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# Investigations of Effect of Process Parameters on Cutting Rate in Wire-cut Electrical Discharge Machining of Inconel 625

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**Abstract—***Super alloys play important roles in many industrial applications. Inconel 625 is one such super alloy which has very good mechanical and thermal properties. It is difficult to machine with traditional machining processes due to high melting point and hardness. Wire EDM is a non - conventional machining process which is mainly used to machine hard and tough materials like Inconel 625. In this paper an attempt has been made to investigate the effect of process parameters like pulse on time, pulse off time and peak current on the cutting rate. Taguchi's L9 orthogonal array has been selected as an experimental design and then analysis of variance (ANOVA) has been done to determine the significant parameters and their contribution on cutting rate. It is found that pulse on time and pulse off time affect significantly the cutting rate.*

## 1. INTRODUCTION

Wire EDM is a widely used non conventional machining process to produce complex two and three dimensional shapes very easily. It is capable to machine all electrically conductive materials irrespective of their toughness and hardness. It is a thermo-electric machining process in which spark is produced between the work piece and wire electrode. Due to this spark work material is melted and evaporated.

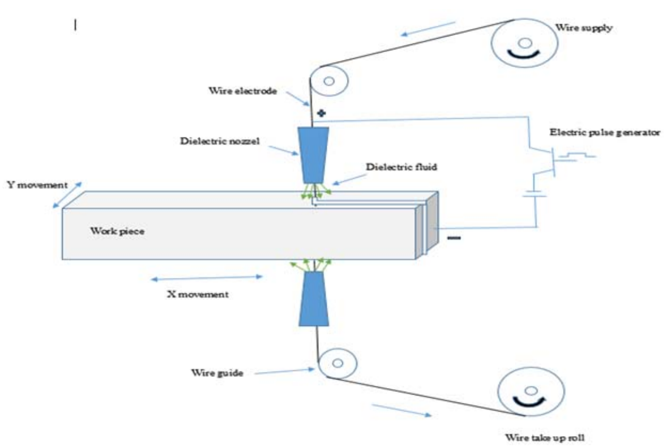


**Fig. 1: Representation of WEDM process**

In wire EDM there is no direct contact between the electrode and work piece, so mechanical stress is negligible. Wire used is made of copper, brass, tungsten or zinc coated of diameter 0.05 – 0.30 mm. Deionized water is generally used as cutting fluid which removes the burr from the cutting zone and also cools the workpiece. Wire acts as cathode and work as anode; and material is removed from the anode by spark erosion mechanism. [1]. Fig. 1 represents the WEDM process.

### 1.1 Inconel 625 and its applications

The Inconel 625 plate of 80mm x 80mm x 10mm size has been used as a work piece material for the present investigation. Most of the engineering materials today function under aggressive environment where the operating temperatures can be around 1000 ◦C, which is well beyond the limits of conventional metals. Inconel-625 is one such alloy which is widely used in aerospace industry, jet engine components such as turbine blades, aircraft ducting systems, engine exhaust systems, because of its unique combination of mechanical, physical and chemical properties. The nickel based super alloy is essentially a nickel-chromium solid solution and is prominently known for its high tensile, fatigue and creep strengths, oxidation resistance, excellent weldability and outstanding corrosion resistance [2]. Table 1 gives the chemical composition of the material.

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

| Elements | Ni | Cr | Mo | Nb + Ta | Fe |
|---|---|---|---|---|---|
| % value | 58 % min. | 20 – 23 % | 8 – 10 % | 3.5 – 4.15 % | 5 % max. |

## 2. LITERATURE REVIEW

**Hari Singh and Rohit Garg** in 2009 have investigated the effect of a number of WEDM process parameters on material removal rate by applying one-factor-at-a-time approach and reported that pulse on time, pulse off time, peak current and sevo voltage have considerable influence [3].

**M.S. Hewidy et al.** in 2005 did modelling for machining parameters of wire electrical discharge machining of *Inconel 601* using response surface methodology (RSM). They used peak current, duty factor, wire tension and water pressure as input parameters and metal removal rate, wear ratio and surface roughness as output parameters. They found that an increase in the peak current leads to the increase of the volumetric metal removal rate. This increase is, however, diminished after 7 A [4].

**Thomas R. Newton et al.** in 2009 tried to find the parameters which affect the formation of re-cast layer in *Inconel 718*. They found that average thickness of re-cast layer increased when energy per spark, current pulse duration and peak discharge current were increased. They found the average thickness of re-cast layer varying from 5 to 9 µm. Wire diameter and spark cycle time do not play major role in the formation of recast layer [5].

**Muthu Kumar V et al** in 2010 used Grey Relational Analysis, Taguchi Method and ANOVA to find out the optimal cutting conditions for cutting Incoloy 800 super alloy in wire EDM process. They selected Gap Voltage, Pulse On-time, Pulse Off-time and Wire Feed as input variables and MRR, surface roughness and Kerf as output variables. They found that optimum conditions for cutting is 50 V Gap Voltage, 10 µs pulse on-time, 6 µs pulse off-time and 8 mm/minute Wire Feed rate. When applying the Gray – Taguchi method, they found that MRR increased from 0.05351 g/min to 0.05765 g/min, surface roughness reduced from 3.31 µm to 3.10 µm and the kerf width reduced from 0.324 to 0.256mm respectively [6].

**Vinod Kumar et al.** in 2012 tried to optimize the process parameters of wire EDM for cutting *Nimonic-90*. They found that cutting speed increased slowly with increasing peak current. But at high pulse duration (Ton =120µs) there was sharp increase of cutting speed with increase of peak current from 40A to 80 A. With increasing pulse on time, the cutting speed increased continuously but machining became unstable at higher pulse on time. Maximum cutting speed is obtained at pulse on time 118 µs and pulse off time 40 µs [7].

**C.D. Shah et al.** in 2013 used RSM to optimize the process parameters in *Inconel 600*. Taguchi Mixed L18 orthogonal array is used to find the best MRR. From the experiment they found that pulse on time and pulse off time are more significant factors [8].

**G. Rajyalakshmi et al.** in 2013 used Taguchi – grey analysis to find the optimum cutting condition for *Inconel 825* in wire EDM. They combined the orthogonal array design of experiment with grey relational analysis. Taguchi L36 orthogonal array is used. From the grey relational analysis optimum condition includes Pon 105µs, Poff 50µs, servo voltage 70 V, flushing pressure 15kg/cm$^2$, wire feed rate 2 m/min, wire tension 9 kg-f. By applying the Taguchi – grey relation analysis they found that MRR increases from 119.625 to126.85mm/min$^3$, surface roughness decreases from 1.68 to 1.44 µm [9].

**Amitesh Goswami et al**. in 2014 proposed multi response optimization method using utility concept for the *Nimonic 80A* alloy in wire EDM. They used $L_{27}$ orthogonal array with six control factors viz. pulse on time, pulse off time, wire feed, wire tension, servo voltage, peak current and three interactions. They took MRR and surface roughness as output parameters. It was found that MRR and surface roughness are increased with increasing values of the pulse on time. They found that pulse on time (46.09%) and pulse off time (32.97%) are more effective parameters than the rest [10].

**E. Atzeni et al.** in 2015 used zinc coated brass wire for cutting of *Inconel 718* to optimize the process parameters and obtaining modification in the surface and sub surface. SEM and EDS were used to evaluate possible variation in the surface chemical composition [11].

**Priyaranjan Sharma et al.** in 2015 found the MRR, SR, recast layer, topography, micro hardness of *Inconel 706* for turbine disk application. The proposed experimental plan was based on OFAT approach. The micro hardness and RLT have been examined using the low and high settings of servo voltage and pulse on time. EDAX analysis has been carried out to study the metallurgical changes in the machined surface. They found that pulse on time, pulse off time and servo voltage are most important factors, whereas servo feed is not important. They also found that wire feed of 6 m/min and flushing pressure of 1.96 bar give higher MRR and SR [12].

## 3. EXPERIMENTAL DESIGN METHODOLOGY

### 3.1 Taguchi Method

The Taguchi method involves reducing the variation in a process through robust design of experiments. The overall objective of the method is to produce high quality product at low cost to the manufacturer. Taguchi developed a method for designing experiments to investigate how different parameters affect the mean and variance of a process performance characteristic that defines how well the process is functioning. The experimental design proposed by Taguchi involves using orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varied. Instead of having to test all possible combinations like the factorial design, the Taguchi method tests pairs of combinations. This allows for the collection of the necessary data to determine which factors most affect product quality with a minimum amount of experimentation, thus saving time and resources.

### 3.2 Selection of orthogonal array and parameters assignment

For the present experimental work the three process parameters each at three levels have been decided. It is desirable to have three minimum levels of process parameters to reflect the true behavior of output parameters of study. The process parameters are renamed as factors and they are given in the adjacent column. The levels of the individual process parameters/factors are given in table 2.

**Table 2: Process parameters and their levels**

| Factors | Parameters | Levels | | |
|---|---|---|---|---|
| | | L1 | L2 | L3 |
| A | Pulse on Time (µs) | 105 | 115 | 125 |
| B | Pulse off Time (µs) | 35 | 45 | 55 |
| C | Peak current (A) | 120 | 140 | 160 |

Selection of a particular OA is based on the number and levels of factors under study. Here, three parameters each at 3 levels have six Degrees of Freedom (DOF). Total DOF of OA should be greater than or equal to the total DOF required for experiment. The nearest possible OA satisfying this requirement is L9 OA. The ''higher-the-better'' quality characteristic has been used for calculating the signal to noise (S/N) ratio for Cutting rate.

$$(S/N)_{HB} = -10 \log (MSD)$$

Where,

$$MSD = (1/y^2_1 + 1/y^2_2 + \ldots\ldots\ldots\ldots + 1/y^2_n)*1/n$$

Where, $y_1$, $y_2 \ldots . y_n$ represent values of n observations in each trial.

## 4. EXPERIMENTAL RESULTS

Nine experiments were conducted using Taguchi experimental design methodology and each experiment was simply repeated two times for obtaining S/N values. In the present study all the designs, plots and analysis have been carried out using Minitab statistical software.

### 4.1 Experimental Results for Cutting Rate

The experimental values of cutting rate (raw data and S/N) are given in table 3.

**Table 3: Experimental data for cutting rate**

| Exp. No. | Factor A Ton | Factor B Toff | Factor C IP | Cutting Rate (mm/min) | S/N ratio |
|---|---|---|---|---|---|
| 1 | 105 | 35 | 120 | 1.015 | 0.129 |
| 2 | 105 | 45 | 140 | 0.718 | -2.877 |
| 3 | 105 | 55 | 160 | 0.395 | -8.068 |
| 4 | 115 | 35 | 140 | 2.350 | 7.421 |
| 5 | 115 | 45 | 160 | 1.958 | 5.836 |
| 6 | 115 | 55 | 120 | 0.993 | -0.061 |
| 7 | 125 | 35 | 160 | 3.80 | 11.595 |
| 8 | 125 | 45 | 120 | 3.431 | 10.708 |
| 9 | 125 | 55 | 140 | 1.90 | 5.575 |

### 4.2 Analysis and discussion of results

Experiments were conducted by using the Taguchi approach to find out the effect of different parameters on the cutting rate. The average value of cutting rate (raw data) and S/N ratio for all levels of all factors have also been calculated. The main effects plots (raw data and S/N data) are shown in figures 2 and 3.

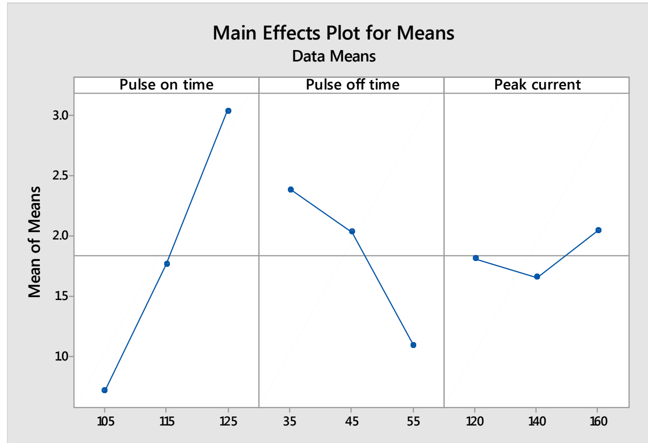


**Fig. 2: Main Effects plot for cutting rate (Raw Data)**

It is revealed from the Fig. 2 that when pulse on time increases, cutting rate also increases. This is attributed to the fact that discharge energy increases with increasing pulse on time leading to more cutting speed. But when pulse off time increases, cutting rate decreases. This is owing to the fact that time between two sparks increased with increasing pulse off time causing reduction in cutting rate. There is very little influence of peak current on cutting rate.

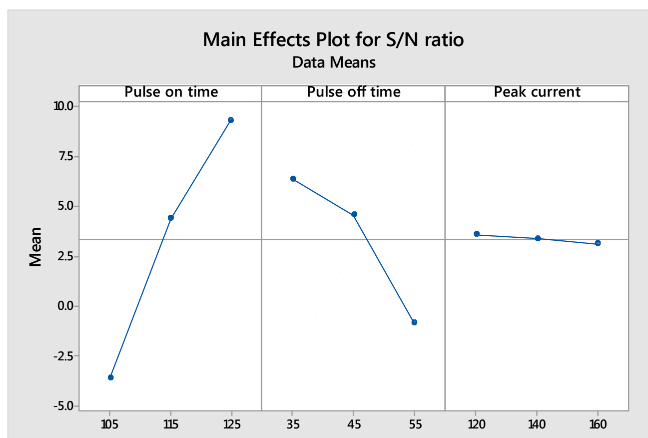


**Fig. 3: Main Effects plot for cutting rate (S/N Data)**

Fig. 3 clearly reinforces the same trend of influence of the factors as in Fig. 2.

### 4.3 Selection of optimal levels

Analysis of variance (ANOVA) was performed in order to determine the significant parameters affecting the cutting rate. In the present investigation, 90% confidence level or 10% level of significance is taken. It was found that peak current is not significant in affecting the cutting rate. So, this factor is pooled and the pooled ANOVAs for raw data and S/N ratio are given in tables 4 and 5. It is clear from the tables that pulse on time and pulse off time have significant effect at 90 % confidence level on the cutting rate.

**Table 4: Pooled ANOVA Table for Raw data**

| Source | DOF | SS | V | F | S' | P% |
|---|---|---|---|---|---|---|
| A | 2 | 8.091 | 4.045 | 25.284 | 7.771 | 68.15 |
| B | 2 | 2.664 | 1.32 | 8.325 | 2.334 | 20.57 |
| Error | 4 | 0.402 | 0.2011 | | | |
| Total | 8 | | | | | |

As the cutting rate is "higher is better" type of characteristic, it is clear from figures 2 and 3 that third level of pulse on time (A3) and first level of pulse off time (B1) result in maximum cutting rate.

**Table 5: Pooled ANOVA Table for S/N data**

| Source | DOF | SS | V | F | S' | P% |
|---|---|---|---|---|---|---|
| A | 2 | 254.342 | 127.171 | 284.49 | 253.44 | 74.32 |
| B | 2 | 84.849 | 42.424 | 94.90 | 83.954 | 24.621 |
| Error | 4 | 1.789 | 0.4472 | | | 1.059 |
| Total | 8 | | | | | |

## 5. CONCLUSIONS

The following conclusions can be drawn from the study:

1. The pulse on time and pulse off time have significant effect on cutting rate.
2. The pulse on time has 68.15% contribution while pulse off time has 20.57% contribution in controlling cutting rate as given in ANOVA for raw data.
3. As pulse on time increases or pulse off time decreases, cutting rate is increased. The peak current has little effect on cutting rate.
4. Pulse on time has 74.32 % contribution while pulse off time has 24.62% contribution on cutting rate as revealed in the S/N ratio analysis.
5. Pulse on time and pulse off time are significant in both the ANOV As, hence affect both the mean value and variance around the mean of cutting rate.

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