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Optimization of Machining Parameters in Wire Electric Discharge Machining Inconel 600 Using Regression analysis

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Abstract

In this investigation, Inconel 600 is used as the workpiece material, which is typically applied in aerospace products, chemical processing equipment, furnace parts etc., due to its good resistance to stress and wear resistance. In this work, the effect of machining parameters of Wire Electric Discharge Machining (WEDM) process is investigated. Molybdenum wire electrode of 0.1mm diameter and de-ionized water dielectric medium are used for machining. Voltage, Pulse on-time, Pulse Off-time, Peak Current and Bed speed are considered as the machining parameters. Recast layer thickness is considered as the response parameter. The type of design of experiments considered for this work is Taguchi's L18 orthogonal array. Analysis of variance is indicating the percentage contribution of each machining parameters on response parameters. The optimum combination of machining parameters yielded minimum Recast layer thickness 4.11µm.

Keywords: *Design of Experiments, Inconel 600, Recast Layer, Wire Electric Discharge Machining*

1.0 Introduction

As manufacturing technology grow and expand, advanced materials and practices are being used more often. There is a fascinating group of materials known as super alloys which have desirable properties for industrial applications. Super alloys are strong, can handle high temperatures, lightweight and corrosion resistant to different types of substances or reactions. Inconel is a specific super alloy that falls into the nickel-chromium family and shows all these characteristics[1]. The temperature prompted due to the electric pulses is the cause for material erosion from workpiece[2]. In WEDM process, both the tool electrode and workpiece are engrossed in the dielectric fluid. The potential difference is induced between tool electrode and workpiece[3]. WEDM is efficient for machining products made from nickel, titanium, tool steels, nimonic, etc[4]. The Surface roughness confirms smooth function in mechanical assemblies[5]. In machining process, larger material removal rate is expected, in order to increase the production rate[6]. Optimization is the system of achieving the preeminent

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result under the set conditions. Design of Experiments (DOE) is the systematic approaches for optimization. A designed experimental procedure is the system to proceed with synchronized evaluation of two or more factors for their effect on the response. Also it designates the level of distinction of a particular product or process nature. The design of experiment is a technique, which is to be executed in a certain arrangement of the experiment to analyze process results. Setup phase, executing phase and investigating phase are the important stages of DOE[7]. Inconel is a hard to machine material. This characteristic leads to many complications during manufacturing. These alloys are popular due to their durability and reliability in various conditions. They find extensive applications in aeronautics, nuclear, and naval turbine blade production due to their resistance to corrosion[8]. When making aeronautical parts, it is crucial to achieve precise dimensional accuracy, even with irregular shapes, aiming for a deviation of just 0.001 mm on all sides. This level of accuracy poses a significant challenge for production teams, especially when working with tough materials. To tackle this challenge, the manufacturing process of these metals often takes place with unconventional tools to simplify the process[9]. Surface details reveals tiny holes, bubbles, cracks and pits on the finished area. A visual study was conducted to provide a thorough explanation of spark production[10]. It was identified that increase in peak current results into removal of larger craters from the workpiece. The surface machined by EDM process contains a layer formed on the machined surface, by the molten material that has not been disintegrated completely from the workpiece. This layer, which has partially disintegrated material and partially integrated material is referred as Recast layer. The recast layer may be detrimental to work pieces which are subject to high stress in service[11]. Research has shown that various WEDM techniques have been used on different materials. Researchers also explored WEDM process for machining AL7071 with brass tool electrode. The effectiveness of the brass wire is well-demonstrated in the study, which even produced a mathematical equation to describe its performance[12]. Using brass wire as an electrode in WEDM is common because of its excellent thermal conductivity under moderate tightness while machining. In this study, experiments are conducted and optimization is applied for machining Inconel 600 with WEDM to figure out the most important factors and the best conditions for machining[13].

2.0 Experimental Procedure

2.1 Wire Electric Discharge Machine

The SINO KA-300 wire electric discharge machine (Figure 1) is used for experimental machining. It includes features like electrode wire supply system, dielectric liquid control arrangement and a support system to control the operation. De-ionized water serves as the dielectric liquid for this investigation. A screen on the console allows to adjust the settings for each experiment. To cut the material right in the middle lengthwise, position the specimen correctly in line with the cutting wire.

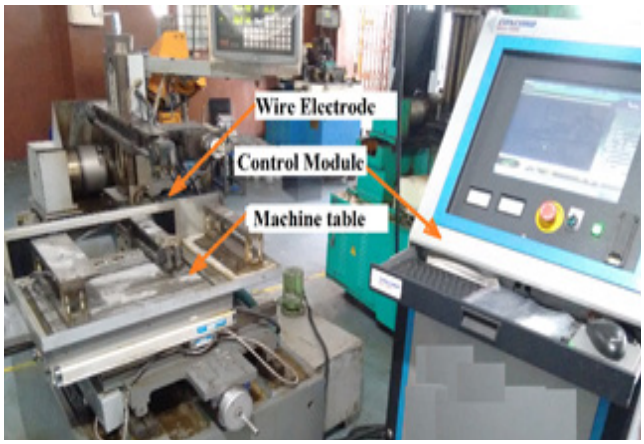


Figure 1. SINO KA-300 wire electric discharge machine.

2.2 Workpiece Material

In the current investigation, Inconel 600 is used as workpiece material. It performs well under high temperatures, resisting oxidation and stress corrosion cracking, as well as water and caustic corrosion. This material is popular for making furnace parts, turbine blades, and aerospace components. To ensure the quality, raw materials undergo testing to verify their chemical composition, which is mentioned in Table 1. aligns with the ASTM standard range. To start the investigation, raw materials were obtained for both pilot trials and real experiments. Pilot experiments help pinpoint key machining factors that impact the desired results. The range of input parameters is mentioned in Table 2. Based

on these pilot findings, experts determine the scope of machining factors, their levels and corresponding values for each level.

Table 1. Chemical composition of Inconel 600

Element	Percentage of composition
Nickel (Ni)	72.9
Chromium (Cr)	15.88
Iron (Fe)	9.51
Manganese (Mn)	0.21
Titanium (Ti)	0.14
Silicon (si)	0.12
Molybdenum (Mo)	0.035

2.3 Input Parameters for Machining

Table 2. Input Parameters with range

Input parameters	Range
Pulse ON time (μs)	25-35
Pulse OFF time (μs)	10-14
Peak Current (A)	2-6
Bed speed (mm/min)	100 -200
Voltage (V)	75-100

According to the planned setting of machining parameters, machining is proceeded. Total 18 machining trials are conducted at predefined values of parameters based on the orthogonal display. Raw material dimensions considered are 9 mm width, 9 mm length and the thickness is 10 mm. Finished specimen dimensions considered are 4.5 mm width, 9 mm length and the thickness is 10 mm.

3.0 Results and Discussions

Machining is carried out at different levels as mentioned in Table 3. The information is arranged in a specific orthogonal arrangement, for the analysis carried out to obtain effect of machining parameters on response parameter. Aim of this work is to identify the optimized combination of levels of factors which provides minimum recast layer thickness. ANOVA analysis provided the influence of machining parameters on the output characteristics. Signal-to-noise ratio is derived to acquire the mean effect plot for result of recast layer study. Here, recast layer thickness is considered as response parameter.

3.1 Design of Experiments

In Table 4, the machining parameters and recast layer thickness values corresponding to each experiment are listed.

Figure 2 shows the main effect plots of S/N ratio of recast layer. It is showed in the main effect plots of S/N ratio of recast layer that the S/N ratio is lesser for second level of voltage (100 V), second level of pulse ON time (30 μs), first level of pulse OFF time (10 μs), third level of current (6 A) and first level of bed speed (100 mm/min). So $A_2B_2C_1D_3E_1$ is the optimum set of parameters to obtain minimum recast layer thickness value.

Table 3. Levels of machining parameters

	Peak current	Pulse ON time	Pulse OFF time	Voltage	Bed speed
Level 1	2	25	10	75	100
Level 2	4	30	12	-	150
Level 3	6	35	14	100	200

Table 4. Taguchi's L18 orthogonal array with response

Sl. No	Voltage (Volt) (A)	Pulse ON time (µs) (B)	Pulse OFF time (µs) (C)	Current (Ampere) (D)	Bed speed (mm/min) (E)	Recast layer thickness (µm)
1	75	25	10	2	100	15
2	75	25	12	4	150	12
3	75	25	14	6	200	10
4	75	30	10	2	150	13
5	75	30	12	4	200	20
6	75	30	14	6	100	18
7	75	35	10	4	100	12
8	75	35	12	6	150	10
9	75	35	14	2	200	9
10	100	25	10	6	200	35
11	100	25	12	2	100	15
12	100	25	14	4	150	16
13	100	30	10	4	200	18
14	100	30	12	6	100	20
15	100	30	14	2	150	22
16	100	35	10	6	150	12
17	100	35	12	2	200	6
18	100	35	14	4	100	8

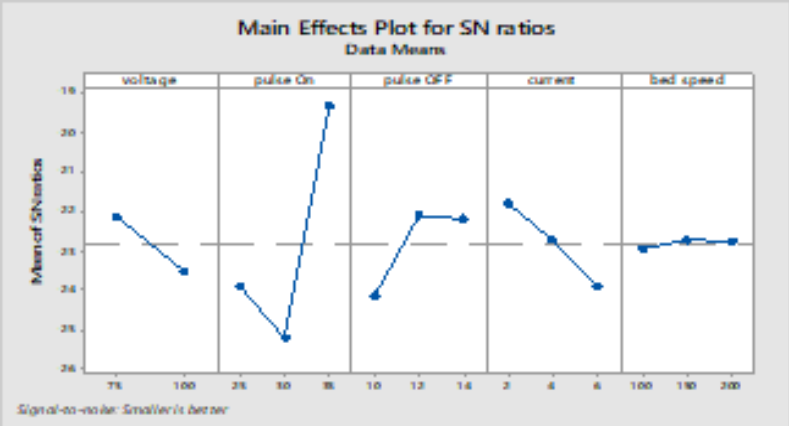


Figure 2. Main effect plots for S/N ratio of recast layer.

3.2 Poisson's Regression Analysis

Regression analysis is carried out to predict theoretical results and to compare the theoretical value with the actual experimental results. In regression analysis, modeling of dependent variable Y is carried out as the estimate of outcome using some or all of the independent variable also called explanatory variables. Poisson's regression is a statistical technique and a form of regression analysis which is used to model contingency and count data. In this regression analysis it is assumed that response variable Y has a Poisson distribution and assumes the logarithm of its expected value can be modeled by linear combination of unknown parameters.

When the response variable is having normal distribution then independent variable can be united using linear function:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k \quad (1)$$

As far as this investigation is concerned, the dependent variable is recast layer thickness and independent variable is voltage, pulse ON, pulse OFF, peak current and bed Speed. In the Poisson's regression since response variable is in a count and all are positive integer so Poisson's distribution is more proper since Poisson means > 0. So, logarithm of response variable has to be linked with linear function of independent variable,

$$log_e Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k \quad (2)$$

Applying exponential on both side, it becomes:

$$Y = \left(e^{\beta}\right)\left(e^{\beta 1 X 1}\right)\left(e^{\beta 2 X 2}\right) \ldots \ldots \left(e^{\beta k X k}\right) \quad (3)$$

By Equation (3), it is clear that a typical Poisson's regression model gives log outcome rate as linear function of set of predictor.

So, from the Minitab software the regression equation obtained as,

Recast layer thickness = *exp (Y)*

Therefore,

Y' = 2.812 + 0.0099 voltage - 0.022 pulse ON - 0.059 pulse OFF + 0.098 current + 0.0097 bed speed (4)

Figure 3 indicates the variation of experimental value with the predicted value. Predicted value for each

Table 5. Optimized combination of levels to get minimum recast layer

Voltage (V)	Pulse ON time (µs)	Pulse OFF time (µs)	Peak current (A)	Bed speed (mm/min)	Thickness of recast layer (µm)
100	30	10	6	100	4.11

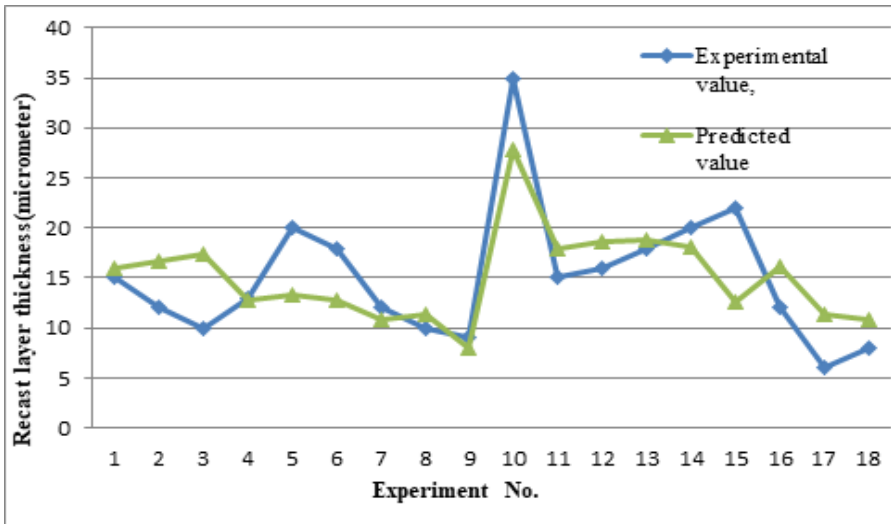


Figure 3. Experimental vs. predicted recast layer thickness.

experiment is obtained by substituting levels of different factors in the equation of regression analysis. Optimum combination of levels for different factors achieved by Taguchi analysis is $A_2B_2C_1D_3E_2$. Optimum level for voltage, pulse ON, pulse OFF, current and bed speed are 100 V, 30 µs, 10 µs, 6 A and 150 mm/min. Response of optimum parameters is obtained when deputize for the regression equation. Confirmation experiment is carried out with the optimum combination of machining parameters, and the result is tabulated in Table 5.

4.0 Conclusion

In this investigation, the influence of machining parameters on output characteristics and best input parameters to obtain the desired output are identified. Application of Taguchi analysis enabled the determination of significant factors and their respective levels in order to achieve desired output. In this experiment Taguchi's mixed level design is used to form orthogonal array. Information from the response table of the signal to noise ratio reveals that pulse ON time has the more influence on the formation of recast layer followed by current, pulse OFF time and voltage. As the requirement is to obtain minimum recast layer thickness, so from the experiment, optimum parametric levels for a set of factors are obtained as which gives the minimum recast layer thickness as calculated by Poisson's regression analysis. Voltage – 100 V, pulse ON time – 30 µs, pulse OFF time – 10 µs, current – 6 A and bed speed – 100 mm/min is the optimum combination of parameters to achieve minimum recast layer thickness 4.11 µm, on the workpiece.

5.0 Acknowledgement

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6.0 References

1. Piasecki A, Kotkowiak M, Makuch N, Kulka M. Wear behavior of self-lubricating boride layers produced on Inconel 600-alloy by laser alloying. Wear. 2019; 426-7:919–33. https://doi.org/10.1016/j.wear.2018.12.026
2. Patel KM, Pandey PM, Rao PV. Determination of an optimum parametric combination using a surface roughness prediction model for EDM of Al2O3/SiCw/TiC ceramic composite. Mater Manuf Process. 2009; 24(6):675-82. https://doi.org/10.1080/10426910902769319
3. Mahapatra SS, Patnaik A. Optimization of Wire Electrical Discharge Machining (WEDM) process parameters using Taguchi method. J Adv Manuf Technol. 2006; 34(9-10):911-25. https://doi.org/10.1007/s00170-006-0672-6
4. Lin Y, Chen Y, Wang DA, Lee HS. Optimization of machining parameters in magnetic force assisted EDM based on Taguchi method. J Mater Process Technol. 2009; 209(7):3374-83. https://doi.org/10.1016/j.jmatprotec.2008.07.052
5. Tamura T. Development of on-the-machine surface modification technology in EDM. Procedia CIRP. 2013; 6:117-22. https://doi.org/10.1016/j.procir.2013.03.049
6. Sengottuvel P, Satishkumar S, Dinakaran D. Optimization of multiple characteristics of EDM parameters based on desirability approach and fuzzy modeling, Procedia Eng. 2013; 64:1069-78. https://doi.org/10.1016/j.proeng.2013.09.185
7. Baraskar SS, Banwait SS, Laroiya SC. Multiobjective optimization of electrical discharge machining process using a hybrid method. Mater Manuf Process. 2013; 28(4):348-54. https://doi.org/10.1080/10426914.2012.700152
8. Ayesta I, Izquierdo B, Flaño O, Sánchez JA, Albizuri J, Avilés R. Influence of the WEDM process on the fatigue behavior of Inconel® 718. Int J Fatigue. 2016; 92:220-33. https://doi.org/10.1016/j.ijfatigue.2016.07.011
9. Hewidy MS, El-Taweel TA, El-Safty MF. Modelling the machining parameters of wire electrical discharge machining of Inconel 601 using RSM. J Mater Process Technol. 2005; 169(2):328-36. https://doi.org/10.1016/j.jmatprotec.2005.04.078
10. Manikandan K, Kumar PR, Kumar DR, Palanikumar K. Machinability evaluation and comparison of Incoloy 825, Inconel 603 XL, Monel K400 and Inconel 600 super alloys in wire electrical discharge machining. J Mater Res Tech. 2020; 9(6):12260-72. https://doi.org/10.1016/j.jmrt.2020.08.049

11. Srinivasan VR, Girishkumar GS, Kamesh MR, Vasu VK, Raja P, Sagar TM, et al. Optimization of process parameters of wire electric discharge machining process for machining AISI A2 tool steel. J Mines Met Fuels. 2024; 119-26. https://doi.org/10.18311/jmmf/2024/38682
12. Bobbili R, Madhu V, Gogia AK. Modelling and analysis of material removal rate and surface roughness in wire-cut EDM of armour materials. Eng Sci Technol. 2015; 18(4):664-8. https://doi.org/10.1016/j.jestch.2015.03.014
13. Alias A, Abdullah B, Abbas NM. Influence of machine feed rate in WEDM of titanium Ti-6Al-4V with constant current (6A) using brass wire. Procedia Eng. 2012; 41:1806-11. https://doi.org/10.1016/j.proeng.2012.07.387