movement between the upper and lower guides. Wire EDM is a 5 axis (X, Y, Z, U, & V) machine in which U & V axis are used for taper cutting. As Kumar et al. (2015) stated that in wire EDM wire is used as an electrode which is made up of brass, titanium, copper, and tungsten of diameter 0.05 to 0.30 mm. The machine on which I conduct experiments, 0.25mm diameter brass wire is used because of its small diameter it is capable of achieving very small corner radius. Mohapatra and Sahoo (2015) identified the gap between work piece and wire tool during machine operation is in micron.

## 2. Literature Review

Paiva et al. (2007) an alternative hybrid approach, while combining PCA and RSM are used form optimizing cutting speed, depth of cut, and feed rate as a processing parameters and finally conclude that cutting speed 238m/min, with a feed rate of 0.08mm/rev and depth of cut 0.32 mm are as optimal parameter on which maximum MRR at minimum surface roughness. V.

Jaiganesh and Raju (2008) solve the problem in product selection or product design is to selection of parameters, levels for optimizing multiple responses and finally they find out the optimal parameters on which MRR, SF, kerfs can be measured. Singh and Garg (2009) the effect of multiple parameters of WEDM like pulse on time, pulse off time, wire feed, gap voltage, wire tension and peak current on MRR while applying on Hot die steel (H-11) have been calculated and provide the optimal parameter on which maximum MRR can be achieved. Siddiquee et al. (2008) presented an application of centerless cylindrical grinding process of operation for IC engine, with the help grey relational analysis coupled with principal component analysis. Gopalsamy et al. (2009) Here Taguchi's technique is applied for finding optimal processing parameters while machining hardened material and finally Taguchi's result is very close to the result of ANOVA method and on CS 204m/min, Feed 0.2mm/tooth, DOC 0.2mm and WOC 0.2mm are the optimal parameters. Lahane et al. (2012) optimize the multi-responses of WEDM using principal component analysis while they considered pulse on, pulse off, upper flush, wire feed and finally provide the optimal parameters on which maximum MRR and minimum WWR of HSS material.

Dharmender et al. (2012) investigated the effect of process parameters on surface roughness (SR) on WEDM while considering input parameters peak current, pulse on time, pulse off time & wire tension for En31 tool steel material and concluded the error between experimental and predicted values for surface roughness (SR) is 5.67%. Paul and Sumam (2012) this research paper they build face recognition system by applying principal component analysis (PCA) technique and Eigen face approach. The system can successfully recognized the human faces and it can easily work in different face orientation. Prajapati and Patel (2013) cutting rate and surface roughness, the pulse ON, pulse OFF are most significant part of optimizing and spark gap is significant for kerfs width. Rajyalakshmi and Ramaiah (2013) discussed the application of the Taguchi method coupled with fuzzy logic to optimize the machining parameters of WEDM and finally conclude the optimal parameter on which MRR & MRPI are maximum at minimum SR and spark gap. Raghuraman et al. (2013) had done optimization of EDM parameters using Grey relational analysis with Taguchi approach for mild steel IS 2026 and they concluded optimal parameters combination as A3B2C1. Rao and Selvaraj (2013), performed their operation on wire EDM and considered Pulse ON time, Pulse OFF time, Peak current, Wire tension, Wire voltage, Servo feed rate as a optimizing parameters for Titanium Alloy material and investigate the effects of process parameters on MRR and SR. Singh and Sharma (2013) they worked on WEDM to optimize the process parameters and improved the machining quality. Theirs input process parameters are Pulse on time, Servo voltage, Pulse off time, Peak current, Wire tension and Wire feed are as input parameters and finally they concluded maximum MRR at minimum surface roughness with the help of MINITAB software. Das et al. (2014) investigate the machining process parameter of WEDM for multi-responses on EN31 tool steel using WPCA and finally optimal result is verified through confirmatory test. Nayak and Mahapatra (2014) optimize the part thickness, pulse duration, taper angle, wire tension and discharge current as processing parameters and investigate the optimal parameter. In this paper they show the importance of WEDM while using taper angle. Chandgude et al. (2015) investigated the optimal processing parameter of end milling machine while machining on AISI D2 hardened steel using principal component analysis on Taguchi orthogonal array. Gupta et al. (2015) hybrid approach of Taguchi and principal component analysis was applied while welding two dissimilar material AA5083-O and AA6063-T6 aluminium alloys. ANOVA results shows that tool rotational speed (35.37%) and welding speed (35.61%) are almost equal process parameter for TPCI.

### 3. Investigative procedure

In the current work, in order to optimize the process parameters, the following procedure prevails: (1) Selection of modern Wire EDM to perform trails; (2) Selection of material according to importance and machining cost; (3) Find out the levels for selected process parameters; (4) Selection of Taguchi  $L_9$  orthogonal array; (5) Implement parameters as per the selected orthogonal array; (6) Record the responses characteristics; (7) Normalizing the responses values; (8) Identify the optimal conditions for Wire EDM for En45A alloy steel; (9) ANOVA is conducted to find out the parameters percentage contribution.

### 4. Proposed methodology: Principal component analysis

Initially, with the help of Taguchi's methodology  $L_9$  orthogonal array is created (Chalisgonkar, 2014). Open Voltage (OV), Servo voltage (SV) and Wire feed (WF) considered as an optimizing parameters for WEDM for machining En45A alloy steel material which is shown in Table 2.

Here, on various process parameters, machining operation was conducted on our En45A alloy steel material and responses are recorded for individual trail. We considered Material Removal Rate (MRR), Machining Time (MT) and Gap Voltage (GV) as responses in Table 4.

**Step 1** Array of responses during machining (Paiva et al., 2007)

$$A = \begin{bmatrix} x_{11} & \dots & x_{1v} \\ \vdots & & \vdots \\ x_{u1} & \dots & x_{uv} \end{bmatrix}$$

Where u is the number of trails and v is the number of responses, A is an array of responses.

**Step 2** Convert into S/N ratio

Now, responses are converted into the signal to the noise (S/N) ratio with the help of equation 1&2 as shown in Table 5. Machining time and gap voltage are converted through “lower-the-better” equation 1 and for material removal rate “higher-the-better” equation 2 is used (Mohapatra and Sahoo, 2015).

For Lower-the-better (LB),

$$(S / N)_{LB} = -10 \log_{10} \left[ \frac{1}{v} \sum_{u=1}^v v x_{uv}^2 \right] \tag{1}$$

For Higher-the-better (HB),

$$(S / N)_{HB} = 10 \log_{10} \left[ \frac{1}{v} \sum_{u=1}^v \frac{1}{x_{uv}^2} \right] \tag{2}$$

where x is responses value, u and v are experimental condition.

**Step 3** Normalization of S/N ratios values

Now, S/N ratio values are normalized with the help of equation 3 & 4. Normalized values will lies between 0 - 1 which is in table 6.

For Lower-the-better (LB),

$$Z = \frac{Max(x_{uv}) - x_{uv}}{Max(x_{uv}) - Min(x_{uv})} \tag{3}$$

For Higher-the-better (HB),

$$Z = \frac{x_{uv} - Min(x_{uv})}{Max(x_{uv}) - Min(x_{uv})} \tag{4}$$

where Z is the normalised value for  $x_{uv}$  responses, Min ( $x_{uv}$ ) is the smallest value of  $x_{uv}$  and Max ( $x_{uv}$ ) is the largest value of  $x_{uv}$ , Z is a normalized array.

$$Z = \begin{bmatrix} z_{11} & \dots & z_{1v} \\ \vdots & & \vdots \\ z_{u1} & \dots & z_{uv} \end{bmatrix}$$

**Step 4** calculate variance-covariance in array B through the normalized values

$$B = \begin{bmatrix} N_{11} & \dots & N_{1v} \\ & \cdot & \\ & \cdot & \\ & \cdot & \\ N_{u1} & \dots & N_{uv} \end{bmatrix}$$

$$N_{u,v} = \frac{Cov(x(u), x(v))}{\sqrt{Var(x(u)) * Var(x(v))}} \tag{5}$$

where  $u=1, 2,3,\dots, v$ , and  $Cov(x(u), x(v))$  is the covariance of  $x(u)$  and  $x(v)$ .

**Step 5** Calculate the Eigen values and Eigen vectors with the help of correlation coefficient, Calculate the Eigen values and Eigen vectors with the help of variance and covariance using equation 5. Eigen values and Eigen vectors are in Table 7. Now find out the correlation coefficient through equation 6.

$$(R - \lambda I_u)V_{uv}=0 \tag{6}$$

where R is correlation,  $\lambda$  is Eigen value, I is identity matrix and V is Eigen vectors.

**Step 6** Find the principal components, Next step is to calculate principal component which can be seen in Table 8.

$$PC_i = \sum_{x=1}^v x_{uv} * V_{uv} \tag{7}$$

where  $i=1,2,3, \dots, n$

**Step 7** Calculate the Total Principal Component Index, Total principal component index is calculated which provide the best solution or process parameter on which material removal rate is maximum and machining time and gap voltage are minimum, in Table 9.

$$TPCI_i = \sum_{x=1}^v PC_i * e(x) \tag{8}$$

where,  $e(x) = \frac{eig(x)}{\sum_{x=1}^v eig(x)}$

$eig(x) = x^{th}$  Eigen value

**Step 8** Generate response table and choose the optimal processing parameters.

Variables	Level 1	Level 2	Level 3
Open Voltage (OV)	$m_1$	$m_2$	$m_3$
Servo Voltage (SV)	$n_1$	$n_2$	$n_3$
Wire Feed (WF)	$o_1$	$o_2$	$o_3$

$$m_1 = \frac{(TPCI)^1 + (TPCI)^2 + (TPCI)^2}{3} \tag{9}$$

$$n_1 = \frac{(TPCI)^1 + (TPCI)^4 + (TPCI)^7}{3} \tag{10}$$

$$o_1 = \frac{(TPCI)^1 + (TPCI)^6 + (TPCI)^8}{3} \tag{11}$$

**Step 9** Now ANOVA is carried out to find the percentage contribution of process parameters, which make it easy to identify most effecting parameter.

**5. Experimental Setup**

*5.1 Machine setup*

Wire EDM was invented in 1967 in USSR by David H. Dulebohn’s group, for making tools from hardened steel. These trails are conducted on 5 axis (X, Y, Z, U, V) computer numerical control (CNC) Wire EDM machine which was developed by master cam, Taiwan company in 2012 which is situated at Micro, Small and Medium Enterprises (MSME) Agra (U.P.). In this machine brass wire of 0.25mm diameter is used as a cutting tool (electrode). This machine contains various input parameters as open voltage, pulse on time, pulse off time, servo voltage, wire tension, wire feed, water flow rate etc. and output parameters as gap voltage, cutting speed, etc.

Specification of machine

- Table size : 740x400mm
- Maximum height of workpiece : 295mm
- Maximum width of workpiece : 295mm
- Maximum machine speed : 250mm<sup>2</sup>/min
- Total AC power input : 220 phase



**Figure 1.** Machine setup

*5.2 Selection of material*

We selected En45A alloy steel as workpiece for our experimental work. It is widely used in most of the field for manufacturing of oil and gases pipeline, springs, construction, automobiles and power plants as Danial Ghodsiyeh, Abolfazl Golshan and Jamal Azimi Shirvanehdeh (2013) described. It is widely used due to its mechanical properties and hardness. Melting temperature of En45A alloy steel is 1425°C and its density is 8.08 gm/cm<sup>3</sup>. Chemical compositions of En45A alloy steel material are as below shown in Table 1 (Durairaj et al., 2014).

**Table 1.** Chemical composition of En45A alloy steel

Elements	Carbon (C)	Silicon (Si)	Manganese (Mn)	Chromium (Cr)	Copper (Cr)	Iron (Fe)
%	0.66	1.62	0.89	0.23	0.20	95.60



**Figure 2.** Top view (a) and side view (b) of En45A Alloy steel material

**Table 2.** Variables with their levels

S. No	Variables	Symbols	Units	Level (L <sub>1</sub> )	Level (L <sub>2</sub> )	Level (L <sub>3</sub> )
1.	Open Voltage (OV)	A	Volts	80	85	90
2.	Servo Voltage (SV)	B	Volts	30	40	50
3.	Wire Feed (WF)	C	m/min	5	6	7

This technique is found by Genichi Taguchi, a Japanese scientist which is based on orthogonal array (Rao and Selvaraj, 2013). Nowever day it is widely using day by day it makes trails compact and make less difficult to find out the optimal parameters. This technique is totally depends on factors and number of trails (level). Here we consider L<sub>9</sub> Taguchi orthogonal array for which our input parameters are Open voltage (OV), Servo voltage (SV), and Wire feed (WF) (following Lokesh et al., 2015). Taguchi L<sub>9</sub> orthogonal array is shown in Table 3.

**Table 3.** Taguchi L<sub>9</sub> orthogonal array

Trails	Open Voltage (A)	Servo Voltage (B)	Wire Feed (C)
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

**Table 4.** Table of experimental responses

Trails	Material Removal Rate (MRR) (mm <sup>3</sup> /min)	Machining Time (MT) (min)	Gap Voltage (GV) (Volts)
1	78.9600	5.2160	30.3400
2	62.8800	6.4500	38.9600
3	55.1200	7.3170	48.5200
4	79.6000	5.1170	30.2000
5	65.9200	6.1670	37.8400
6	51.2000	7.9000	50.6900
7	75.6000	5.4000	30.5200
8	58.3200	6.9500	42.1200
9	49.2800	8.2170	51.2300

**Table 5.** Sequences of S/N ratio

Trails	S/N (MRR) (dB)	S/N (MT) (dB)	S/N (GV) (dB)
1	37.9481	-14.3467	-29.6403
2	35.9702	-16.1912	-31.8124
3	34.8262	-17.2867	-33.7184
4	38.0183	-14.1803	-29.6001
5	36.3803	-15.8015	-31.5590

**Table 5 (Cont'd).** Sequences of S/N ratio

Trails	S/N (MRR) (dB)	S/N (MT) (dB)	S/N (GV) (dB)
6	34.1854	-17.9525	-34.0984
7	37.5704	-14.6479	-29.6917
8	35.3163	-16.8397	-32.4898
9	33.8534	-18.2943	-34.1905

**Table 6.** Normalized S/N ratio values

Trails	Normalized (MRR)	Normalized (MT)	Normalized (GV)
1	0.9832	0.0405	0.0012
2	0.5083	0.4888	0.4744
3	0.2336	0.7551	0.8897
4	1.0000	0.0000	0.0000
5	0.6067	0.3941	0.4192
6	0.0797	0.9169	1.0000
7	0.8925	0.1136	0.0124
8	0.3513	0.6464	0.6220
9	0.0000	1.0000	0.9925

**Table 7.** Eigen values & Eigen vectors

	PC1	PC2	PC3
Eigen Vectors	-0.4780	0.373	0.726
	0.4780	-0.441	0.687
	0.476	0.816	-0.039
Eigen Values	2.9882	0.0116	0.0002
Proportion	0.9960	0.0040	0.0000
Cumulative	0.9960	1.0000	1.0000

**Table 8.** Principal component for experimental trails

Trails	VPC1	VPC2	VPC3
1	-0.2417	0.3499	0.7415
2	0.3620	0.3611	0.6863
3	0.1139	0.4801	0.6536
4	0.6780	0.3730	0.7260
5	0.6245	0.3946	0.6949
6	0.5991	0.4414	0.6488
7	-0.4430	0.2929	0.7255
8	0.1044	0.3535	0.6748
9	0.6497	0.3689	0.6483

**Table 9.** Total principal component index with ranks

Trails	TPCI	Ranks
1	-0.2393	8
2	0.3620	5
3	0.1153	6
<b>4</b>	<b>0.6768</b>	<b>1</b>
5	0.6237	3
6	0.5985	4
7	-0.4401	9
8	0.1054	7
9	0.6486	2

ANOVA is conducted to identify the most significant factor which is affecting the performance and result of ANOVA is given in Table 10. It shows the individual affect with percentage contribution of Open voltage, Servo voltage & Gap voltage. In our F-test, if F value of any input parameter is high, it means that input parameter is affecting most (following Gopalsamy et al., 2009).

**Table 10.** ANOVA table

Symbol	DOF	Sum of square	Variance	F-values	Contribution (%)
A	2	0.586	0.293	12.466	42.96
B	2	0.348	0.174	7.401	25.50
C	2	0.383	0.192	8.151	28.09
Error	2	0.047	0.023		3.45
<b>Sum</b>					100

## 6. Results and Discussion

We consider Open voltage, Servo voltage & Wire feed as our input parameters and material removal rate, machine timing, & gap voltage as our responses. The experimental data is analyzed, using the PCA method with the aim to identify the optimum combination of machining parameters on which MRR is maximum at minimum MT and GV. Here, for MRR, higher-the-better criterion and for all machining time and Gap voltage parameters lower-the-better criterion have been carried out. According to (H. Singh and R. Grag, 2009) normalization is done to decrease the variation between 0 to 1. Responses are checked whether they were correlated or not using Pearson's correlation coefficient. Eigen value, Eigen vector, and accountability proportion (AP) are shown in Table 7. Finally, Total principal component index (TPCI) for each trail is computed which is in Table 9. We identify best process parameters ( $A_2B_1C_2$ ), means on 85 Open Voltage, 30 Servo Voltage and 6 Wire feed, machining will be optimum it will give maximum MRR at minimum MT and GV which is in Table 11.

**Table 11.** Optimal process parameters

S. No.	Open Voltage	Servo Voltage	Wire Feed	Material Removal Rate	Machining Time	Gap Voltage
1	85	30	6	79.6000	5.1170	30.2000

Individual optimal process parameters are identified and shown in Table 12. According to this optimal process parameters are ( $A_3B_1C_2$ ).

**Table 12.** Main effect of factors on the TPCI

Inputs	Level 1	Level 2	Level 3	Max-Min	Rank
Open Voltage (OV)	0.0794	-0.0009	0.1549*	0.1558	3
Servo Voltage (SV)	0.6330*	0.3637	0.5625	0.2693	1
Gap Voltage (GP)	0.1046	0.4541*	0.0996	0.3545	2

\* Optimal values

## 7. Conclusions

Taguchi method of experimental design has been carried out for optimizing multi response parameters for wire EDM are optimized with  $L_9$  orthogonal array. Optimal parameters found for finish machining are 90 open Voltage, 30 Servo Voltage and 6 Wire feed. In these process parameters Open voltage is most affecting parameters. Percentage contribution was determined with the help of ANOVA. The conclusions of this experimental optimization work are summarized as follows:

- The experimental results were found with good agreement.
- The optimal parameters combination was identified as  $A_3B_1C_2$  i.e. Open voltage 90V, Servo Voltage 30V and wire feed 6m/min.
- ANOVA shows the percentage contribution of individual parameters.
- The result of ANOVA shows affect of Open voltage is more, than other input parameters.
- ANOVA find out the 3.45% of error in experimental calculation.



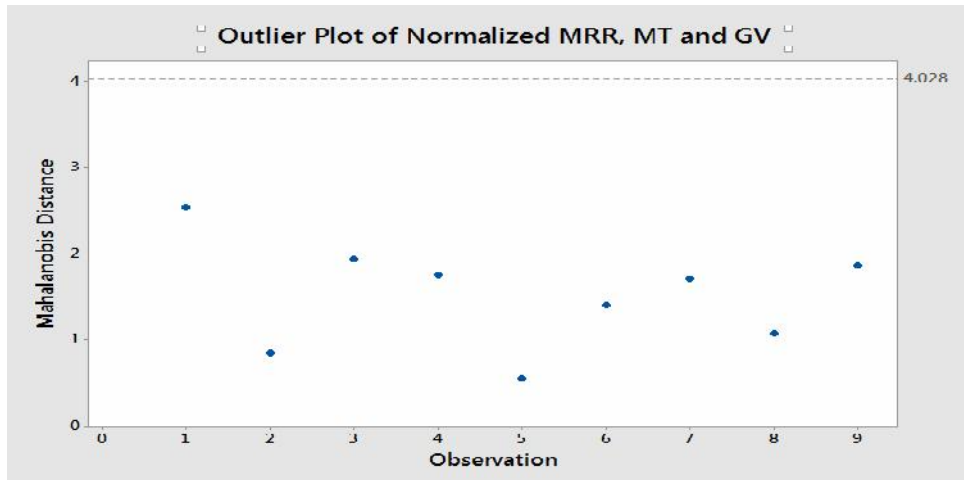


Figure 3. Normalized MRR, MT & GV outer plot

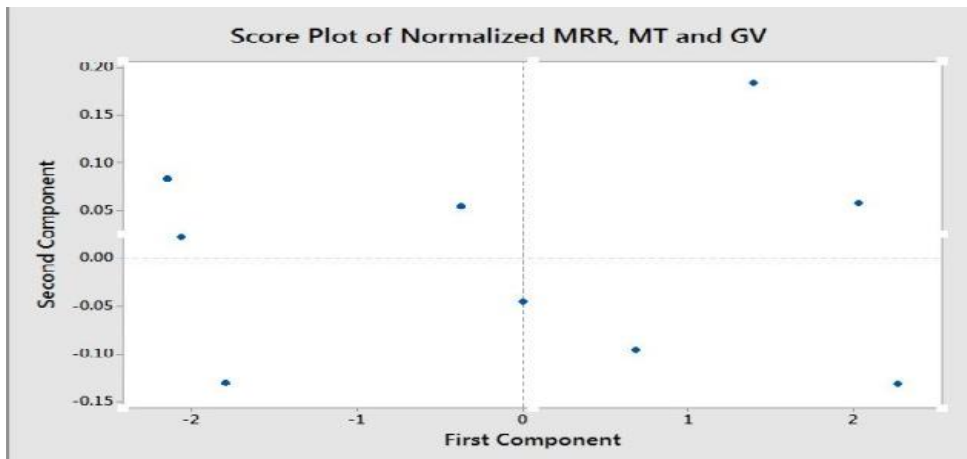


Figure 4. Normalized MRR, MT & GV score plot

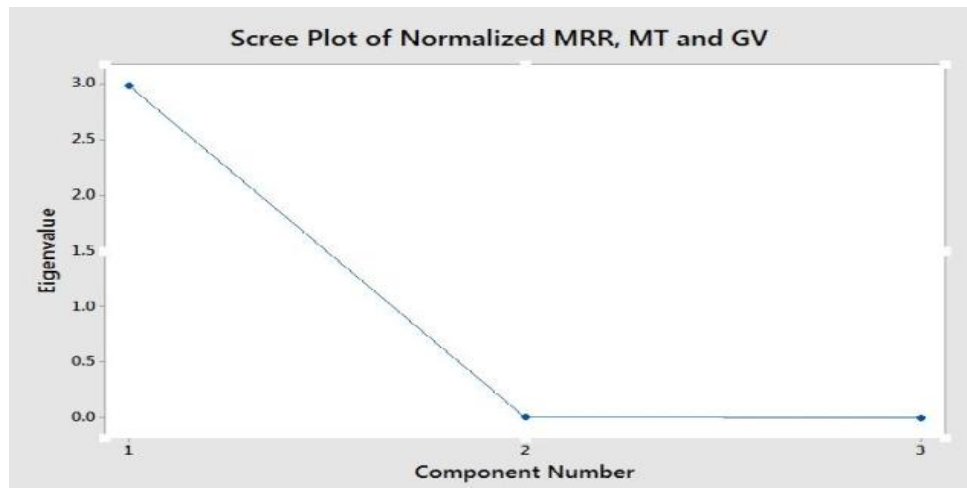


Figure 5. Normalized MRR, MT & GV scree plot

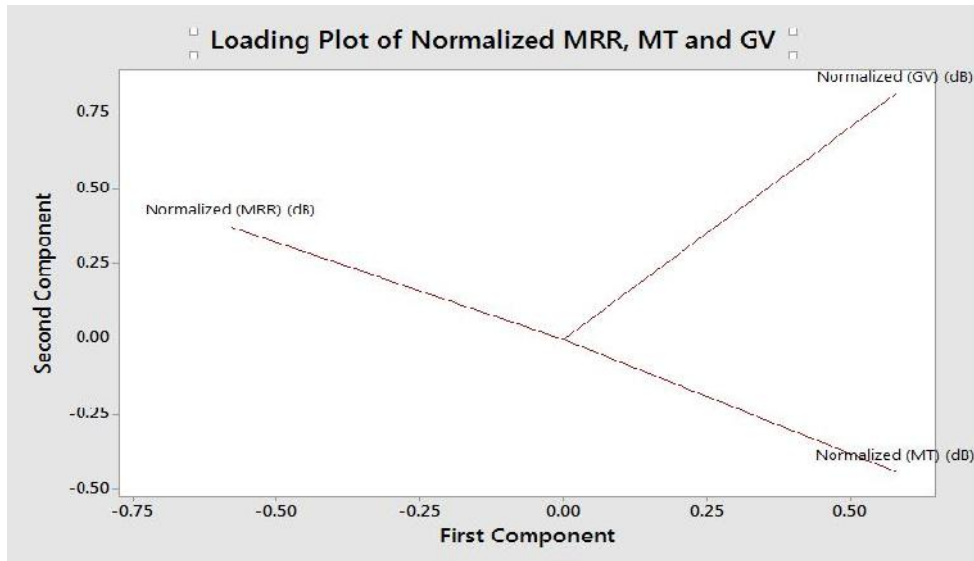


Figure 6. Normalized MRR, MT & GV loading plot

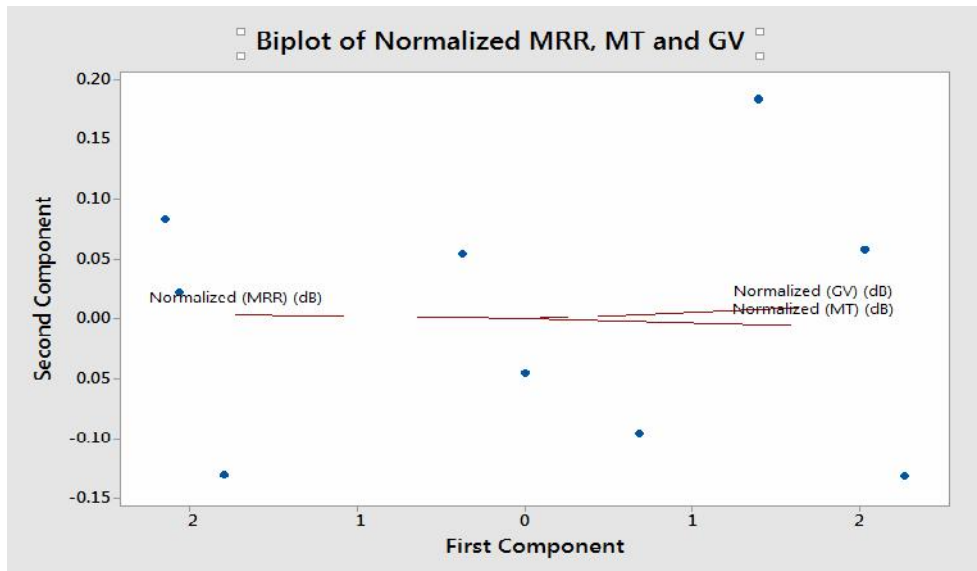


Figure 7. Normalized MRR, MT & GV biplot plot

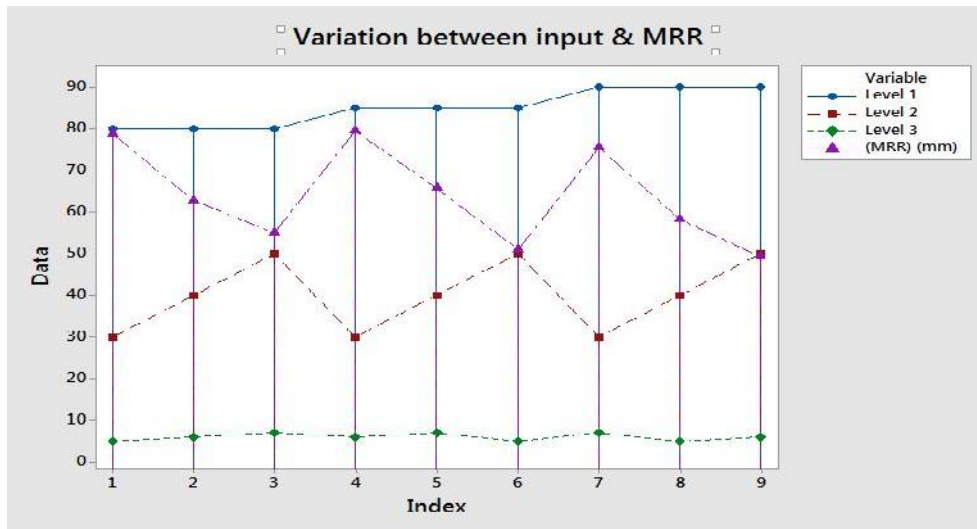


Figure 8. Variation between input values and MRR

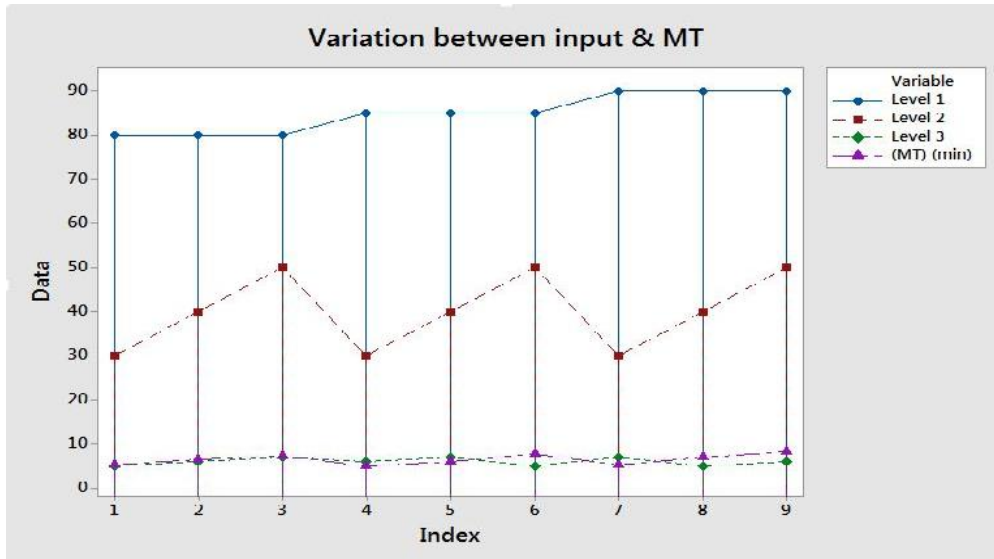


Figure 9. Variation between input values and MT

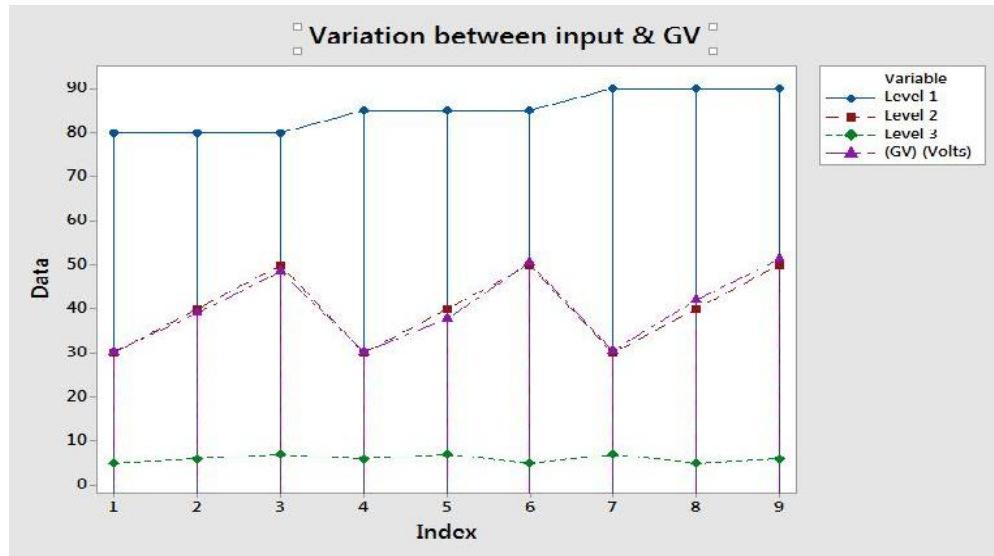


Figure 10. Variation between input values and GV

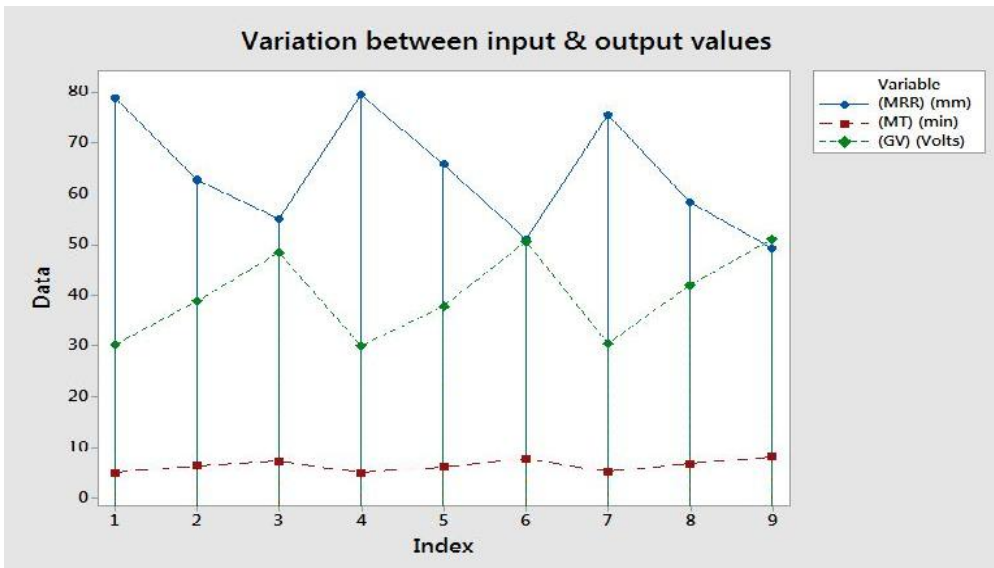


Figure 11. Variation between input & output values

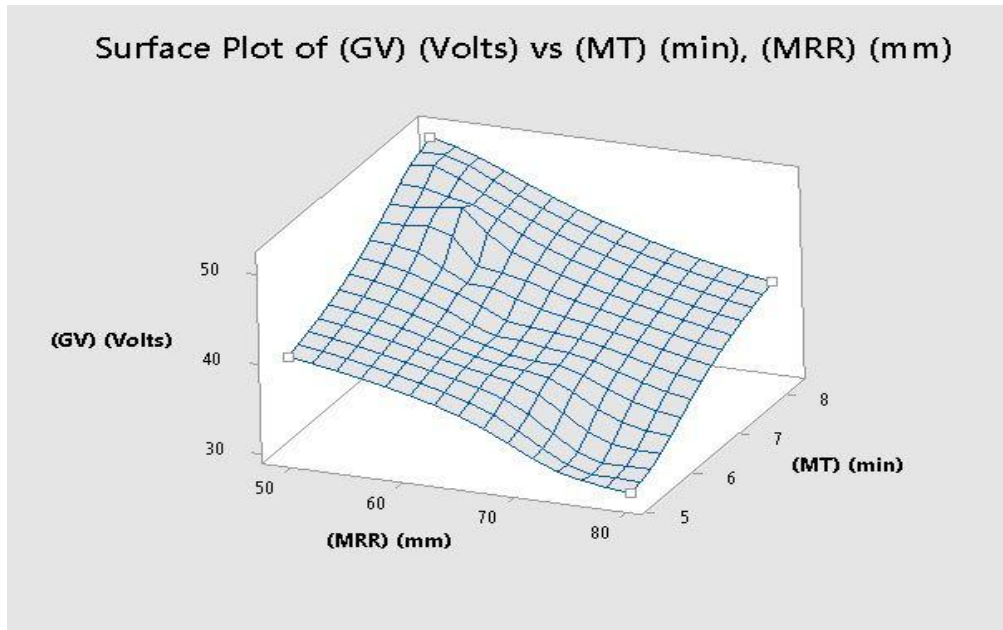


Figure 12. Surface plot of responses

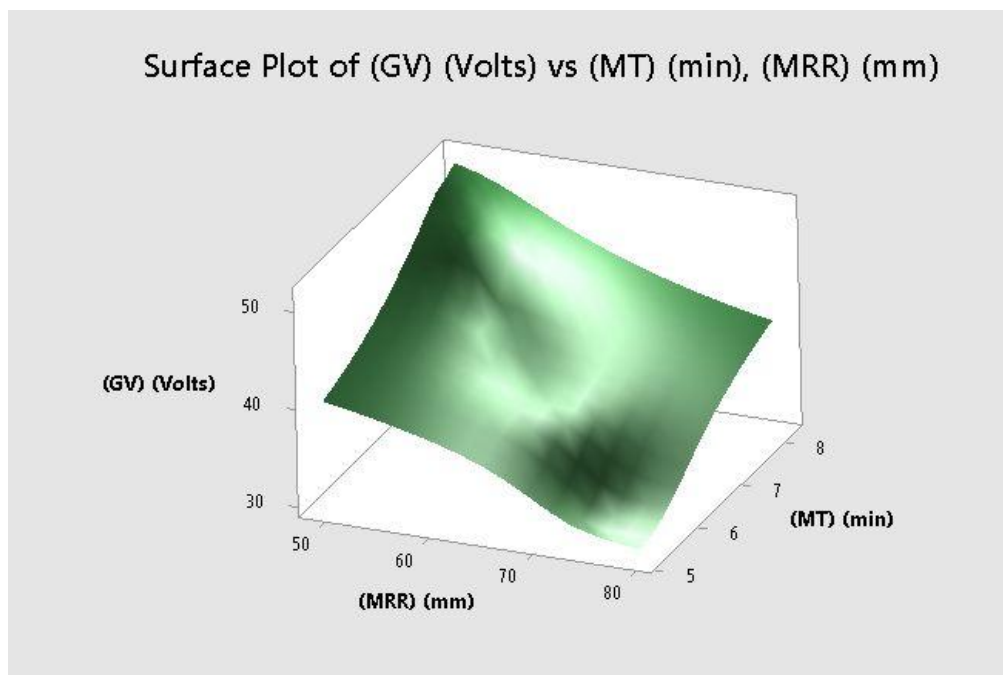


Figure 13. Surface plot of responses

**Nomenclature**

$x_{uv}$	The $v$ th response of the $u$ th experiment
$X_{uv}$	Normalized S/N ratio of the $u$ th performance characteristic in the $v$ th experiment
$Z$	Normalized array
$Cov(x(u))$	Covariance of sequence $x(u)$
$Cov(x(v))$	Covariance of sequence $x(v)$
$Var(x(u))$	Variance of $x(u)$
$Var(x(v))$	Variance of $x(v)$
$R_{uv}$	Correlation coefficient array
$\lambda_x$	Eigen values
$V_{uv}$	Eigenvectors corresponding

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