Investigation of Surface Roughness for Inconel 625 using Wire Electric Discharge Machining

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Abstract: Due to the increase in the demand of materials with good surface finish and complex shapes, conventional machining processes became out of date. This directed to the increasing demand of non-conventional machining processes. This research work is focuses on the optimization of Surface Roughness (SR) using Wire Electrical Discharge Machining (WEDM) method on Inconel 625 super alloy material. The diffused wire tool electrode (plain and cryo-treated) is used for experimental work. Taguchi’s L18 (21*35) orthogonal array’s has been used to design for experimental run. The machining parameters selected for optimization are tool electrode, current (Ip), pulse on time (Ton), pulse off time (Toff), wire feed (Wf) and wire tension (Wt). Rectangular slits has been fabricated, which are useful for many industrial application like increase the heat transfer rate of fluids, micro-channels, micro-fins etc. Design of Experiment (DoE) optimization technique is used to find the most significant factor.

Key Words: WEDM, Taguchi’s, Surface Roughness, Cryogenic, DOE, Super alloys

1. Introduction

WEDM process is one of the most popular non-conventional machining process. Its ability to produce difficult and complicated shapes with precise dimensioning and even handed surface finish led to its increase in popularity in various industries like automobile, aerospace, medical and many other manufacturing industries. WEDM process is an electro thermal process where the tool electrode is used to shape the work piece with the help of discrete sparks generated between work piece material and tool electrode. The wire used is as thin as 0.1-0.3 mm and the whole process is controlled by CNC machining. Manjaih, M et al. (2016) An investigation was conducted on D2-Steel material by wire electro discharge machining using Taguchi’s methodology to find the effect of different input parameters (Ton,Toff,SV,WF) on the response parameters (MRR, Ra). It was found the MRR increase with increase in Ton and Ra decreases with increases in SV. It was concluded that the recast layer thickness increases with the increase in Ton, oxides are prepared on the machined surface and the hardness was improved. K.Kanlayasiri et al. (2007) also conducted an experiment on newly developed DC-53 die steel using WEDM process and ANOVA was used to find the effects of the machining parameters on surface roughness. Final results showed that increase in pulse on time and pulse peak current increased the surface roughness. Pujari Srinivasa et al. (2014) calculated the effect of WEDM constraints on aluminum alloy using Taguchi’s approach. After experiments, it was determined that Ton, Ip, SV show’s good amount of effect on MRR and SV. Wire tension in SR, Toff and Servo feed rate in MRR also played an important role. Genetic optimization revealed that to increase surface quality, cutting efficiency should be reduced and vice versa. Adeel et al.(2013) considered the effect and optimization of eight process parameters on three response variables (SR, MRR and Kerf) was carried out using Taguchi’s design of experiment. The surface roughness was found to be most affected by pulse on time and open voltage. Kerf was affected by pulse in time, wire tension and open
voltage. For MRR the major factors affecting were pulse on time, open voltage and serve voltage. Material thickness didn’t play any significant role in any cases. A.B.Puri et al. (2003) conducted an experiment using Taguchi’s method to find the influence of machining factors. It was observed that MRR is mostly effected by T-on, T-off and peak current for rough-cut and by T-on for trim cut. The wire lag is effected by T-on, T-off and Ip for rough cut and pulse peak voltage, servo voltage, dielectric flow rate, wire offset and constant cutting speed for trim cut. The wire lag is effected by T-on, T-off and Ip for rough cut and pulse peak voltage, servo voltage, dielectric flow rate, wire offset and constant cutting speed for trim cut. Paolo Baldissera et al. (2009) investigated on the effects of deep cryogenic treatment on static mechanical properties of 18NiCrMo5 carburized steel. It was studied through hardness and tensile stress monitored by optical Fracto graphic observations and compared the results between deep cryogenic tempering and tampering done after conventional case hardening. Ahsan Ali Khan et al. (2008) studied to increase the tool life using cryogenic cooling. The tool had been reformed to apply liquid nitrogen straight to the machining zone. The materials used were silicon nitride, titanium alloy and Inconel. It was concluded that the tool life increases more than four times and the application of the cryogenic cooling was found to be more actual at higher cutting speed and is more effective at higher feed rate than at a greater depth of cut . A. kumar et al. (2013) used zinc coated and uncoated brass wire to investigate finish cutting operation of WEDM process of commercially pure titanium. Experiment’s was performed for rough-cut followed by finish-cut. Roughness was looked to improve in trim cut using cryogenically treated wire electrode. The craters, debris and spherical droplets on the work surface were found to be of much smaller size after n- cutting operations as compared to rough cut operation. Y.Yildiz et al. (2011) investigated the effect of cold and cryogenic treatments on the machinability of Beryllium-copper alloy. The Beryllium-copper alloy was subjected to around -150 F and for cold treatment and around -300 F for cryogenic treatment. From the experimental results they determined that 20-30% increment was there in MRR of cold and cryogenic treated work pieces. Vineet Srivastava et al. (2013) planned and compared the performance between sintered Cu-Tic electrode tip and conventional copper electrode tip and analysed them in ultra-sonic assisted cryogenically cool electrical discharge machining (UACEDM). It was seen that EWR and out of roundness decrease. It was also observed that MRR and SR increased when Cu-Tic was used. The thickness of crack on work piece was also found to be less. From review of literature it was observed that researchers have used design of experiments and Taguchi’s method during machining of different work piece materials. But very few researchers have strained to establish the relationship between input parameters and WEDM performance measures during machining of Inconel 625 super alloy. In WEDM process the work piece, tool electrode and thermal conductivity plays an essential role to enhance the efficiency of WEDM process. The objective of the present study was to optimize WEDM parameters for machining process parameters for better surface roughness during machining of Inconel 625 super alloy.

2. Experimental Details

The experiments were performed on WEDM (Electronica Spring cut 734 model, Electronica ltd. The process parameters i.e., diffused wire tool electrode (plain and cryogenic treated), current intensity, pulse on time, pulse off time, wire feed and wire tension were considered for the response parameters i.e., Surface Roughness. Some parameters were kept constant during the fabrication of rectangular slits on WEDM process are thickness of material (3 mm), wire diameter (0.25mm), dielectric flow rate (5 LPM) and servo voltage (20V).

The work material in the form of rectangular plate (150mmX50mm) has been used for experimental work and rectangular slits were fabricated cut. The selection of tool electrode play an important role for the effective working of WEDM process. There are different types of wire electrode are available in market like plain electrode , brass wire electrode, coated electrode, composite, diffusion annealed, etc. for current research work, diffused tool electrode was selected for experimental work. Mitutoyos SURFTEST (SJ-210) was used to measure surface roughness of machined surface. Measurements were taken three times for surface roughness and the average of measurements was used for analysing the result. Figure 1 shows the surface roughness tester used for measurement.
Taguchi’s suggests two different routes to carry out the complete analysis. First is the standard approach, where the results of a single run or the average of repetitive runs are processed through main effect and ANOVA analysis. The second approach, which Taguchi’s strongly endorses for multiple runs, is to use the S/N ratio for the same steps in the analysis. The S/N ratio is a simultaneous quality metric related to the loss function. The studies of S/N ratio and ANOVA were carried out to study the relative effect of machining parameters on the performance parameters. The S/N ratio characteristics can be classified into three categories, “larger-is-better,” “smaller-is-better,” and “nominal-is-better.”

For Surface Roughness, Smaller is better (SB)

\[
\left( \frac{S}{N} \right)_{sb} = -10 \log \left( \frac{1}{n} \sum_{j=1}^{n} Y_j^2 \right) 
\]

Where,
\( y_j = \text{value of the characteristic in an observation } j \)
\( n = \text{number of repetitions in a trial} \)

Alternately,
\[
\left( \frac{S}{N} \right)_{LB} = -10 \log (MSD_{LB})
\]

Table 1 present the machining parameters, selected for the experimental purpose. Based on these parameters Taguchi’s L18 orthogonal array (\(2^4\times3^5\)) has been designed and experiments has been performed and surface roughness has been analysed.

Table 1 Machining factor and their levels

| Symbol | Control factor            | Unit     | Level 1 | Level 2         | Level 3 |
|--------|---------------------------|----------|---------|-----------------|---------|
| A      | Tool electrode            | -----    | Plain   | Cryo- treated   | -       |
| B      | Current Intensity         | A        | 10      | 12              | 14      |
| C      | Pulse on time             | µs       | 105     | 115             | 125     |
| D      | Pulse off time            | µs       | 48      | 54              | 60      |
| E      | Wire feed                 | m/min.   | 4       | 6               | 8       |
| F      | Wire tension              | N        | 7       | 9               | 11      |

3. Result and Discussion

Table 2 shows the observed data of the surface roughness and signal to noise ratio (db) has been obtained. Fig. 2 shows the main effects plots for S/N ratio on surface roughness. It is observed that better surface roughness is obtained by cryogenically treated tool electrode as compared to plain tool
electrode. It may be due to the high conductivity of cryogenic tool more discharge energy is delivered to process and wire keep good mechanical properties at high energy due to high possible pre-load which improve the accuracy and surface finish.

| S.No. | Process Parameters | SR (µm) | SR (µm) | S/N (db) |
|-------|-------------------|---------|---------|----------|
|       | Tool electrode    | Current | Ton     | Toff     | WF       | WT       | 1       | 2       | 3       |          |
| 1     | 1                 | 10      | 10      | 48       | 4        | 7        | 2.81    | 2.75    | 2.78    | -8.880   |
| 2     | 1                 | 10      | 11      | 54       | 6        | 9        | 2.47    | 2.5     | 2.49    | -7.924   |
| 3     | 1                 | 10      | 12      | 60       | 8        | 11       | 2.04    | 1.71    | 1.93    | -5.529   |
| 4     | 1                 | 12      | 10      | 48       | 6        | 9        | 2.72    | 2.74    | 2.73    | -8.723   |
| 5     | 1                 | 12      | 11      | 54       | 8        | 11       | 2.62    | 2.59    | 2.62    | -8.332   |
| 6     | 1                 | 12      | 12      | 60       | 4        | 7        | 2.16    | 1.87    | 2.07    | -6.149   |
| 7     | 1                 | 14      | 10      | 54       | 4        | 11       | 3.46    | 3.34    | 3.58    | -10.781  |
| 8     | 1                 | 14      | 11      | 60       | 6        | 7        | 2.81    | 2.84    | 2.84    | -9.035   |
| 9     | 1                 | 14      | 12      | 48       | 8        | 9        | 2.92    | 2.91    | 2.96    | -9.337   |
| 10    | 2                 | 10      | 10      | 60       | 8        | 9        | 3.09    | 2.94    | 2.64    | -9.218   |
| 11    | 2                 | 10      | 11      | 48       | 4        | 11       | 2.77    | 2.75    | 2.73    | -8.786   |
| 12    | 2                 | 10      | 12      | 54       | 6        | 7        | 2.83    | 2.81    | 2.79    | -8.974   |
| 13    | 2                 | 12      | 10      | 54       | 8        | 7        | 3.34    | 3.42    | 3.23    | -10.448  |
| 14    | 2                 | 12      | 11      | 60       | 4        | 9        | 2.48    | 2.49    | 2.47    | -7.889   |
| 15    | 2                 | 12      | 12      | 48       | 6        | 11       | 2.51    | 2.53    | 2.52    | -8.028   |
| 16    | 2                 | 14      | 10      | 60       | 6        | 11       | 2.91    | 2.88    | 2.94    | -9.277   |
| 17    | 2                 | 14      | 11      | 48       | 8        | 7        | 2.98    | 3.28    | 3.14    | -9.910   |
| 18    | 2                 | 14      | 12      | 54       | 4        | 9        | 2.84    | 2.79    | 2.8     | -8.974   |

It is also seen that there is an increase in surface roughness with increase in pulse on time. This may be due to increased pulse on time which produces larger discharge energy between electrode and work piece and ceases to melt amounts of material which helps to create a larger and deeper crater. Hence this influences the increase in surface roughness. (Kapoor et al. 2012 & M. Manjaiah et. al., 2016) From the plots it can also be seen that the value of surface roughness is high at low value of Toff (48µs), this is due to because with a short pulse off time, there is not enough time to clear the melted small particles from the gap between the wire electrode and work piece. It is observed that SR first decreases with increase in Toff and then increases with Toff. This is because more energy is required to establish the plasma channel and therefore there is higher electrode wear and higher surface finish. For wire feed rate surface roughness value decrease with increase in wire feed rate, because new wire comes in contact rapidly when feed rate increases, low wire speed tends to breakage of wire but with increase in wf rate, the consumption of wire increase and the machining cost also increase. Wire tension increases continuously and current decreases in SR.
Table 3 shows the calculated P-values of ANOVA for SR to find out the significance of parameters in WEDM process of Inconel 625. The values of ‘P’ shown in table 3 which are 0.05 and less than 0.05 indicates that the parameters corresponding to these values are considered to be statistically significant. As shown in table 5, among all the process parameters considered, pulse on time is the most significant in terms of SR because it has the largest impact and has been ranked one, while wire tension is the second most important process parameter due to its control the chance of wire breakage and reduced the fluctuation during machining leading to reduces on SR. The plot of the main effects of one noise factor and five control factors based on the S/N ratio for the SR has been shown in figure 2. The optimal parametric settings are A1, B1, C3, D3, E2, and F3.

Table 3 shows the results of Analysis of Variance (ANOVA) based on the S/N ratio for SR. The S/N ratio calculated for SR from the observed experimental data has been used to analyse ANOVA. It is seen that peak current, pulse on time and pulse off time have large impact on the response at 95% confidence interval level since p-value is less than 0.05.

Table 3 Analysis of Variance for SR

| Source | DF | Seq SS | Adj MS | F- Value | P-Value | % Contribution |
|--------|----|--------|--------|----------|---------|----------------|
| A      | 1  | 0.19636| 0.19636| 4.51     | 0.078   | 7.71           |
| B      | 2  | 0.64870| 0.32435| 7.44     | 0.24    | 25.46          |
| C      | 2  | 0.81323| 0.40662| 9.33     | 0.014   | 31.92          |
| D      | 2  | 0.54863| 0.27432| 6.30     | 0.034   | 21.54          |
| E      | 2  | 0.02563| 0.01282| 0.29     | 0.755   | 1.01           |
| F      | 2  | 0.05363| 0.02682| 0.62     | 0.571   | 2.11           |
| Error  | 6  | 0.26141| 0.04357|          |         | 10.26          |
| Total  | 17 | 2.54760|        |          |         | 100            |
4. Confirmation Experiments

Once model equation is generated for all, factors and their levels, it was required to predict this model equation for optimal solution. This task was completed by confirmation experiments result by using Taguchi’s method. It was noted that if the optimal combination of factors and their levels coincidently match with one of the experiments in the OA (L18), then no confirmation test is required.

So, same experiment (on optimal solution) was required to perform on same machine (WEDM) to find Ra for this optimal solution and then compare with estimated values. The confirmation test table is shown below (table 8).

\[
SR= 5.71 + 0.209 \text{ Tool Electrode} + 0.1025 I_p - 0.02592 T_{on} - 0.0251 T_{off} + 0.0196 W_f - 0.0321 W_t
\]  

(3)

| Level     | Optimal Solution | Difference | % Difference |
|-----------|------------------|------------|-------------|
| Estimated | Experiment       |            |             |
| A1-B1-C3-D3-E1-F3 | 1.92   | 2.13       | 0.21        | 9.85        |

Table 4 Confirmation test table (SR)

5. Conclusion

This experiment discusses the optimization of surface roughness during machining of Inconel 625 super alloy in wire cut electrical machining process. Tool electrode (normal and cryogenic), current, pulse on time, pulse off time, wire feed and wire tension were considered as a machining parameter. Based on the investigation the optimal of input parameter are first level of tool electrode i.e. plain treated tool electrode (A1), first level of current i.e. 10 ampere (B1), third level of pulse on time 125 micro seconds (C3), third level of pulse off time i.e. 60 micro second (D3), first level of wire feed i.e. 4 m/min (E1), and third level of wire tension i.e. 11 N (F3). The improved surface roughness obtained was 9.85 % based on optimal setting of input parameters and the obtained surface roughness lies between the calculated confidence interval. Hence, Taguchi’s method is useful in optimizing single objective of WEDM process parameters. In the future of work can be extended to the discussion the tool material removal rate, dimensional accuracy and tool wear ratio during machining of other advanced material.

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