Analysis of Effects of Cutting Parameters of Wire Electrical Discharge Machining on Material Removal Rate and Surface Integrity

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Abstract. As wire electrical discharge machining is pioneered as a vigorous, efficient and precise and complex nontraditional machining technique, research is needed in this area for efficient machining. In this paper, the influence of various input factors of wire electrical discharge machining (WEDM) on output variable has been analyzed by using Taguchi technique and analysis of variance. The design of experiments has been done and by applying L8 orthogonal arrays method and experiments have been conducted and collected required data. The objectives of the research are to maximize the material removal rate and to minimize the surface roughness value (Ra). Surface morphology of machined workpiece has been obtained and examined by employing scanning electron microscopy (SEM) technique.

Keywords: wire EDM; Inconel 625; Material Removal Rate (MRR); surface Roughness; scanning electron microscopy (SEM).

1. Introduction

Wire electrical discharge machining process has been established as a crucial non-conventional thermoelectric machining technique to machine the materials which are a conductor of electricity. The mechanism of material removal is same as the common EDM process. The cutting tools are electric sparks, which have been set up and controlled with the help of a generator. Because the wire electrode is not quite touching the workpiece, the electrical charge has produced to a voltage that permits it to cross the gap between electrode and workpiece, and zaps off a tiny bit of the workpiece. The electrolyte not only cools down the cutting zone but also wash away the debris between wire electrode and workpiece to restrict them from being obstacles for the next spark. This process is employed in the aerospace and automotive, die & tool manufacturing industries. It is possible to obtain and measure the desired surface finish on a workpiece during machining in wire EDM process in any intricate shape of the workpiece irrespective of its hardness. As in Wire EDM, wire electrode cannot be reused, therefore, it is difficult to control the wire wastage and minimize the cost of wire. Inconel alloys are difficult to cut materials by the conventional machining process. It, however,
is essential to find a productive and competent machining technique for Inconel alloys. For machining electrically conductive materials, wire EDM is pioneered as a vigorous, dynamic and precise technique. Parameters’ details and procedures provided in machine manufacturer’s manual have not contained enough information for machining new materials and different profiles desired by researchers or production engineer. The sophisticated software adjusts the gap and various parameters in the generator of machine in real time to develop sparks controlled carefully. Sparks with less energy develops less heat; which results in smaller heat-affected zones. A lot of research is being performed by many researchers for investigating the influence of wire EDM on the material removal rate, surface integrity of nickel alloys regarding recast layer and HAZ.

2. Literature Review

Kanlayasiri K & Boonmung S. [1] [2] came upon that pulse on time and pulse peak current had been important factors affecting the surface roughness during wire electrical discharge machining of DC53 die steel. The surface roughness of workpiece was increased when the pulse on time and pulse peak current was raised. Mao Yong Lin et al. [3] used micro-milling EDM for machining of Inconel 718 and optimized the machining parameters for obtaining desired results of multiple performance parameters by using Grey Taguchi method. Sharma N et al. [4] shown that the pulse on time is an important factor, which affects the cutting speed and dimensional accuracy in wire electrical discharge machining of HSLA steel. Experiments had been carried out on the basis of the central composite rotatable design of response surface methodology. Neeraj Sharma et al. [5] investigated the effect of parameters on metal removal rate for WEDM using HSLA as work-piece. They have observed that metal removal rate and surface roughness increases with increase in pulse on time and peak current. Response Surface methodology (RSM) is used to optimize the process parameter for metal removal rate and surface roughness. Somashekhar K.P. et al. [6] presented the formulation and solution of optimization of various process parameters for the selection of the best control settings on a micro-wire electrical discharge machining process.

Durairaj M. Sudharsun D. et al. [7] summarized the Grey relational theory and Taguchi optimization technique, in order to optimize the cutting parameters in Wire EDM for SS304. The objective of optimization is to attain the minimum kerf width and the best surface quality simultaneously and separately. Ho K H & Newman S T et al. [8] reviewed the research activities done in the field of wire EDM in which optimization of process parameters, monitoring and control of wire EDM process has been reported. Nithin Arvind et al. [9] optimized performance parameters using Taguchi’s experimental design of WEDM with brass wire is fed to the workpiece. The authors predicted the optimal input parameters to maximize MRR and minimize surface finish. Palmers J, Stappen M V et al. [10] compared the white layers formed on workpiece surfaces in grinding and wire EDM in relation to the PVD TIN coating adhesion. They have suggested that white layers could be removed by tempering or annealing of the machined surface.

From the above literatures following statements have been reviewed: Electrode wire tension, wire wear rate and wire breakage and have not been examined appropriately and in many of the research papers. The authors have not performed complex cutting types such as taper cutting, turning, corner cutting, gear cutting etc. Heat distribution and heat transfer in the workpiece during WEDM process have not been explored in any research paper. The least number of researches have been done in which surface roughness is measured by direct contact method and surface morphology is examined by scanning electron microscopy (SEM).
3. Experimental Methodology

Inconel 625 has been used as a workpiece material in this research work which is known as a difficult to machine material and has the application in aerospace, tool and dies; medical parts manufacturing industries. The shape of the workpiece of Inconel 625 is a rectangular block which has been cut in total eight small pieces of 2 mm thickness. The specification of each piece is 10 mm cutting length (l); 15 mm cutting thickness (h) and 0.37 mm kerf (k) in the rectangular shape as illustrated in figure (1). The chemical composition of Inconel 625 is material shown in the table (1). Electronica MAXICUT wire electrical discharge machine has been used for conducting the experiments and measured the machining time for each workpiece. In this machine, all the axes are servo controlled and can be programmed to follow a CNC code which is fed by the control board.

![Fig. 1](image)

**Table 1.** Chemical composition of Inconel 625

| Element | Ni | Cr | Mo | Nb | Fe | Al | Ti | C | Mn |
|---------|----|----|----|----|----|----|----|----|----|
| Content (%) | 58 | 21.5 | 09 | 3.95 | 5 | 0.4 | 0.4 | 0.1 | 0.5 |

In this wire EDM tool, all three axes have an accuracy of 1μm. A brass wire electrode of 0.25 mm diameter has been used and taken de-ionized water as the dielectric fluid. Diamond guides usually expensive to replace, but last a long time. The input parameters such spark voltage, pulse on time, and pulse off time and wire tension are considered for analysis with two different levels of each parameter as shown in the table (2) and other parameters remain constant. Surface Roughness has been measured and noted by using Talysurf surface roughness tester instrument of Taylor-Hobson. The design of experiments has been carried out by using L8 orthogonal arrays method and experiments have been conducted and collected the required output data as illustrated in table (3).

**Table 2.** Input factors and their levels for wire electrical discharge

| Sr. No. | Input Parameter | Unit       | Level 1 | Level 2 |
|---------|-----------------|------------|---------|---------|
| 1       | spark voltage   | volts      | 9       | 14      |
| 2       | on time         | µs         | 6       | 9       |
| 3       | off time        | µs         | 10      | 16      |
| 4       | wire tension    | gram-force | 1200    | 1350    |
Table 3. Experimental design by using L₈ orthogonal arrays and output parameters

| Exp. NO. | Spark Voltage | On Time | Off Time | Wire Tension | MRR     | Surface Roughness |
|----------|---------------|---------|----------|--------------|---------|------------------|
| 1        | 9             | 6       | 10       | 1200         | 1.968085 | 1.817            |
| 2        | 9             | 6       | 16       | 1350         | 1.554187 | 2.15             |
| 3        | 9             | 9       | 10       | 1350         | 2.120749 | 1.6              |
| 4        | 9             | 9       | 16       | 1200         | 1.676737 | 1.922            |
| 5        | 14            | 6       | 10       | 1350         | 2.328997 | 2.566            |
| 6        | 14            | 6       | 16       | 1200         | 1.616662 | 2.139            |
| 7        | 14            | 9       | 10       | 1200         | 2.724595 | 2.232            |
| 8        | 14            | 9       | 16       | 1350         | 2.494382 | 2                |

4. Experimental Results and Analysis

A collection of data is accomplished after cutting the Inconel 625 material by wire EDM. Machining time has been observed and noted after each experiment and material removal rate (MRR) have been calculated by applying formula shown in equation (1). Similarly, Surface roughness of each machined piece has also been measured by utilizing Telysurf instrument. These collected data have been analyzed by using powerful statistical software Minitab 16. In this software, Taguchi method has been considered for analysis of collected values of response parameters.

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MRR = \frac{l \times h \times k}{t_m} \quad (\text{mm}^3/\text{minute})
\]  

Where, \(l\) = cutting length, \(h\) = cutting thickness, \(k\) = kerf of cutting, \(t_m\) = machining time

During statistical analysis and ANOVA analysis, larger is better concept is used for deciding the significant input parameters during analysis of MRR. Smaller is better criterion is considered for deciding the significant input parameters during analysis of surface roughness (Ra). ANOVA for the signal to noise ratio of MRR is shown in the table (4); and ANOVA for signal to noise ratios of surface roughness (Ra) is shown in the table (5). ANOVA has been conducted to identify and determine the significant input factors and their interactions which have the greatest impact on output parameters so that these input parameters can be controlled to obtain desired value of response parameters. Signal to noise (S/N) ratios for each output variable has also been computed. Response tables of the signal to noise ratios of MRR and surface roughness have also been calculated as illustrated in the table (6) and table (7). By using Minitab software, main effects plot and normal probability plot of signal to noise ratios of MRR and surface roughness have been drawn as shown in figure (2) and figure (3) respectively.

Table 4. Analysis of variance for signal to noise ratios of MRR

| Source         | DF | SS   | MS   | F    | P    |
|----------------|----|------|------|------|------|
| Spark Voltage  | 1  | 6.9025 | 6.9025 | 8.1 | 0.065 |
| On Time        | 1  | 5.1805 | 5.1805 | 6.08 | 0.09 |
| Off Time       | 1  | 8.0583 | 8.0583 | 9.45 | 0.054 |
| Wire Tension   | 1  | 0.7163 | 0.7163 | 0.84 | 0.427 |
| Residual Error | 3  | 2.5571 | 0.8524 |     |      |
| Total          | 7  | 23.4117 |      |      |      |

SS = sum of squares, MS = mean of squares, DF = degree of freedom
Table 5. Analysis of variance for signal to noise ratios of Surface Roughness

| source          | DF | SS    | MS     | F     | P     |
|-----------------|----|-------|--------|-------|-------|
| spark voltage   | 1  | 4.7903| 4.79028| 3.61  | 0.154 |
| on time         | 1  | 1.8753| 1.8753 | 1.41  | 0.32  |
| off time        | 1  | 0.0338| 0.03382| 0.03  | 0.883 |
| wire tension    | 1  | 0.0308| 0.0308 | 0.02  | 0.889 |
| residual error  | 3  | 3.986 | 1.32865|       |       |
| Total           | 7  | 10.7162|       |       |       |

SS = sum of squares, MS = mean of squares, DF = degree of freedom

Table 6. Response table for signal to noise ratios of MRR (Larger is Better)

| level | spark voltage | on time | off time | wire tension |
|-------|---------------|---------|----------|--------------|
| 1     | 5.183         | 5.307   | 7.115    | 5.812        |
| 2     | 7.04          | 6.916   | 5.108    | 6.411        |
| Delta | 1.858         | 1.609   | 2.007    | 0.598        |
| Rank  | 2             | 3       | 1        | 4            |

Table 7. Response table for signal to noise ratios of surface roughness

| level | spark voltage | on time | off time | wire tension |
|-------|---------------|---------|----------|--------------|
| 1     | -5.398        | -6.656  | -6.107   | -6.11        |
| 2     | -6.946        | -5.688  | -6.237   | -6.234       |
| Delta | 1.548         | 0.968   | 0.13     | 0.124        |
| Rank  | 1             | 2       | 3        | 4            |

Fig. 2. Main effects plot and Normal probability for SN ratios of MRR

Surface Texture Analysis

JEOL JSM-6390LV Scanning electron microscopy has been used for surface morphology examination. It is a high-performance, low-cost, scanning electron microscope with a high resolution of 3.0nm. The specimen chamber can accommodate a specimen of up to 6-inches in diameter. The
surface texture of machined pieces with various experiment numbers are shown in figure (4). SEM analysis of Exp. No- 02 and Exp. No- 07 has been carried out because they possess minimum MRR and Maximum MRR respectively. SEM analysis of Exp. No- 03 and exp. No- 05 has been performed because they concerned with the lower and higher surface roughness (Ra) respectively. It has been revealed that surface texture changes with variation in input parameters. Some material defects such as daub and black spots have been also observed in SEM image of exp. No. (07); and kerf of cutting is also recorded as shown in figure (5).

![Main Effects Plot for SN ratios of Roughness (Ra)](image)

**Fig. 3.** Main effects plot and normal probability plot for SN ratios of surface roughness

![SEM images of machined pieces with various experiment numbers](image)

**Fig. 4.** SEM images of machined pieces with various experiment numbers
Fig. 5. Exp No -07 with material defect daub, Exp no- 02 representing Kerf of cutting.

Conclusion

There is the following conclusions are made after analysis of data obtained:

(i) Wire tension has no effect on both the output parameters.
(ii) On time has the highest impact on both the output parameters (MRR and surface roughness).
(iii) SEM images revealed that surface morphology of machined piece changes with the variation in input parameters.
(iv) Experiment number 7 has the maximum MRR value as obtained by experiments.
(v) Experiment number 03 has the minimum surface roughness ($R_a$) value.
(vi) Input parameter off time has the greatest impact on MRR whereas spark voltage has the largest impact on surface roughness ($R_a$) among all other parameters.

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