Multi Regression Analysis of Wire Electrical Discharge Machining Based on Taguchi Method

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Abstract: This paper presents an investigation on the effect and optimization of machining parameters on the kerf (cutting width) and material removal rate (MRR) in wire electrical discharge machining (WEDM) operations. The experimental studies were conducted under varying pulse on time, pulse off time, and open circuit voltage. The settings of machining parameters were determined by using Taguchi experimental design method. The level of importance of the machining parameters on the cutting kerf and MRR is determined by using analysis of variance (ANOVA). The optimum machining parameter combination was obtained by using the analysis of signal-to-noise (S/N) ratio. The variation of kerf and MRR with machining parameters is mathematically modeled by using regression analysis method. The optimal search for machining parameters for the objective of minimum kerf together with maximum MRR is performed by using the established mathematical models**.**

***IndexTerms* - WEDM, Taguchi Experimental Design, Signal to Noise Ratio, ANOVA, Regression Analysis.**

I. INTRODUCTION

The objectives of human lives are distinguished from all other forms of life. We use tools and intelligence to create goods that serve to make life easier and more enjoyable. Through the centuries both the tools and energy sources to power these tools have evolved to meet the increasing sophistication and complexity of mankind's ideas. The last century has seen the creation of products made from the most durable and, consequently, the most un-machinable materials in history. In an effort to meet the manufacturing challenges created by these materials, tools have now been evolved to include materials such as alloy steels, carbide, diamond and ceramics. Every time new tools, tool materials, and power sources are utilized, the efficiency and capabilities of manufacturers are greatly enhanced. However as old problems are solved, new problems and challenges arise.

Scientific and engineering advances have placed unusual demands on the manufacturing industry. One of the aspects of these demands is that engineering materials such as cold rolled composites with high strength-to-weight ratios have been developed to serve specific purposes. Although they have been successfully introduced in few commercial applications, their potential of wide spread application is still impeded due to the challenges in machining these materials. They are difficult to-machine due to the presence of hard and abrasive ceramic reinforcements. The issues like rapid tool wear, surface and sub-surface damage, along with high cost are associated. Therefore, these materials have attracted researcher worldwide in last decade. As a result of this lot of work has been carried in conventional machining of these materials. In addition, nonconventional machining process like electrical discharge machining has also been employed to machine these materials. This process show promise in machining of these materials. However, relatively a very few research have been undertaken in wire electrical discharge machining (WEDM) of these materials.

Since its introduction to industry in 1970, the wire electro-discharge machining (WEDM) has become a key technology for precision manufacturing of complex shapes rapidly and accurately, especially, on modern and 'difficult-to-machine' materials (like titanium, nimonics, zirconium, etc.) for aerospace, nuclear and automotive applications. However, even the state-of-the-art machine tools do not provide any technology to machine these metal matrix composites. This is attributed to lack of research in WEDM of these materials. Therefore, it is necessary to carry out comprehensive investigations into WEDM of metal matrix composites. The work reported in the present thesis is an attempt in this direction.

II. WORKPIECE MATERIAL

Work piece is a stripped piece of a large metal sheet which has been cold rolled and gone through a tempering process to remove the residual stress and the change in chemical composition is noticeable.

Figure 1: Workpiece before and after machining

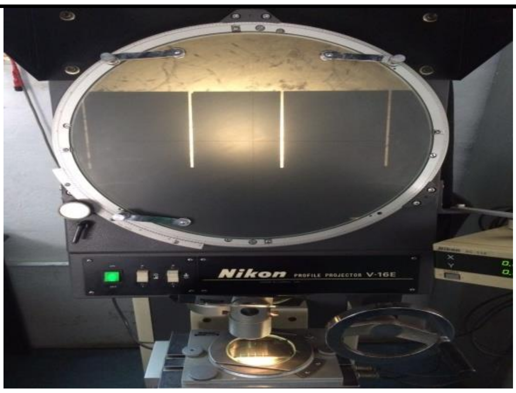

Figure 2: Profile projector

As the table show cases three objective functions as a varying parameter, we have selected L9 orthogonal array for further moving of the project.

Table 1: Taguchi's l3 representation

Factors	Levels			Units
	1	2	3	
VOLTAGE (X)	82	93	102	Volts
T-ON (Y)	3	2	1	μs
T-OFF (Z)	1	2	3	μs

Table 2: L9 ORTHOGONAL ARRAY WHICH WAS OBTAINED BY TAGUCHI METHODOLOGY WITH OUTPUT RESPONSES:

Exp. No	VOLTAGE	T-ON	T-OFF	MRR	KERF
1	82	3	1	0.053	0.3
2	82	2	2	0.053	0.3
3	82	1	3	0.052	0.305
4	93	3	2	0.0531	0.285
5	93	2	3	0.0535	0.281
6	93	1	1	0.0491	0.3
7	102	3	3	0.0606	0.298
8	102	2	1	0.05	0.291
9	102	1	2	0.0497	0.302

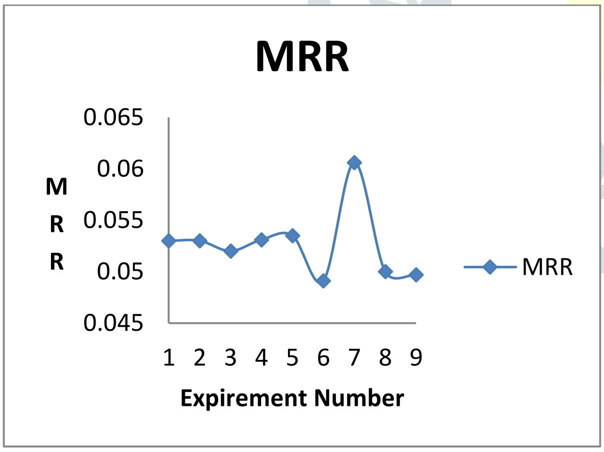

Figure 3: MRR vs Number of experiments

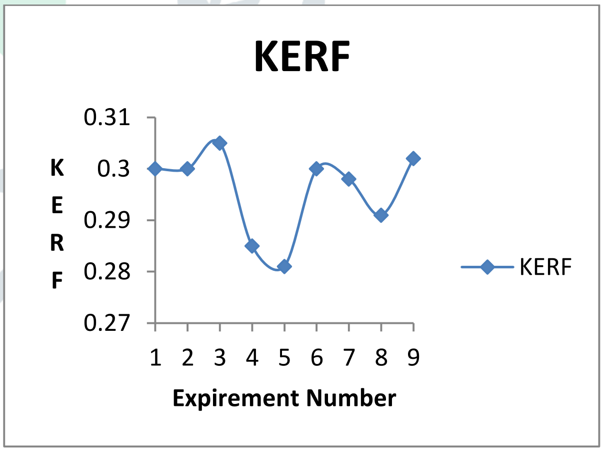

Figure 4: Kerf width vs Number of experiments

Taguchi's method is systematic and experimentally designed to find the main process parameters and will locate a good combination of process parameters to improve the output quality by using the experiments of orthogonal array (Ross 1996). In this method each experimental value is converted t-on a signal to noise (S/N) ratio that is defined as the deviation between the experimental value and the ideal value. In general, the S/N ratio conversion has three styles, the higher the better, the lower the better, the nominal the better.

For any style, a higher S/N ratio represents a better output quality and combines the best level of each parameter that has the highest S/N ratio compared with the other levels to obtain an optimal combination of process parameters. Since, optimizing multiple output qualities of a process require the calculation of overall S /N ratio and may not optimize the multiple output qualities simultaneously by using Taguchi method.

III. METHODLOGY

3.1 SIGNAL TO NOISE RATIO (S/N)

Taguchi method is one of the simple and effective solutions for parameter design and experimental planning. Signal to noise ratio is used to represent a performance characteristic and the largest value of s/n ratio is required.

The S/N ration with a lower the better characteristic that can be expressed as

$$\eta ij = -10\log\left(\frac{1}{n}\sum_{j=1}^{n} Y_{ij}^{2}\right) \qquad (1)$$

The S/N ration with a higher the better characteristic that can be expressed as

$$\eta ij = -10\log\left(\frac{1}{n}\sum_{j=1}^{n} 1/Y_{ij}^{2}\right) \qquad (2)$$

The S/N ration with a normal the better characteristic that can be expresses as

$$\eta ij = -10\log\left(\frac{1}{ns}\sum_{j=1}^{n} Y_{ij}^{2}\right) \qquad (3)$$

Where Y_{ij} is the outcome of the i^{th} experiment at the j^{th} test, n is the total number of the tests and s is the standard deviation.

3.2 SIGNAL TO NOISE RATIO FOR MRR

Taguchi Analysis is carried out for MRR versus VOLTAGE (X), T-ON (Y), T-OFF (Z). Larger is better condition is implemented for calculations of signal to noise ratios.

Table 3: Response Table for Signal to Noise Ratios

Level	VOLTAGE(X)	T-ON (Y)	T-OFF (Z)
1	-25.57	-25.12	-25.90
2	-25.70	-25.66	-25.70
3	-25.48	-25.98	-25.15
Delta	0.22	0.86	0.75
Rank	3	1	2

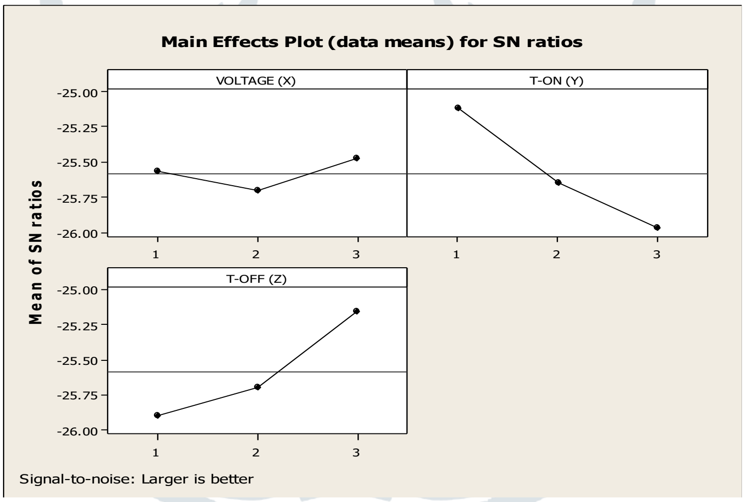

Figure 5: Main Effects Plot (data means) for SN ratios

From the above-mentioned tabular results and the graphs shown, it can be observed that the Signal-to-Noise ratio when larger is better shows the optimum conditions for it as: Voltage: 93 volts, Ton: 3µs and Toff: 3µs

3.3 SIGNAL TO NOISE RATIO FOR KERF

Taguchi Analysis is carried out for KERF versus VOLTAGE (X), T-ON (Y), T-OFF (Z). Smaller is better condition is implemented for calculations of signal to noise ratios.

Table 4: Response Table for Signal to Noise Ratios for kerf

LEVEL	VOLTAGE(x)	T-ON(Y)	T-OFF(Z)
1	10.41	10.63	10.55
2	10.8	10.74	10.59
3	10.55	10.39	10.62
Delta	0.39	0.34	0.07
Rank	1	2	3

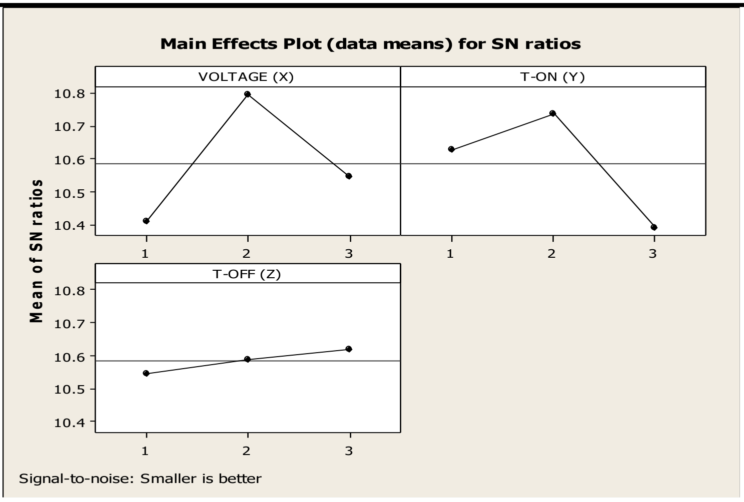

Figure 6: Main Effects Plot (data means) for SN ratios (kerf):

From the above-mentioned tabular results and the graphs shown, it can be observed that the Signal-to-Noise ratio for kerf width when smaller is better shows the optimum conditions for it as: Voltage: 93 volts, Ton: 2µs and Toff: 3µs

IV. ANALYSIS OF VARIANCE (ANOVA)

Analysis of variance (ANOVA) tests the hypothesis that the means of two or more populations are equal. ANOVAs assess the importance of one or more factors by comparing the response variable means at the different factor levels. The null hypothesis states that all population means (factor level means) are equal while the alternative hypothesis states that at least one is different.

To perform an ANOVA, there must be a continuous response variable and at least one categorical factor with two or more levels. ANOVAs require data from approximately normally distributed populations with equal variances between factor levels. However, ANOVA procedures work quite well even if the normality assumption has been violated, unless one or more of the distributions are highly skewed or if the variances are quite different. Transformations of the original dataset may correct these violations.

4.1 SIGNAL TO NOISE RATIO (S/N)

General Linear Model is applied for calculating ANOVA. The analysis was carried between MRR versus VOLTAGE (X), T-ON (Y), T-OFF (Z).

Table 7: Analysis of Variance for MRR, using Adjusted SS for Tests

SOURCE	DF	SeqSS	AdjSS	AdjMS	F	P
VOLTAGE(X)	2	0.0000035	0.0000035	0.0000018	0.31	0.761
T-ON(Y)	2	0.0000433	0.0000433	0.0000216	3.85	0.206**
T-OFF(Z)	2	0.0000351	0.0000351	0.0000175	3.12	0.243
Error	2	0.0000112	0.0000112	0.0000056		
Total	8	0.0000931				

**From the above table it can be incurred that “Ton” plays the most significant role in the metal removal rate by wire edm as the “P” value for it is the least when compared with the voltage and Toff. **-Y is more significant compare to X and Z.

4.2. ANOVA RESULTS FOR KERF WIDTH

General Linear Model is applied for calculating ANOVA. The analysis was carried between KERF versus VOLTAGE (X), T-ON (Y), T-OFF (Z).

Table 8: Analysis of Variance for KERF, using Adjusted SS for Tests

SOURCE	DF	SeqSS	AdjSS	AdjMS	F	P
VOLTAGE(X)	2	0.0002602	0.0002602	0.0001301	4.52	0.181**
T-ON(Y)	2	0.0002136	0.0002136	0.0001068	3.71	0.212
T-OFF(Z)	2	0.0000082	0.0000082	0.0000041	0.14	0.875
Error	2	0.0000576	0.0000576	0.0000288		
Total	8	0.0005396				

**From the above table it can be incurred that “Voltage” plays the most significant role in the kerf width by wire edm as the “P” value for it is the least when compared with the Ton and Toff. *- x IS SIGNIFICANT COMPARE TO y AND Z

V. REGRESSION ANALYSIS

A mechanical researcher knows that a number of predictor variables (voltage, pulse on time and pulse off time) can affect material removal rate and kerf. Fit Regression Model is a versatile tool for investigating relationships between a response variable and both categorical and continuous predictor variables.

5.1 REGRESSION ANALYSIS FOR MRR

Mathematical model using multiple regression analysis

$$MRR = A*(X)^{a}*(Y)^{b}*(Z)^{c}$$

$$\log(MRR) = \log(A) + a\log(X) + b*\log(Y) + c*\log(Z)$$

Regression Analysis: LOG(MRR) versus LOG(X), LOG(Y), LOG(Z)

The regression equation is

LOG(MRR) = - 1.28 + 0.0059 LOG(X) - 0.0896 LOG(Y) + 0.0739 LOG(Z)

Table 9: Coefficients for MRR

Predictor	Coeff	SE Coeff	T	P
Constant	-1.27668	0.01264	-100.97	0.000
LOG(x)	0.00587	0.02577	0.23	0.829
LOG(y)	-0.08961	0.02577	-3.48	0.018
LOG(z)	0.07388	0.02577	2.87	0.035

S = 0.0152325 R-Sq = 80.3% R-Sq(adj) = 68.4%

Table 10: Analysis of parameters MRR

Source	DF	SS	MS	F	P
Regression	3	0.0047233	0.0015744	6.79	0.033
Residual Error	5	0.0011601	0.0002320		
Total	8	0.0058834			

Table 11: Sequential Analysis of MRR

Source	DF	Seq SS
LOG(x)	1	0.0000120
LOG(y)	1	0.0028049
LOG(z)	1	0.0019063

$$MRR = 0.052481*(X)^{0.0059}*(Y)^{-0.0896}*(Z)^{0.0739}$$

$$Error\,\% = \left(\frac{(Experimental\,Value - Predicted\,Value)}{Experimental\,Value}\right)*100$$

Table 12: Regression Analysis for MRR

Exp. No	V	T-ON	T-OFF	MRR	SNRA	PSNRA	PMRR	Error %
1	1	1	1	0.053	-25.5145	-25.4258	0.052481	0.9792
2	1	2	2	0.053	-25.5145	-25.7514	0.051913	2.051
3	1	3	3	0.052	-25.6799	-25.5318	0.051584	0.8008
4	2	1	2	0.0531	-25.4981	-25.3499	0.055466	-4.4551
5	2	2	3	0.0535	-25.4329	-25.3442	0.053711	-0.3948
6	2	3	1	0.0491	-26.1784	-26.4153	0.047756	2.7372
7	3	1	3	0.0606	-24.3505	-24.5874	0.05729	5.4626
8	3	2	1	0.05	-26.0206	-25.8724	0.049641	0.717
9	3	3	2	0.0497	-26.0729	-25.9841	0.050386	-1.3811

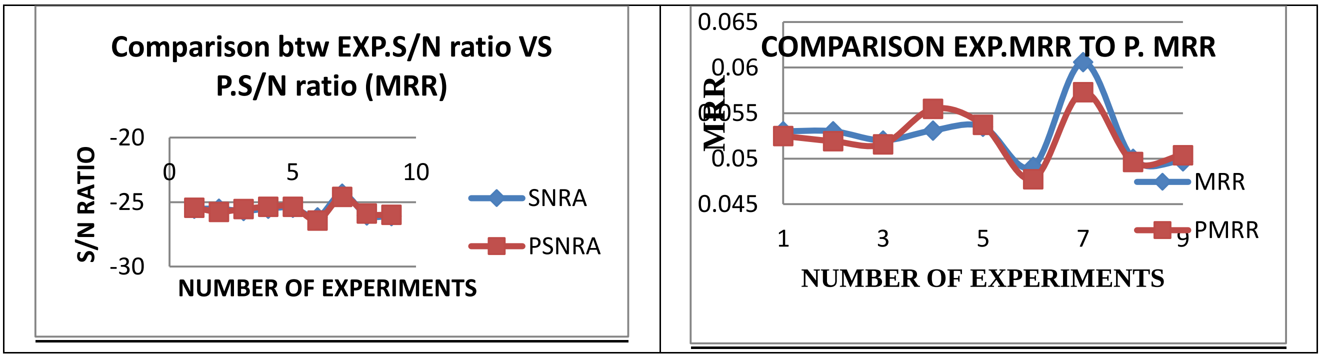

Figure 7: Comparison between experimental and predicted data of MRR

5.2 REGRESSION ANALYSIS FOR KERF WIDTH

Mathematical model using multiple regression analysis

$$KERF = A*(X)^{a}*(Y)^{b}*(Z)^{c}$$

$$\log(KERF) = \log(A) + a\log(X) + b*\log(Y) + c*\log(Z)$$

Regression Analysis: LOG(KERF) versus LOG(X), LOG(Y), LOG(Z)

The regression equation is

LOG(KERF) = - 0.527 - 0.0196 LOG(X) + 0.0200 LOG(Y) - 0.0075 LOG(Z)

Table 13: coefficients of Kerf width

Predictor	Coeff	SE Coeff	T	P
Constant	-0.5273	0.0111	-47.49	0
LOG(x)	-0.0196	0.02263	-0.87	0.425
LOG(y)	0.02001	0.02263	0.88	0.417
LOG(z)	-0.0075	0.02263	-0.33	0.753

S = 0.0133763 R-Sq = 24.8% R-Sq(adj) = 0.0%

Analysis of Variance:

Table 14: Analysis of parameters Kerf width

Source	DF	SS	MS	F	P
Regression	3	0.0002943	0.0000981	0.55	0.671
Residual Error	5	0.0008946	0.0001789		
Total	8	0.0011890			

Table 15: Sequential analysis of Kerf width

Source	DF	Seq SS
LOG(x)	1	0.0001346
LOG(y)	1	0.0001398
LOG(z)	1	0.0000198

$$KERF = 0.29717*(X)^{-0.0196}*(Y)^{0.02}*(Z)^{-0.0075}$$

$$Error\,\% = \left(\frac{(Experimental\,Value - Predicted\,Value)}{Experimental\,Value}\right)*100$$

Table 16: Regression analysis of Kerf width

Exp. No	V	T-ON	T-OFF	KERF	SNRA	PSNRA	PKERF	Error %
1	1	1	1	0.3	10.4576	10.4135	0.29717	0.9433
2	1	2	2	0.3	10.4576	10.5643	0.299756	0.0813
3	1	3	3	0.305	10.314	10.2513	0.301279	1.2200
4	2	1	2	0.285	10.9031	10.8404	0.29164	-2.329
5	2	2	3	0.281	11.0259	10.9818	0.294813	-4.915
6	2	3	1	0.3	10.4576	10.5643	0.299673	0.1091
7	3	1	3	0.298	10.5157	10.6224	0.288453	3.2037
8	3	2	1	0.291	10.7221	10.6594	0.294899	-1.340
9	3	3	2	0.302	10.3999	10.3558	0.295759	2.0665

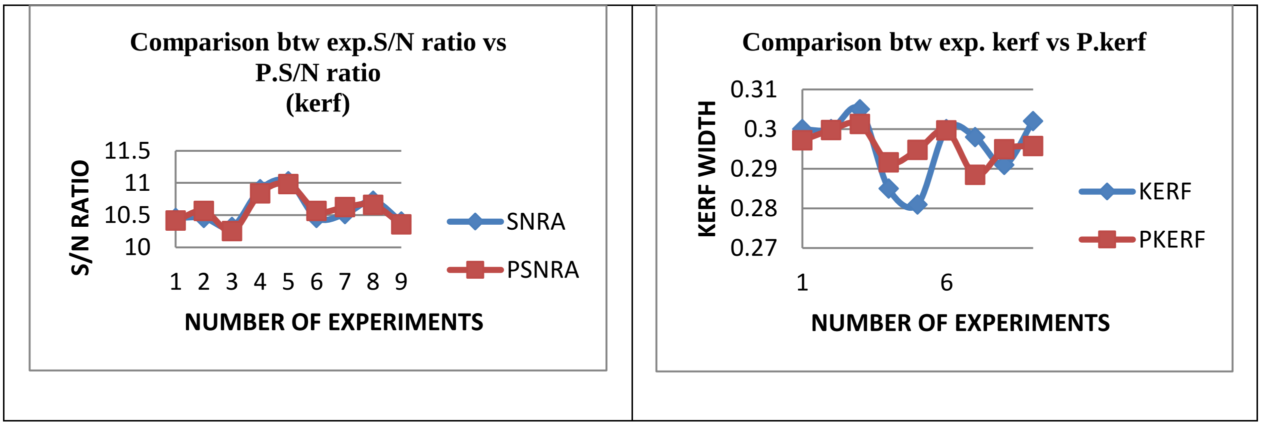

Figure 8: Comparison between experimental and predicted data of KERF

VI. CONCLUSIONS

The above study was solely dedicated to understand the effects caused by various machining parameters like voltage, pulse on time and pulse off time and their contribution to the variation of metal removal rate (MRR) and Kerf width. Thus, the conclusions of the above research are as follows:

Input energy is a function of pulse duration and voltage. As the Signal-to-Noise ratio for MRR when larger is better shows the optimum conditions for it as : Voltage:93volts ,Ton:3µs ,Toff:3µs It can be concluded that signal to noise ratio varies for different parameters. As the Signal-to-Noise ratio for Kerf width when smaller is better shows the optimum conditions for it as: Voltage: 93volts, Ton: 2µs, Toff 3µs. It can be concluded that signal to noise ratio varies for different parameters, for producing optimal working condition. From the Regression analysis for MRR it can be observed that, when the experimentally carried out readings are compared to predicted readings the error percentage is less than 5.5%. Hence, it can be concluded that optimization for material removal rate was accomplished. From Regression analysis for Kerf width it can be observed that, when the experimentally carried out readings are compared to predicted readings the error percentage is less than 5%. Hence, it can be concluded that optimization for Kerf width was accomplished. By using ANOVA, we can observe that 'T-on' plays the most significant role for change in MRR. Role for change in Kerf width.

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