Parametric Study Of Wire EDM through Design of Experiments

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I. BACKGROUND AND MOTIVATION

Wire Electrical Discharge Machining (Wire EDM) is an important non-traditional machining process used to cut complex shapes in electrically conductive materials with precision. Unlike traditional machining methods, wire EDM achieves material removal through a series of rapid and repetitive spark discharges between a thin wire electrode and the workpiece, separated by a dielectric fluid, without any direct mechanical contact. This allows wire EDM to machine very hard and complex geometries, where conventional techniques may face limitations.

A fundamental performance indicator in Wire EDM is the Material Removal Rate (MRR). A higher MRR means shorter machining times and reduced manufacturing costs. However, MRR is influenced by many operational parameters, like pulse-on time, pulse-off time, discharge current, voltage, wire tension, wire feed rate, and duty cycle. It is a big challenge to achieve optimal performance in WEDM, due to the process's inherent complexity and the presence of interacting variables.

While existing research has explored the impact of diverse parameters on MRR, a thorough understanding and effective optimization of the WEDM process remain ongoing areas of focus. This is particularly important as MRR directly affects manufacturing time and ultimately the final production cost. This course project is motivated by the need to address these knowledge gaps by systematically investigating the influence of input parameters on the MRR through the application of statistical methodologies. By employing a structured Design of Experiments (DOE) approach, this project aims to provide a more comprehensive insight into the relationships between key machining parameters and the resulting material removal rate in WEDM.

II. LITERATURE REVIEW

Wire EDM is a crucial non-traditional machining process widely employed for creating complex and intricate shapes in electrically conductive materials with high precision. WEDM is vital in numerous industries, including tool and die making, aerospace, and electronics, particularly when machining hard materials.

A primary focus in wire EDM research is understanding and optimizing key performance indicators, most notably the Material Removal Rate (MRR), which directly impacts machining efficiency and cost.

The study by Walid Meslameni experimentally investigated the impact of four EDM machining parameters on the MRR when machining C45 steel. They employed a full factorial 2^4 experimental design, resulting in 16 unique tests, each repeated twice. The experiments were conducted on an EROTECH basic 450 EDM machine. Statistical analysis was performed using ANOVA to determine the significance of the parameters and their interactions.

Evaluated Parameters and their influence on MRR:

- Pulse time (Ton): A longer pulse time (7 µs to 10 µs) showed a significant positive effect on MRR. It also amplified the effect of the discharge current on MRR.
- Rest time (Toff): Increasing rest time (6 µs to 8 µs) had a reversed negative effect on MRR as compared to Ton and discharge current.
- Discharge current (I): Varied between 32 A and 64 A and was identified as an influential factor for MRR, with MRR increasing as the discharge current increased. This is attributed to the greater discharge energy.
- Electrical resistivity of the electrode (Rho): Explored by using both graphite (1300 x 10^{-8} Ωm) and copper (1.72 x 10^{-8} Ωm) electrodes. The study found that the electrode material had a

[1]

very low influence on MRR.

Effect on Wire Wear (Wr): Wr was found to be significantly influenced by pulse time (Ton) (negatively correlated), discharge current (I) (positively correlated), and the electrode material (Rho), with graphite showing lower wear than copper.

The paper by Ramakrishnan and Karunamoorthy focuses on optimizing WEDM operations for multiple responses, including MRR, surface roughness, and wire wear ratio (WWR), using Taguchi's robust design approach with an L16 orthogonal array. Experiments were performed on a Robofil 290P CNC WEDM machine using a 0.25 mm diameter zinc-coated brass wire as the electrode and heat-treated tool steel as the workpiece. Each experiment was repeated four times under different cutting conditions.

Evaluated Parameters and their influence on MRR:

- Pulse on time: Evaluated at four levels and identified as one of the most influential factors affecting MRR. Higher levels of pulse on time generally resulted in an increased MRR.
- Wire tension: Explored across four levels. The study noted that increased wire tension at high discharge energy rates could lead to more wire breakage, potentially affecting MRR negatively in such conditions.
- Pulse off time: Varied across four levels, increased delay time was associated with more uniform and stable sparks, which can indirectly influence MRR.
- Wire feed speed: Examined at four levels but found to be statistically insignificant for MRR.
- Ignition current intensity: Varied across four levels and identified as another key influential factor on MRR. Higher ignition current intensity generally led to increased MRR.

Effect on Wire Wear Ratio (WWR): Pulse on time and ignition current intensity were found to significantly affect the wire wear ratio.

In summary, these papers consistently highlight the critical roles of pulse-on time and discharge/peak current in significantly influencing the Material Removal Rate in Wire EDM. While other parameters are explored and can have effects, these two consistently emerge as dominant factors.

While MRR is a primary concern, surface roughness is another critical aspect of the machined component's quality. Research indicates that parameters such as pulse-peak current, in addition to pulse-on time, have a substantial effect on the resulting surface finish. Increasing pulse-peak current tends to increase surface roughness, likely due to the more intense and energetic discharges creating larger craters on the machined surface. In contrast to pulse-on time and peak current, pulse-off time and wire tension have sometimes been found to have a less significant or even negligible impact on surface roughness under certain conditions.

The inherent complexity of WEDM arises from the numerous interacting variables, making it challenging to pinpoint individual parameter effects in isolation. To systematically investigate these complex relationships and optimize process performance, the application of statistical methodologies, such as Design of Experiments (DOE), is frequently employed. This approach allows for the identification of significant parameters, the understanding of their main effects, and the exploration of potential interaction effects between them. Ultimately, the goal of research is to develop predictive models for key performance indicators like MRR and surface roughness, and to identify optimal or near-optimal parameter settings to achieve desired machining outcomes.

III. OBJECTIVES

The overall goal of this project is to investigate the effect of various input parameters in the Wire EDM process on the Material Removal Rate (MRR) using a statistical Design of Experiments (DOE) approach.

The specific objectives of this project are to:

- Identify the significant input parameters (wire feed, pulse on and off time, voltage) that have a statistically significant effect on the Material Removal Rate (MRR) in the Wire EDM process.
- Understand the main effects of each significant input parameter on the MRR
- Evaluate potential interaction effects between the input parameters
- Develop a statistical model to predict the Material Removal Rate (MRR).
- Check the validity of the developed model
- Identify optimal or near-optimal settings for the significant input parameters to achieve a desired MRR.

IV. EXPERIMENTAL DESIGN

Resources & Equipment:
Material: Aluminium sheet (Thickness = 2mm) (acquired from MTL)

Machine: AccuteX AU-300iA Wire EDM Machine

Digital Microscope: Elikliv (High Performance & Sustainable Manufacturing Lab)

Independent Variables:

Input Parameters (variable) : (All input parameters are considered for 2 levels as follows)

- Ton (Pulse on Time) = **600 ns, 1050 ns**
- Toff (Pulse off time) = **4us, 9us**

  Pulse duration controls how long the electrical discharge lasts. A longer pulse duration may lead to deeper sparks, affecting material removal and surface finish
- V (open circuit voltage) = **89V, 131V**

  The applied voltage controls the discharge energy in the EDM process, affecting the spark intensity and the material removal rate
- WF (Wire Feed) = **92mm/s, 205 mm/s**

  A higher wire feed rate generally increases MRR by improving cutting speed and debris removal, but beyond an optimal limit, it can cause wire breakage or instability. A lower wire feed rate reduces MRR due to inefficient material removal and poor flushing

Constant Parameters - **kept constant** during experiment

- Ip - **mode 9** (AC Low energizing fine finish cutting)
- Cutting Speed **- 125 mm^2 / min**
- Wire Tension - **700 grams** (standard, easily available)
- Wire Material - **High Quality Brass Wire** (higher tensile strength, lower m.p., higher vapor pressure)
- Wire Diameter **- 1 mm**
- Dielectric fluid type - **Deionized water**
- Dielectric fluid flow rate - **4 Bar/kg**

Output Parameter(Dependent Variable) (Response):
MRR (Material Removal rate)

Design of Order of Experiments

- Used a **2^4 full factorial design** (16 unique runs, 2 replicates → 32 total experiments).
- Randomize run order to avoid influence of unknown factors and to minimize bias from machine warm-up or environmental drift.
- Thus, the randomization order we followed for running the experiments was 27, 9, 29, 21, 15, 25, 23, 6, 3, 4, 18, 8, 24, 28, 14, 19, 17, 12, 10, 30, 5, 32, 1, 7, 13, 2, 20, 22, 16, 31, 11, 26

Blocking Strategy: To reduce the effect of uncontrollable variations, the experiment will be blocked based on:

- Workpiece Material Batch – Different material batches can introduce variability, so experiments will be conducted in a single batch per block.
- Replication Strategy : Each run will be replicated two times to account for correct estimation of error.

Expected outcomes

- Factor Significance: Identification of dominant parameters (e.g., ton and voltage likely critical).
- Interaction Effects: Discovery of key interactions (e.g., ton×toff affecting debris accumulation).

Permissions were acquired from MTL and preliminary experiments were conducted under the supervision of Mr. Arun Nair.

V. PRELIMINARY EXPERIMENTS

For preliminary trails, wire feed was kept constant. Following are the set of parameters we chose to vary for the 4 trials:

1. Ton
2. Toff
3. Voltage

Length of cut (loc) = **10 mm**
Thickness (t) = **2 mm**

Ton (ns)	Toff (µs)	Voltage (V)	Time (s)	Kerf Width (mm)	MRR (mm^3/s)
600	4	89	313	0.37	0.023985
600	9	89	309	0.35	0.0229649
1050	4	131	287	0.407	0.0288633
1050	9	89	316	0.4	0.0257139

For the first run, wire breakage was observed.

$$\text{MRR} = \frac{(kw \times loc \times t) + (\frac{\pi}{2} \times (\frac{kw}{2})^2 \times t)}{time}$$

where, kw = kerf width

loc = length of cut

t = thickness (2 mm)

Post-processing:

A digital microscope was utilized to capture the images of the machined sample and ImageJ software was used to measure the kerf width for each run. Since the image processing software involves manually placing the line for measurements, it could introduce significant sources of error.

Fig: Microscope setup

Fig: Specimen under microscope for measuring widths

Potential Source of Variability		
Source of Variability	Impact on Experiment	Control Strategy
Machine warm-up effects	MRR may fluctuate due to thermal expansion	Randomize run order to distribute effects evenly
Environmental factors (temperature, humidity)	Affects dielectric fluid properties, machining stability	Conduct experiments in a controlled lab setting
Wire electrode wear	Alters cutting precision over time	Use new wire for each experimental run
Measurement error	Inconsistent MRR calculations (due to human error)	Use calibrated measuring instruments and repeat measurements

EXPERIMENTAL DATA

Exp No.	Ton(ns)	Toff(us)	Voltage (V)	Wire Feed (mm/s)	Time1 (s)	kerf Width1 (mm)	MRR1 (mm3/s)	Time2 (s)	Kerf Width 2 (mm)	MRR2 (mm3/s)
1	600	4	89	92	313	0.37	0.023985516	311	0.35	0.022671
2	600	4	89	205	311	0.373	0.024338316	309	0.351667	0.022927
3	600	4	131	92	307	0.383666667	0.025370962	306	0.353	0.023315
4	600	4	131	205	307	0.38	0.025124932	308	0.36	0.023784
5	600	9	89	92	309	0.35	0.022964927	310	0.34	0.0223
6	600	9	89	205	308	0.353	0.023239669	307	0.361667	0.023818
7	600	9	131	92	307	0.353	0.023315368	305	0.360333	0.023806
8	600	9	131	205	307	0.351333333	0.023203789	306	0.355667	0.023494
9	1050	4	89	92	316	0.4	0.025713924	315	0.38	0.024409
10	1050	4	89	205	314	0.407666667	0.02638151	312	0.384	0.024827
11	1050	4	131	92	287	0.407666667	0.028863394	289	0.380667	0.026924
12	1050	4	131	205	289	0.385333333	0.028713179	292	376	0.027148
13	1050	9	89	92	307	0.382666667	0.025303856	308	0.38	0.025125
14	1050	9	89	205	316	0.384	0.024670104	317	0.387	0.024866
15	1050	9	131	92	128	0.374333333	0.026137492	126	0.388333	0.027137
16	1050	9	131	205	135	0.378333333	0.026599012	133	0.374	0.026245

A total of 16 unique experimental runs were conducted, each repeated once, resulting in 32 trials overall. For each experiment, Kerf width was measured using a microscope. To minimize human and measurement errors, three readings were taken for each trial, and the average value was used as the final kerf width.

Using this average kerf width and the known experimental parameters, the Material Removal Rate (MRR) was calculated in mm³/s based on the standard formula..

Interesting Observation:

We observed that for experiment number 15 and 16 in the above table there was wire breakage 4 times. Due to which it was not able to operate for the whole 10 mm length of cut.

So to calculate MRR for this two experiments the length of cut was not 10 mm, instead it was 4.32 mm (for experiment 15) and 4.59 mm (for experiment 16). This length of cut value in mm was the length of material that was cut till 4 times the wire was broken. We can say that the parameter data of experiment 15 and 16 is not feasible for cutting aluminium sheets of 2 mm thickness.

From this Interesting observation we observed that when ton is high level, toff is high level, voltage is high level then there is more frequency of wire breaks irrespective of what the wire feed level is high or low. It becomes inefficient to operate with these parameters.

All these experiments were performed in randomized order as described above. All experiments were completed in 2 days. 16 set of experiments were performed on one day (leaving 5 mins in between consecutive runs to ensure no warm up effects) and other 16 experiments were performed on another day. By doing this we are ensuring that the one set of experiments (16) are operated under the same Lab temperature and other environmental conditions.

This approach helps in minimizing the influence of uncontrolled variables, such as fluctuations in ambient temperature, humidity, or machine wear over time. By isolating these external factors, we can ensure that any observed variations in performance or MRR are attributable to the process parameters alone, thereby enhancing the validity and repeatability of the experimental results.

Repeatability & Measurement Consistency:

The repeated trials helped confirm the consistency of the readings, especially for MRR values in stable parameter settings. The variation between the two sets of trials for each experiment was found to be minimal, indicating good repeatability and low experimental noise.

Cut Quality vs. Productivity Trade-Off:

In some cases, higher MRRs were achieved at the cost of surface finish or tool stability. For example, experiment numbers 15 and 16 yielded higher MRRs but with frequent interruptions due to wire failure. This indicates that a trade-off exists between achieving maximum MRR and maintaining a stable, continuous cut.

Impact of Wire Feed:
While wire feed seemed less influential in isolation, its interaction with other parameters (e.g., Voltage × Wire Feed or Ton × Wire Feed) might have a secondary influence on MRR and wire life. This aspect could be explored more rigorously in a follow-up factorial design.

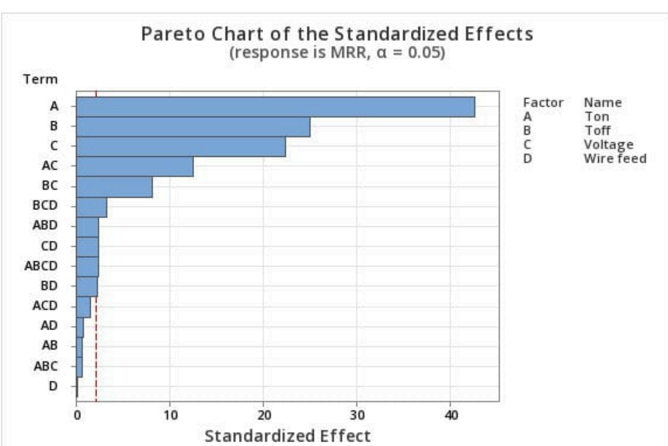
VI. Statistical Analysis

ANOVA analysis

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	**16**	**0.000101**	**0.000006**	**201.21**	**0**
Blocks	**1**	**0**	**0**	**1**	**0.333**
Linear	**4**	**0.000092**	**0.000023**	**739.39**	**0**
Ton	1	0.000057	0.000057	1821.93	0
Toff	1	0.00002	0.00002	630.96	0
Voltage	1	0.000016	0.000016	504.62	0
Wire feed	1	0	0	0.05	0.821
2-Way Interactions	**6**	**0.000007**	**0.000001**	**39.23**	**0**
Ton*Toff	1	0	0	0.53	0.476
Ton*Voltage	1	0.000005	0.000005	156.65	0
Ton*Wire feed	1	0	0	0.72	0.409
Toff*Voltage	1	0.000002	0.000002	66.48	0
Toff*Wire feed	1	0	0	5.14	0.039
Voltage*Wire feed	1	0	0	5.83	0.029
3-Way Interactions	**4**	**0.000001**	**0**	**4.91**	**0.01**
Ton*Toff*Voltage	1	0	0	0.52	0.481
Ton*Toff*Wire feed	1	0	0	6.21	0.025
Ton*Voltage*Wire feed	1	0	0	2.33	0.148
Toff*Voltage*Wire feed	1	0	0	10.57	0.005
4-Way Interactions	**1**	**0**	**0**	**5.77**	**0.03**
Ton*Toff*Voltage*Wire feed	1	0	0	5.77	0.03
Error	**15**	**0**	**0**		
Total	**31**	**0.000101**			

Below Plot shows the significance order of main effects and interaction effects where the red line is the F critical line.



(Minitab was used for the above ANOVA table, the zeros in Adj SS and Adj MS values are not numerically equal to 0. These values are just very close to zero and the software tends to round off these values to zero as output)

$$\hat{y} = 0.02490 + 0.00129x_1 - 0.00038x_2 + 0.00068x_3 + 0.00006x_4 - 0.00005x_5 + 0.00035x_6 - 0.00007x_7 - 0.00020x_8 - 0.00006x_9 - 0.00010x_{10} - 0.00006x_{11} - 0.00009x_{12} + 0.00006x_{13} - 0.00001x_{14} + 0.00010x_{15}$$

This above equation was calculated from [beta] = ([X*] Yexp)/([X*][X])
where [X*] is the transpose of X.

Here in this above equation:
x1 = Ton (in ns)
x2 = Toff (in us)
x3 = V (in volts)
x4 = WF (inn mm/s)
x5 = Ton . Toff
x6 = Ton . V
x7 = Ton . WF
x8= Toff . V
x9 = Toff . WF
x10 = V . WF
x11 =Ton . Toff . V
x12 = Ton . Toff . WF
x13 = Ton . V . WF
x14 = Toff . V . WF
x15 = Ton . Toff . V . WF

The value of Fcritical found (with 95% confidence interval) was 4.54 and from the above ANOVA table only the following interactions were found to be significant:
x1, x2, x3, x6, x8, x9, x10, x12, x14, x15

After including only significant parameters from ANOVA analysis. Our final regression model becomes as follows:

$$\hat{y} = 0.02490 + 0.00129x_1 - 0.00038x_2 + 0.00068x_3 + 0.00035x_6 - 0.00020x_8 - 0.00006x_9 - 0.000010x_{10} - 0.00009x_{12} - 0.00001x_{14} + 0.00010x_{15}$$

VII. Model Adequacy Analysis

Before looking at the results from ANOVA for this study, assumptions of normality, independence, and constant variance of residuals has to be verified from the above regression equation.

1. **Normality of residuals** was first checked using a normal probability plot. The normal probability plot of the residuals for this experiment is shown in below figure.

   Coefficient of correlation (r) of the plot was then performed. At 95% confidence level, when the number of residuals is 16, the critical value of coefficient of correlation between residuals and its expected value under normality is 0.954. From below plot, the correlation coefficient of the plot is 0.9924, which is greater than its critical value. This indicates that the normal distribution of residuals was satisfied.

2. **Independence :** Plotting the residuals in time order of data collection. This method is helpful in checking independence assumption on the residuals. It is desired that the residual plot should contain no obvious patterns. However, it is noticeable from below figure that there is no pattern in residuals.

   At 95% confidence level, when the number of experimental variables is 4 and the number of residuals is 32, the upper bound value of Durbin–Watson test is 1.75. Durbin–Watson test statistic for this experiment was 1.955, which is larger than the upper bound value. Therefore, independence assumption on the residuals was fulfilled for this experiment.

3. **Constant Variance:** Plot of residuals versus predicted values. This plot is the typical testing for the assumption of constant variance. If the assumption is satisfied, the residual plot should be structureless. It is obvious from the below plot that the pattern is structureless.

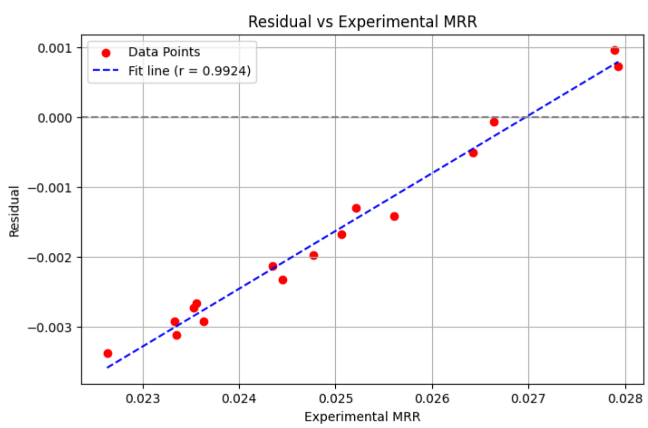


Fig: Residual vs Experimental MRR (Normality check)

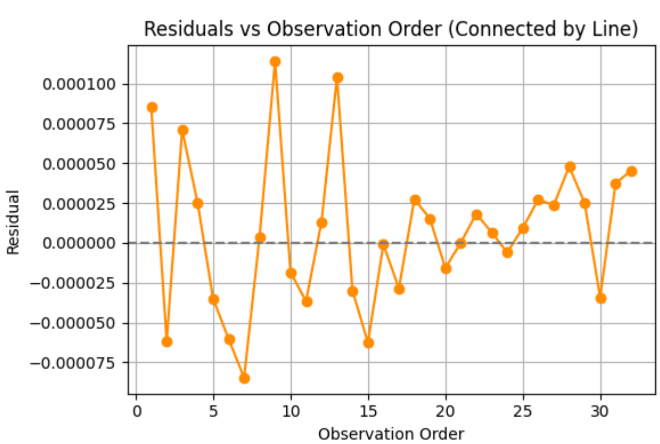


Fig: Residual vs Observation Order (Independence check)

After the validity of the assumptions was carefully checked, no assumption was violated. Therefore, the ANOVA of this screening experiment was sufficiently reliable

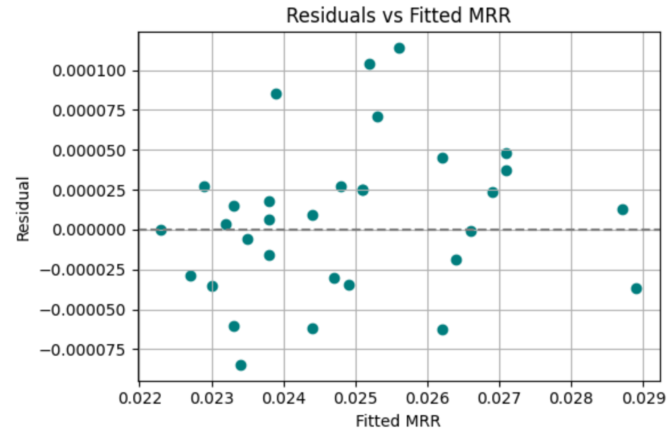


Fig: Residual vs Predicted MRR (Constant Variance check)

VIII. OPTIMIZATION

In this project, we used Response Surface Methodology to model MRR as a function of four variables: Ton, Toff, Voltage, and WireFeed.

RSM is a set of statistical tools used to **optimize a process** by finding the best combination of input variables (like Ton, Toff, Voltage, etc.) to maximize or minimize a response (like Material Removal Rate, MRR)

Approach: Steepest Ascent Method

Initial Guess Point (Origin)

The starting point ("Origin") was chosen as

Origin = Ton=900 ns, Toff=9 us, Voltage=120 V, WireFeed=170 mm/s.
We used our Final regression equation as our Response surface.

- Gradient Calculation:
  The coefficients of the model determined the direction of improvement. Variables with positive coefficients (e.g., Ton, Voltage) were increased, while those with negative coefficients (e.g., Toff) were decreased.
- Steepest Ascent Path:
  We moved in the direction of the gradient (Δ) to maximize MRR. Each step adjusted the variables by a small amount proportional to their impact on MRR

Analysis of the Steepest Ascent Table:

Steepest Ascent Table:

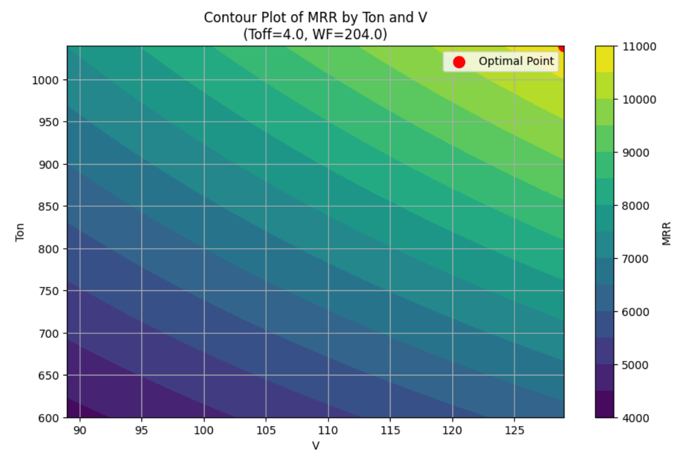
	Step	Ton	Toff	Voltage	WireFeed	Predicted MRR
0	Origin	900.00	9.00	120.00	170.0	0.025176
1	Origin + 1Δ	900.06	8.00	120.02	170.0	0.025389
2	Origin + 2Δ	900.12	7.00	120.04	170.0	0.025602
3	Origin + 3Δ	900.19	6.01	120.06	170.0	0.025816
4	Origin + 4Δ	900.25	5.01	120.08	170.0	0.026030
5	Origin + 5Δ	900.31	4.01	120.11	170.0	0.026243
6	Origin + 6Δ	900.37	3.01	120.13	170.0	0.026458
7	Origin + 7Δ	900.44	2.02	120.15	170.0	0.026672
8	Origin + 8Δ	900.50	1.02	120.17	170.0	0.026886
9	Origin + 9Δ	900.56	0.02	120.19	170.0	0.027101
10	Origin + 10Δ	900.62	-0.98	120.21	170.0	0.027316

From the Plot blow it is seen that:

The upward trend confirms that moving in the gradient direction improves MRR. The linear increase suggests the model works well in this region.

MRR Increases: From 0.025176 to 0.026243 in our experiment range steps. After that MRR increases out of our experiment domain till 10th step where the toff goes negative, which is not possible,Variable Trends:

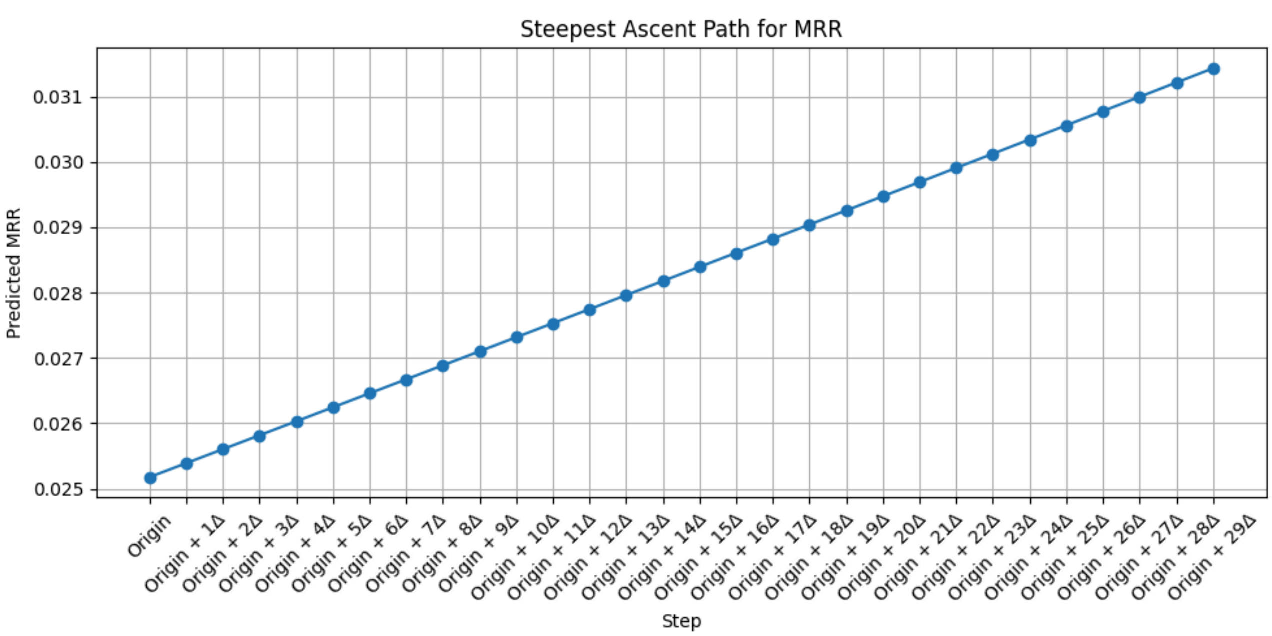
- Ton: Gradually increases (positive coefficient).
- Toff: Decreases sharply (negative coefficient).
- Voltage: Slightly increases (positive coefficient).
- WireFeed: Unchanged (its coefficient was negligible in the model).



So in our range the optimal parameter settings is:

Ton :900.31ns   Toff :4.01us V :120.11V

WF(not significant)



IX. CONCLUSIONS

In conclusion we experimented on the influence of Wire EDM input parameters (pulse-on time, pulse-off time, voltage, and wire feed) on the Material Removal Rate (MRR) using a full factorial Design of Experiments. Statistical analysis through ANOVA identified pulse-on time, pulse-off time, and voltage as significant main effects, along with several significant two-way and higher-order interactions. A regression model was developed and validated for its adequacy by confirming the normality, independence, and constant variance of residuals.

Optimization using the Steepest Ascent Method of Response Surface Methodology indicated that increasing pulse-on time and voltage while decreasing pulse-off time leads to improved MRR within the experimental domain. The wire feed rate was found to be statistically insignificant for MRR in this study. The near-optimal parameter settings identified within the explored range were approximately Ton: 900.31 ns, Toff: 4.01 µs, and V: 120.11 V. This study provides valuable insights into the complex relationships between WEDM parameters and MRR, offering a foundation for further optimization efforts and improved machining efficiency.

X. ACKNOWLEDGEMENT

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XI. REFERENCES

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