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Optimization of machining parameters in WEDM of AISI D3 Steel using Taguchi Technique

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Abstract

Wire Electric Discharge Machining (WEDM) is a non-traditional process of material from conductive material to produce parts with intricate shape and profiles. Machine tool industry has made exponential growth in its manufacturing capabilities in last decade but still machine tools are not utilized at their full potential. In the present work, an attempt has been made to optimize the machining conditions for surface roughness based on (L\textsubscript{9} Orthogonal Array) Taguchi methodology. Experiments were carried out under varying pulse-on-time, pulse-off-time, peak current, and wire feed. An orthogonal array, the signal-to-noise (S/N) ratio, and the analysis of variance (ANOVA) were employed to study the surface roughness in the WEDM of AISI D3 Steel. It was observed that the discharge current was the most influential factors on the surface roughness. To validate the study, confirmation experiment has been carried out at optimum set of parameters and predicted results have been found to be in good agreement with experimental findings.

Keywords: WEDM, Surface roughness, Taguchi method, Analysis of variance

1. Introduction

Wire Electrical Discharge Machining (WEDM) is a non-traditional process of material removal from electrically conductive materials to produce parts with intricate shape and profiles. WEDM is revolutionized the tool and die, mold, punch, and metalworking and aerospace industries \cite{1}. It is considered as a unique adaptation of the conventional EDM process, which uses an electrode to initialise the sparking process. However, WEDM utilises a continuously travelling wire electrode made of thin copper, brass or tungsten of diameter 0.05–0.3 mm, which is capable of achieving very small corner radii. The wire is kept in tension using a mechanical tensioning device reducing the tendency of producing inaccurate parts. The wire work-piece gap usually ranges from 0.025 to 0.05 mm and is constantly maintained by a computer controlled positioning system. In setting the machining parameters, the main goal is the minimum surface roughness. The setting of machining parameters relies strongly on the experience of operators and machining parameters tables provided by machine tool builders. It is difficult to utilize the optimal functions of a machine owing to their being too many adjustable machining parameters.

2. Literature Review

Wire Electric Discharge Machining (WEDM) is an essential operation in several manufacturing in some industries, which gives importance to variety, precision and
This study also demonstrated the capability of wire EDM on surface roughness in WEDM process. For DC53 die metal, the experiments have been successfully carried out and practical results can be used industry in order to select the best suitable parameters combination to get the required surface roughness values for the products. A mathematical model was developed using multiple regression method to formulate the pulse-on time and peak current to the surface roughness. Rao and Satyanarayana [7] proposed a new approach, for the parametric optimization of WEDM process based on L18 (21×44) orthogonal array using Taguchi’s robust design. The machining parameters, namely pulse on time, peak current, flushing pressure of dielectric fluid, wire feed rate, wire tension are optimized with consideration performance characteristics MRR improving the machining efficiency. Mathematical and Artificial Neural Network models have been developed relating the machining performance and process parameters. Bhangoria et al. [8] used the statistical and regression analysis of kerf width using DOE L32 (21×44) mixed orthogonal array Taguchi’s method. Experimental results shown that both approaches can be optimized machining parameters (gap voltage, pulse on time, pulse off time, wire feed and dielectric flushing pressure) effectively, with consideration of the response kerf width. Analysis of variance (ANOVA) technique was used to find the variables affecting the kerf width. Ramakrishnan and Karunamoorthy [9] developed an Artificial Neural Network (ANN) by using Inconel 718 as work material to predict the performance characteristics namely MRR and surface roughness based on Taguchi’s L9 orthogonal array. The response by optimized concurrently using multi-response-signal-to-noise (MRSN) ratio in addition to Taguchi’s parametric design approach. ANOVA was employed to identify the level of importance of the machining parameters on the multi-performance characteristics. Shankarya et al. [10] conducted an experiment in order to Modeling and analysis of surface roughness in WEDC of SiCp/6061 Al MMC through response surface methodology. The WEDC parameters servo voltage, pulse-on time, pulse-off time and wire feed rate were varied to study effect on the quality of cut in SiCp/6061 aluminum MMC using surface roughness as response parameter. The mathematical relationship between WEDC input process parameters and surface roughness was established to determine the value of surface roughness mathematically. To identify the significant factors for WEDC process, analysis of variance (ANOVA) was employed. Haddad and Tehrani [11] proposed a new approach, for the investigated of CWEDT process with multiple performance characteristics based on a 22×32 mixed full factorial design. The machining parameters, namely power, voltage, pulse off time and spindle rotational speed are considerations of multiple performance characteristic including MRR, Ra and roundness. The resolution of the factorial design estimate all the main effects, factor interactions and pure quadratic effects and regression models have been developed by using the Response Surface Methodology (RSM). Shing and Garg [12] stated that effect of process parameters on material removal rate in WEDM like pulse on time (T_{on}), pulse off time, gap voltage, peak current, wire feed and wire...
tension to reveal their impact on material removal rate of hot die steel (H-11) using one variable at a time approach. The optimal set of process parameters has also been predicted to maximize the material removal rate. Golshan et al. [13] stated that Computational intelligence in optimization of WEDM of Cold work steel 2601. In this paper study, two performance surface roughness and volumetric removal rate optimized based on computational intelligence method. The machining parameters including electric current, pulse-off time, open-circuit voltage and gap voltage and output parameters is studied via experimental results analysis and mathematical modeling. Output extracted from non-dominated sorting genetic algorithm used for optimization. Puri and Bhattacharya [14] performed analysis of wire-tool vibration in order to achieve a high precision and accuracy in WEDM with the system equation based on the force acting on the wire in a multiple discharge process. It was clarified from the solution that the wire vibration during machining got mainly manipulated by the first order mode (n = 1). Also, a high tension without wire rupture proved always beneficial to reduce the amplitude of wire-tool vibration. Huang and Lio [15] proposed that grey relational analyses could be applied to determine the optimal selection of machining parameters for WEDM process. Based on Taguchi quality design concept, an L_{18} mixed orthogonal array table was chosen for the experiments. Moreover, the optimal machining parameters setting for maximum metal removal rate and minimum surface roughness could be obtained by approach.

The literature review above indicates that most of the studies have been concentrated on other types of steels. In recent years, alongside other types of steels, AISI D3 steel has also emerged as an important material for industrial applications. Despite extensive research on WEDM process, determining the desirable operating conditions during WEDM of AISI D3 steel, in industrial setting, still relies on the skill of the operators and trial-and-error methods. So the aim of the present work is to obtain the optimum machining conditions for WEDM of AISI D3 steel, for minimizing the surface roughness based on Taguchi technique. Experiments were carried out to study the effect of various parameters viz. pulse peak current, pulse on time, pulse off time, and wire feed, on the surface finish. The levels of significance on the surface roughness were statistically evaluated by using analysis of variance (ANOVA).

3. Experiment
The experimental studies were performed on a ELECTRONICA SUPER CUT 734 WEDM machine tool. The composition of AISI D3 steel work-piece material used for experimentation in this work is given in Table 1. Zinc coated brass wire of diameter 0.25 mm tensile strength) was used in the experiments. The parameters, selected for different settings of pulse on time, pulse off time, peak current and wire feed were used in the experiments (Table 2). The photographic view of the machine and machining zone has been shown in fig. 1 (a) and (b) respectively. The other details of the experimentation have been shown in Table 3. The surface roughness was measured by with Mitutoyo Surftest SJ-201P on the work-piece after machining.

Table-1 Chemical composition of AISI D3 steel (wt %)

| Material | C | Cr | Mn | Ni | Mo | V | Si |
|----------|---|----|----|----|----|---|----|
| AISI D3  | 2.05 | 11.10 | 0.589 | 0.065 | 0.042 | 0.055 | 0.498 |

Table-2 Machining settings used in the experiments

| parameter       | Unit | Level | Level | Level |
|-----------------|------|-------|-------|-------|
| Pulse on time   | μs   | L1    | L2    | L3    |
| Pulse off time  | μs   | 18    | 21    | 24    |
| Pulse off time  | µs   | L1    | L2    | L3    |
| Peak current    | A    | 51    | 55    | 59    |
| Peak current    | A    | 180   | 190   | 200   |
| Wire feed       | mm/min | 4    | 5    | 6    |

Table-3 Fixed parameters

| Wire          | Zinc coated brass wire of diameter 0.25 mm |
|---------------|--------------------------------------------|
| Shape and size of work-piece | Rectangular piece of 200 x 100 x 10 mm |
| Dielectric fluid     | Deionized water                             |
| Conductivity of dielectric fluid | 20 mho                                     |

Fig. 1. (a) Experimental setup; (b) Machining zone.
3.1 Design of experiment based on Taguchi method

To evaluate the effects of cutting parameters of Wire EDM process in terms of cutting performance characteristics such as Surface Roughness a Taguchi method was used here to model the Wire EDM process. In this study, Taguchi method, a powerful tool for parameter design of performance characteristics, for the purpose of designing and improving the product quality [16]. In the Taguchi method, process parameters which influence the products are separated into two main groups: control factors and noise factors. The control factors are used to select the best conditions for stability in design or manufacturing process, whereas the noise factors denote all factors that cause variation.

According to Taguchi based methodology, the characteristic that the smaller value indicates the better machining performance, such as Surface Roughness is addressed as the-smaller-the-better type of problem. The S/N Ratio, i.e. η, can be calculated as shown below:

\[ \eta = -10 \log \left( \frac{1}{N} \sum_{i=1}^{N} y_{i}^2 \right) \]

4. Results and Discussion

The experimental results are collected for surface roughness and 9 experiments were conducted using Taguchi (L9) experimental design methodology and there are two replicates for each experiment to obtain S/N values. In the present study all the designs, plots and analysis have been carried out using Minitab statistical software. Lower amount of surface roughness show the high productivity of Wire EDM. Therefore, small the better are applied to calculate the S/N ratio of surface roughness respectively.

### Table 4. Experimental design using L9 orthogonal array

| Exp. No. | T_{on} (μm) | T_{off} (μm) | I_p (A) | W_{f} (mm/min) | R_{a} (μm) | S/N Ratio (dB) |
|----------|--------------|--------------|---------|----------------|------------|----------------|
| 1        | 1            | 1            | 1       | 1              | 1.0        | 1.0            |
| 2        | 1            | 2            | 2       | 2              | 1.0        | 1.0            |
| 3        | 1            | 3            | 3       | 3              | 1.0        | 1.0            |
| 4        | 2            | 1            | 2       | 3              | 1.0        | 1.0            |
| 5        | 2            | 2            | 3       | 1              | 1.0        | 1.0            |
| 6        | 2            | 3            | 1       | 2              | 1.0        | 1.0            |
| 7        | 3            | 1            | 3       | 2              | 1.0        | 1.0            |
| 8        | 3            | 2            | 1       | 3              | 1.0        | 1.0            |
| 9        | 3            | 3            | 2       | 1              | 1.0        | 1.0            |

Regardless of category of the performance characteristics, a greater η value corresponds to a better performance. Therefore, optimal level with the greatest η value. By applying Eqs. (1) The η values for each experiment of L9 (table 3) was calculated in Table 5.

The optimal machining performance for SR was obtained as 18 μs pulse-on time (Level 1), 51 μs pulse-off time (Level 1), 180 A peak current (Level 1) and 6 mm/min wire feed (Level 3) settings that give the minimum SR. Fig. 2 shows the effect of machining parameters on the SR. That surface roughness increases with the increase of pulse on time, and peak current and decreases with increase in pulse off time, and wire feed. The discharge energy increases with the pulse on time and peak current and larger discharge energy produces a larger crater, causing a larger surface roughness value on the work piece. As the pulse off time decreases, the number of discharges increases which causes poor surface accuracy.

### Table 5. Response table for S/N ratio

| Control factor | Mean η by factor level (dB) | Delta | Rank |
|----------------|-----------------------------|-------|------|
| T_{on} (μm)   | L1 -9.1576, L2 -10.655, L3 -9.0050 |       | 2    |
| T_{off} (μm)  | L1 -9.379*, L2 -10.317, L3 -9.4551 |       | 3    |
| I_p (A)       | L1 -8.730*, L2 -10.006, L3 -10.317 |       | 1    |
| W_{f} (mm/min)| L1 -9.829, L2 -9.773, L3 -9.452* |       | 4    |

At least 95% confidence
Table 7. Pooled of ANOVA for SR

| Process parameter | DOF | SS   | V  | F- ratio | Contribution % |
|-------------------|-----|------|----|----------|----------------|
| TON               | 2   | 0.224| 0.112| 5.233    | 26.14          |
| TOFF              | 2   | 0.045| 0.022| 1.057    | 5.174          |
| Ip                | 2   | 0.5016 | 0.250| 11.67    | 60.35          |
| Wf                | 2   | 0.0429| 0.0214| -        | -              |
| Error             | 0   | 0.0429| 0.0214| -        | -              |
| Total             | 8   | 0.8148 |      |          | 100            |

At least 95% confidence indicates that the variation of the process parameter makes a big change on the performance characteristics. F-values of the machining parameters are compared with the appropriate confidence Table.

According to F-test analysis, the significant parameters on the SR are pulse-on time and peak current. The percent contributions of the machining parameters on the SR are shown in Table 6. Peak current is found to be the major factor affecting the SR (61.56%). The percent contribution of pulse-on time, pulse-off time and wire feed on the SR are 27.59, 5.174 and 5.27%, respectively.

Fig. 3. Percent Contribution of control factors for SR

4.1 Confirmation experiment

The confirmation experiment is performed by conducting a test using a specific combination of the factors and levels previously evaluated. The sample size of confirmation experiment is larger than the sample size of any specific trial in the previous factorial experiment. The final step of the Taguchi’s parameter design after selecting the optimal parameters is to predict any verify the improvement of the performance characteristics with the selected optimal machining parameters [15]. The predicted S/N ratio using the optimal levels of the machining parameters can be calculated with the help of following prediction equation:

$$\eta_{\text{opt}} = \eta_m + \sum_{j=1}^{k} (\eta_j - \eta_m)$$

Here, \(\eta_{\text{opt}}\) is the predicted optimal S/N ratio, \(\eta_m\) is the total mean of the S/N ratios, \(\eta_j\) is the mean S/N ratio of at optimal levels and \(k\) is the number of main design parameters that affect the quality characteristics.

The results of experimental confirmation using optimal machining parameters are shown in Tables 8. From the above observations, it can be interpreted that the obtained SR have reasonable accuracy for resulting model because an error of 3.042% for S/N ratio of SR is measured.

4.2 Results of SEM Micrographs of WEDM Surface

To observe the surface characteristics and type of surface integrity of the machined work-piece, there was a need of SEM micrographs. The numbers below the photographs shows the respective experiment performed on WEDM according to L9 orthogonal array. In experiment No. 1; 18\(\mu s/51\mu s/180\text{Amp}\) shows the control parameters, pulse-on time/ pulse-off time/ peak current, used to conduct this experiment. The experiments numbers 1, 6 and 8 shows the desired surface roughness. The machined surfaces of Die Steel are examined by SEM that is shown in the below figures. From these SEM micrographs, it is obvious that the surfaces are covered with re-solidified layer formation films. As can be seen from the topography, there are many droplets on the Wire EDM surface. SEM micrographs indicate that a foamy structure is caused by the generation of many gas bubbles during machining; the generations of bubbles are clearly visible. These effects are related to the oxidation and/ or decomposition of AISI D3 steel induced by the thermal energy (temperature \(10,000^\circ C\) – \(12,000^\circ C\) during sparking) of WEDM process. The oxidation and decomposition of Die steel generate a large amount of gas
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5. Summery
This paper described the optimization of the WEDM 
process using parametric design of Taguchi methodology. It 
was observed that the Taguchi’s parameter design is a 
simple, systematic, reliable, and more efficient tool for 
optimization of the machining parameters. The effect of 
various machining parameter such as pulse-on time, pulse- 
off time, peak current and wire feed has been studied 
though machining of AISI D3 steel. It was identified that 
the pulse on time and current have influenced more than the 
other parameters considered in this study. The confirmation 
experiment has been conducted. Result shows that the 
errors associated with SR is only 3.042 %. The selection of 
 optimum values is essential for the process automation 
and implementation of a computer integrated manufacturing 
system. Thus the optimized condition, not only makes the 
WEDM a more commercially viable process for industrial 
applications, but also turns a spotlight on WEDM process as a promising field for further advancements.

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