Establishing a relationship between machining parameters and output responses for cutting stainless steel ICSS 1218 by Wire EDM

Dr Rajeev N1, Jishnu J2
1 Associate Professor, Department of Mechanical Engineering, NSSCE Palakkad
2 Mtech Student, Department of Mechanical Engineering, NSSCE Palakkad

E-mail: rajeevmaliyil@gmail.com

Abstract. Stainless steel ICSS 1218 have large potential in the aerospace sector due to their inherent characteristic and advantageous properties like strength, ductility, weldability and corrosion resistance. The Wire Electric Discharge Machining (Wire EDM) is a thermal machining process capable of accurately machining parts with high hardness or complex shapes. One of the statistical softwares Minitab 17 was used for conducting the analysis and develop a mathematical model of the relation connecting the input parameters pulse on time, flushing discharge, and wire feed rate and output responses surface roughness and material removal rate. This model is found reasonably accurate. Experimentation was conducted in a series of tests called runs, in which changes are made in the input variables in order to identify the reasons for changes in the output response.

1. Introduction

Machining is an important manufacturing process to obtain various shapes of the components. Over the decades conventional machining has sufficed the requirement of industries. But new exotic work materials as well as innovative geometric design of products and components are putting pressure on capabilities of conventional machining processes to manufacture the components with desired tolerances economically. This has lead to the development of non-conventional manufacturing processes in the industry as efficient and economic alternatives to conventional ones. Wire Electrical Discharge Machining (WEDM) is one of such nonconventional manufacturing processes. As the metal removal is based on complex thermal and chemical phenomena, in order to understand its effects on the machined components investigation has been made in this research. Wire-electrical discharge machining (WEDM) is a non-traditional machining process in which a pulsed voltage difference between a wire electrode and a conductive work piece initiates sparks which erode work piece material. Removing material in such away that it often advantageous when the work piece material would be difficult to machine with traditional machine tools due to high strength, hardness, toughness, etc.

1.1 Wire Electric Discharge Machining (WEDM)

It is probably the most exciting and diversified machining process developed for this industry in the recent years. Common materials such as steel, aluminum, copper, and graphite, to exotic space-age alloys including hastelloy, waspalloy, inconel, titanium, carbide, polycrystalline diamond compacts, conductive ceramics etc. are popularly processed by WEDM. “For the first time, we have indigenously developed and processed the aerospace grade stainless steel in Salem. The steel slabs were provided by ISRO. The end result was development of import-substitute exotic Russian grade (ICSS-1218) slabs that are used in the construction of the rocket launch vehicles. It will be shipped to ISRO’s Liquid Propulsion System Centre (LPSC) soon,” claimed by Salem Steel technical team. Seeking the help of ISRO scientists, a SAIL team processed electro-slag re-melted (ESR) and forged slabs. The final product conforms to ICSS-1218 that is equivalent to SS 321 grade stainless steel slabs. “We have been regularly...
processing stainless steel for various satellite launch vehicles, including the Polar Satellite Launch Vehicles that carried the Chandrayaan and Mangalyaan missions into the space, as per ISRO press release.

2. Literature review

A thorough literature review was done to amass the knowledge about the recent advances in the area of WEDM and the following observations were made. Thomas R Newton [1] conducted an experiment to determine the main EDM parameters which contribute to recast layer formation in Inconel 718. It was found that average recast layer thickness increased primarily with energy per spark, peak discharge current and current pulse duration. Over the range of parameters tested, the recast layer was observed to be between 5 and 9 µm in average thickness, although highly variable in nature.

Sasan Khalaj Amineh [2] explored the feasibility of removing the recast layer formed on aluminium alloy cylindrical specimens machined by wire electric discharge machining by using magnetic abrasive finishing (MAF). This investigation demonstrated that MAF process can improve the quality of WEDM machined surfaces effectively by removing the recast layer. This work studied the effect of some parameters, ie, linear speed, working gap, abrasive particle size, and finishing time on surface roughness and recast layer thickness using full factorial analysis. Three level full factorial technique was used as design of experiments for studying the selected factors.

Bhosale Sachin [3] conducted an experiment to determine the main EDM parameters which contribute to recast layer thickness and micro hardness of MDN 250 alloy. Experimentation has been done using Taguchi’s L9 orthogonal array. Each experiment was conducted under different combinations of pulse on time, pulse off time, and wire feed. The optimum machining parameter combination was obtained by using the analysis of signal-to-noise (S/N) ratio, analysis of means and analysis of variance (ANOVA) in Minitab 15 software.

B Naga Raju [4] made an attempt to study the effect of WEDM parameters like pulse on time, pulse off time, and peak current on surface roughness and material removal rate in aluminium metal matrix composites. Experimentation was conducted in a series of runs, in which changes are made in the input variables in order to identify the reasons for changes in the output response using Response Surface Methodology.

Rajesh Kumar Bhuyan [5] explored the effect of process parameters such as pulse on time, peak current, and flushing pressure on material removal rate, tool wear rate, and surface roughness during EDM of Al-SiC12% MMC. The experiment was followed by Central composite design (CCD) method under different combination of process parameters. Response surface methodology was used to develop the mathematical model and to correlate the process parameters with the response. Further, analysis of variance technique was employed to check the significance of the model and confirmation test is conducted to compare the experimental data with the predicted data to identify the effectiveness of the proposed method.

It was observed from the literature review that researchers have focussed on different combinations of input parameters and output responses for their studies. It was observed that there is a need to focus on a more sets of input parameters and explore their effect on multiple output responses, Therefore, the present paper investigates the effect of input parameters like pulse on time, flushing discharge, and wire feed rate on the output responses, surface roughness and material removal rate.

3. Experimental work

The details of the Work piece selected for the study is as follows. Stainless Steel ICSS 1218 of size 10mm x 10mm x 20mm. 27 similar pieces were prepared for the experiments, since three parameters with three levels were considered. A total 27 combinations of parameters were selected ($3^3$). The fig 1 shows the work piece. Choices of the factors that need to be varied in the experiment should be made. Control parameters are parameters which are directly affecting the response variables. From the available literatures, it was observed that the main parameters that affects Wire EDM are pulse on time, pulse off time, wire feed rate, and peak current. Flushing discharge also found to have significant impact on surface roughness.
Therefore, the test parameters selected for this work are pulse on time, flushing discharge, and wire feed rate. The parameter level selected as three. Proper selection of the cutting parameters was carried out based on the data available from the literatures and operator's opinion. The experiments were conducted at pulse on time 108, 110, 112 µs, flushing discharge 8, 10, 12 L/min, and wire feed rate 4, 6, 8 m/min respectively, as shown in Table 1.

| Parameters                  | Symbol | Levels       |
|-----------------------------|--------|--------------|
| Pulse on time (µs)          | $T_{on}$| 108, 110, 112|
| Flushing discharge (L/min)  | $F_d$  | 8, 10, 12    |
| Wire feed rate (m/min)      | $W_f$  | 4, 6, 8      |

### 4. Equipments used

#### 4.1 CNC Wire EDM

Computer numerical control (CNC) machines are widely used in manufacturing industry. The CNC machine comprises of the computer in which the program is fed for cutting of the metal of the job as per the requirements. The main function of CNC machines is to remove some of the metal so as to give it proper shape such as round, rectangular, etc. ELECTRONIC ULTRACUT S1 CNC WIRE EDM was used for machining in this experiment. Figure 2 shows the ELECTRONICA ULTRACUT S1 CNC machine.

Surface roughness and material removal rate are the performance measures taken for this work. Inspection and assessment of surface roughness of machined work pieces was carried out by Taylor/Hobson Precision form Surtronic 3+. Material removal rate can be calculated by taking the weight of the work piece before and after machining and dividing the difference of weight by density of the material and machining time. The figure 3 shows the surface roughness tester.
4.2 Material Removal Rate Calculation

Material removal rate is defined as the amount of material removed per unit time. Material removal rate is calculated as the ratio of amount of material removed to the time taken for machining.

\[
\text{MRR} = \frac{(W_b - W_a)}{\rho \times t} \quad [7]
\]

where

- \(W_b\) – weight of the specimen before machining
- \(W_a\) – weight of the specimen after machining
- \(\rho\) – density of the material (7.92 g/cm\(^3\))
- \(t\) – machining time

4.3 Data Collection

Stainless Steel ICSS 1218 specimen were prepared first with the help of conventional milling machine. Twenty seven number of samples of same material and same dimensions were made. After that the weight of each samples have been measured accurately with the help of a weighing machine. Then using different levels of the process parameters specimens were machined in CNC Wire EDM accordingly. After machining, the surface roughness have been measured with the help of Taylor/Hobson Precision tester. The results were tabulated as shown in Table 2.

| Exp no | Pulse on time (µs) | Flushing discharge (L/min) | Wire feed rate (m/min) | \(R_a\) (microns) | MRR (mm\(^3\)/min) |
|--------|-------------------|---------------------------|-----------------------|-----------------|------------------|
| 1      | 110               | 8                         | 4                     | 3.07            | 7.72             |
| 2      | 110               | 8                         | 6                     | 3.12            | 7.46             |
| 3      | 110               | 8                         | 8                     | 3.04            | 7.18             |
| 4      | 110               | 10                        | 4                     | 2.82            | 7.21             |
| 5      | 110               | 10                        | 6                     | 2.92            | 7.36             |
| 6      | 110               | 10                        | 8                     | 2.76            | 6.62             |
| 7      | 110               | 12                        | 4                     | 2.66            | 6.91             |
| 8      | 110               | 12                        | 6                     | 2.9             | 7.89             |
| 9      | 110               | 12                        | 8                     | 3.02            | 7.48             |
| 10     | 108               | 8                         | 4                     | 2.98            | 5.62             |
|   |   |   |   |   |   |
|---|---|---|---|---|---|
| 11 | 108 | 8 | 6 | 2.3 | 5.23 |
| 12 | 108 | 8 | 8 | 2.56 | 5.11 |
| 13 | 108 | 10 | 4 | 2.62 | 5.82 |
| 14 | 108 | 10 | 6 | 2.52 | 5.989 |
| 15 | 108 | 10 | 8 | 2.78 | 5.22 |
| 16 | 108 | 12 | 4 | 2.7 | 5.68 |
| 17 | 108 | 12 | 6 | 2.68 | 5.86 |
| 18 | 108 | 12 | 8 | 2.4 | 6.05 |
| 19 | 112 | 8 | 4 | 2.7 | 11.72 |
| 20 | 112 | 8 | 6 | 2.76 | 7.91 |
| 21 | 112 | 8 | 8 | 2.78 | 7.69 |
| 22 | 112 | 10 | 4 | 2.92 | 8.69 |
| 23 | 112 | 10 | 6 | 2.78 | 7.66 |
| 24 | 112 | 10 | 8 | 2.84 | 8.02 |
| 25 | 112 | 12 | 4 | 3.1 | 8.24 |
| 26 | 112 | 12 | 6 | 3.08 | 8.14 |
| 27 | 112 | 12 | 8 | 2.74 | 7.63 |

5. Data Analysis

5.1 Multiple Regression Model

The relationship between a set of independent variables x and the response variable y is determined by a mathematical model called regression model. In general, a multiple-regression model with q independent variable takes the form of

For second degree model

\[ y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i<j} \beta_{ij} x_i x_j + \sum_{i=1}^k \beta_{ii} x_i^2 + \epsilon \]  [6]

Where y is the corresponding response

Mathematical relationship between the input parameters and surface roughness

For second degree

\[ R_s = -551 + 10.21 x T_{on} - 1.89 x F_d - 0.55 x W_f - 0.0469 x T_{off}^2 + 0.0093 x F_d^2 + 0.0051 x W_f^2 + 0.0154 x T_{on} x F_d + 0.0042 x T_{on} x W_f + 0.0015 x F_d x W_f. \]  
The data analysis was done by Minitab 17 and the results were tabulated as shown in Table 3.
Table 3 Fitted value compared with experimental value

| Exp no | Pulse on time (µs) | Flushing discharge (L/min) | Wire feed rate (m/min) | $R_a$ (microns) | $R_a$ predicted | % error  |
|--------|-------------------|-----------------------------|------------------------|-----------------|-----------------|----------|
| 1      | 110               | 8                           | 4                      | 3.07            | 2.9862037       | 2.7295   |
| 2      | 110               | 8                           | 6                      | 3.12            | 2.9237037       | 6.2915   |
| 3      | 110               | 8                           | 8                      | 3.04            | 2.9023148       | 4.5291   |
| 4      | 110               | 10                          | 4                      | 2.82            | 2.9414814       | -4.3078  |
| 5      | 110               | 10                          | 6                      | 2.92            | 2.8848148       | 1.2049   |
| 6      | 110               | 10                          | 8                      | 2.76            | 2.8692592       | -3.9586  |
| 7      | 110               | 12                          | 4                      | 2.66            | 2.9712037       | -11.699  |
| 8      | 110               | 12                          | 6                      | 2.9              | 2.920370        | -0.7024  |
| 9      | 110               | 12                          | 8                      | 3.02            | 2.9106481       | 3.6209   |
| 10     | 108               | 8                           | 4                      | 2.98            | 2.7567592       | 7.4913   |
| 11     | 108               | 8                           | 6                      | 2.3             | 2.6775925       | -16.417  |
| 12     | 108               | 8                           | 8                      | 2.56            | 2.6395370       | -3.1069  |
| 13     | 108               | 10                          | 4                      | 2.62            | 2.6503703       | -1.1591  |
| 14     | 108               | 10                          | 6                      | 2.52            | 2.5770370       | -2.2633  |
| 15     | 108               | 10                          | 8                      | 2.78            | 2.5448148       | 8.4598   |
| 16     | 108               | 12                          | 4                      | 2.7              | 2.6184259       | 3.0212   |
| 17     | 108               | 12                          | 6                      | 2.68            | 2.5509259       | 4.8161   |
| 18     | 108               | 12                          | 8                      | 2.4             | 2.5245370       | -5.1890  |
| 19     | 112               | 8                           | 4                      | 2.7             | 2.8400925       | -5.1886  |
| 20     | 112               | 8                           | 6                      | 2.76            | 2.7942592       | -1.2412  |
| 21     | 112               | 8                           | 8                      | 2.78            | 2.7895370       | -0.3430  |
| 22     | 112               | 10                          | 4                      | 2.92            | 2.8570370       | 2.1562   |
| 23     | 112               | 10                          | 6                      | 2.78            | 2.8170370       | -1.3322  |
| 24     | 112               | 10                          | 8                      | 2.84            | 2.8181481       | 0.7694   |
| 25     | 112               | 12                          | 4                      | 3.1             | 2.9484259       | 4.8894   |
The following plots were generated by the software and they provide more insights into the behavior of selected parameters.

5.2 Normal probability plot for Ra

The normal probability plot as shown below represents clear pattern indicating that all the factors and their interaction given in are affecting the Ra.

![Normal Probability Plot](image)

5.3 Versus Fits for Ra

The below graph shows the standardized residual Vs fitted value for surface roughness. This indicates that the maximum variation which shows the high correlation that exists between fitted values and observed values.

![Versus Fits](image)

The results were further analysed with ANOVA and F test was performed to check the adequacy of the model. The result obtained is shown in the Table 4, which shows that most influencing parameter that affect surface roughness is pulse on time. A P-value less than 0.05 indicate that the performance of the parameter is statistically significant (Kothari, 2009).

| Source | Sum of squares | DF  | Mean square | F value | P value |
|--------|----------------|-----|-------------|---------|---------|
| Model  | 055451         | 9   | 0.061612    | 1.72    | 1.60    |
| $T_{on}$ | 0.25902      | 1   | 0.259200    | 7.24    | 0.015   |
| $F_d$ | 0.00005        | 1   | 0.000050    | 0.00    | 0.971   |
| $W_f$ | 0.02347        | 1   | 0.023472    | 0.66    | 0.429   |
| $T_{on}^2$ | 0.21156     | 1   | 0.2111563   | 5.91    | 0.026   |
| $F_d^2$ | 0.00831      | 1   | 0.008313    | 0.23    | 0.636   |
For second degree

\[
MRR = -1135 + 18.7 \times T_{on} + 9.39 \times F_d + 8.89 \times W_f + 0.0747 \times T_{on}^2 + 0.0603 \times F_d^2 + 0.0224 \times W_f^2 - 0.1029 \times T_{on} \times F_d - 0.0952 \times T_{on} \times W_f + 0.1127 \times F_d \times W_f
\]

The results were tabulated and values were obtained as shown in Table 5.

| Exp no | Pulse on time (µs) | Flushing discharge (L/min) | Wire feed rate (m/min) | MRR (microns) | MRR predicted | % error |
|-------|-------------------|---------------------------|------------------------|----------------|---------------|---------|
| 1     | 110               | 8                         | 4                      | 7.72           | 8.34          | -8.038  |
| 2     | 110               | 8                         | 6                      | 7.46           | 7.43         | 0.3629  |
| 3     | 110               | 8                         | 8                      | 7.18           | 6.70         | 6.6235  |
| 4     | 110               | 10                        | 4                      | 7.21           | 7.55         | -4.725  |
| 5     | 110               | 10                        | 6                      | 7.36           | 7.09         | 3.6151  |
| 6     | 110               | 10                        | 8                      | 6.62           | 6.81         | -2.964  |
| 7     | 110               | 12                        | 4                      | 6.91           | 7.24         | -4.823  |
| 8     | 110               | 12                        | 6                      | 7.89           | 7.24         | 8.2716  |
| 9     | 110               | 12                        | 8                      | 7.48           | 7.41         | 0.9286  |
| 10    | 108               | 8                         | 4                      | 5.62           | 5.85         | -4.154  |
| 11    | 108               | 8                         | 6                      | 5.23           | 5.33         | -1.849  |
| 12    | 108               | 8                         | 8                      | 5.11           | 4.98         | 2.5628  |
| 13    | 108               | 10                        | 4                      | 5.82           | 5.48         | 5.9224  |
| 14    | 108               | 10                        | 6                      | 5.989          | 5.39         | 9.8452  |
| 15    | 108               | 10                        | 8                      | 5.22           | 5.50         | -5.412  |
| 16    | 108               | 12                        | 4                      | 5.68           | 5.58         | 1.7677  |
| 17    | 108               | 12                        | 6                      | 5.86           | 5.95         | -1.612  |
| 18    | 108               | 12                        | 8                      | 6.05           | 6.51         | -7.578  |
| 19    | 112               | 8                         | 4                      | 11.72          | 10.23        | 12.715  |
5.4 Normal probability plot for MRR

The normal probability plot as shown below represents clear pattern indicating that all the factors and their interaction given in are affecting the MRR

![Normal Probability Plot](image1)

Fig 6 Normal Probability Plot

5.5 Versus Fits for MRR

The below graph shows the standardized residual Vs fitted value for MRR. This graph also indicate the maximum variation which shows the high correlation that exists between fitted values and observed values.

![Versus Fits](image2)

Fig 7 Versus Fits

The results were further analysed with ANOVA and F test was performed to check the adequacy of the model. The result obtained is shown in the Table 6, which shows that most influencing parameter
that affect MRR is pulse on time, wire feed rate and interactions of pulse on time, flushing discharge and wire feed rate. A P-value less than 0.05 indicate that the performance of the parameter is statistically significant (Kothari, 2009).

Table 6 Parameter that affect MRR

| Source       | Sum of squares | DF | Mean square | F value | P value |
|--------------|----------------|----|-------------|---------|---------|
| Model        | 44.8051        | 9  | 4.9783      | 13.58   | 0.000   |
| $T_{on}$     | 35.0591        | 1  | 35.0591     | 95.61   | 0.000   |
| $F_d$        | 0.1721         | 1  | 0.1721      | 0.47    | 0.503   |
| $W_f$        | 2.4273         | 1  | 2.4273      | 6.62    | 0.020   |
| $T_{on}^2$   | 0.5362         | 1  | 0.5362      | 1.46    | 0.243   |
| $F_d^2$      | 0.3491         | 1  | 0.3491      | 0.95    | 0.343   |
| $W_f^2$      | 0.0481         | 1  | 0.0481      | 0.13    | 0.722   |
| $T_{on} \times F_d$ | 2.0336 | 1  | 2.0336      | 5.55    | 0.031   |
| $T_{on} \times W_f$ | 1.7404 | 1  | 1.7404      | 4.73    | 0.044   |
| $F_d \times W_f$ | 2.4390 | 1  | 2.4390      | 6.65    | 0.020   |

6. Results and Conclusions

Experiments were done successfully with considered input parameters and was evaluated using appropriate statistical techniques. Mathematical equation have been developed showing the relation between input parameters and responses with the help of Regression analysis. The normal probability plot and Versus Fits graphs were plotted successfully according to the research objectives. The association between input parameters and output responses are observed in literature. These associations were further consolidated using the regression models. Thus, the most important input parameters which influence MRR and Surface roughness during the WEDM process of ICSS 1218 steel were evaluated.

7. References

[1] Thomas R Newton, Shreyas N Melkote and Thomas R Watkins “Investigation of the effect of process parameters on the formation and characteristics of recast layer in wire EDM of Inconel 718”, Journal of Material science and Engineering Elsevier (2009).

[2] Sasan KhalajAmineh, Alireza Fadaei Taharani and Aminollah Mohammadi “Improving Surface Quality in WEDM specimen by removing recast layer using MAF method”, International Journal of Advanced Manufacturing Technology (2012).

[3] Bhosale Sachin, Sheldge Shrinivas, Bhagwat Vishal “Study and Analysis of Recat layer formation during WEDM process”, International Journal of Innovative Research in science Engineering and Technology , (2015).

[4] B Naga Ragu, M Raja Roy, S Rajesh, K Ramji “Optimization of machining parameters for cutting AMMC’s on Wire cut electric discharge machining using RSM” International Journal of Engineering Trends and Technology vol 23 (2015).

[5] Rajesh Kumar Bhuyan, B C Routara, Arun kumar Parida and A K Sahoo “Parametric Optimization of Al-SiC12% MMC machining by EDM” International Design and Research Conference (2014).

[6] Kothari R, “Research Methodology” New age publications (2009).

[7] Dr Rajeev N and Aswathy V G, “Effect of Machining Parameters on Surface roughness, Material removal rate and Roundness error during the wet turning of Ti-6Al-4V alloy” (2015)