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A STUDY ON MICRO HARDNESS IN WIRE ELECTRICAL DISCHARGE MACHINING BASED ON TAGUCHI METHOD

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Abstract: Wire electric discharge machining (WEDM) is a widely accepted non-traditional material removal process for manufacturing of components with intricate shapes**.** In the present work, an investigation into the wire electric discharge machining of high strength and low alloy (HSLA) steels has been carried out. HSLA steels provide better mechanical properties and greater resistance to atmospheric corrosion. Experimentation has been done using Taguchi's L_9 orthogonal array. Each experiment was conducted under different combinations of pulse on time, pulse off time and peak current.
The optimum machining parameter combination was obtained by using the analysis of signal-to-noise (S/N) ratio, analysis of means and analysis of variance (ANOVA). Further, the level of importance of the machining parameters on micro-hardness was determined by using ANOVA. The study shows that the Taguchi's method is suitable to solve the stated problem with minimum number of trails.

Keywords: WEDM, micro-hardness, taguchi method, Design of Experiment, HSLA

I. INTRODUCTION

Considering the challenges brought on by advanced technology, the electrical discharge machining (EDM) process is one of the best alternatives for machining an ever increasing number of high-strength, non-corrosion, and wear resistant materials [1]. The technology of monitoring and control of the machining process has been accelerated because of the need to improve machining efficiency and part quality. WEDM was introduced in the late 1960s', and has revolutionized the tool and die, mold, and metal working industries. It is probably the most exciting and diversified machine tool developed for this industry in the last fifty years as it offers numerous advantages. WEDM process has been a key process for the tooling and manufacturing industry. It can machine any material or alloy that is electrically conductive regardless of the hardness. The range of materials that can be machined with better precision and accuracy on WEDM is very wide including relatively common materials such as tool steel, aluminum, copper, and graphite, to exotic space-age alloys including hastalloy, wasp alloy, inconel, titanium, carbide, polycrystalline diamond compacts and conductive ceramics. In WEDM, material is removed by means of rapid and repetitive spark discharges across the gap between the tool and the work piece. A WEDM generates spark discharges between a small diameter wire electrode (usually less than 0.5 mm diameter) and a work piece with deionized water as the dielectric medium and erodes the work piece to produce complex two and three dimensional shapes according to a numerically controlled (NC) path. However, the efficiency of machining is low as compared to the conventional machining. WEDM basically consists of a machine composed of a work piece contour movement control unit (NC unit), work piece mounting table and wire driven section for accurately moving the wire at constant tension; a machining power supply which applies electrical energy to the wire electrode and a unit which supplies a dielectric fluid with constant specific resistance.

The material studied here is High-strength low-alloy (HSLA) steel. HSLA steel is one of the widely used materials for various products which often require a high degree of finish and accuracy. It has inherent issues with regard to machinability, cutting speed and quality of machined surface because of its high strength and hardness. HSLA steels are designed to provide better mechanical properties and greater resistance to atmospheric corrosion than conventional carbon steels. They are not considered to be alloy steels in the normal sense because they are designed to meet specific mechanical properties rather than a chemical composition. HSLA steels have yield strengths greater than 275 MPa. The chemical composition of specific HSLA steel may vary for different product thicknesses to meet mechanical property requirements. The HSLA steels in sheet or plate form have low carbon content (0.05 to 0.25% C) in order to produce adequate formability and weldability, and they have manganese content up to 2.0%. Small quantities of chromium, nickel, molybdenum, copper, nitrogen, vanadium, niobium, titanium and zirconium are used in various concentrations. Copper, titanium, vanadium, and niobium are added for strengthening purposes. Although, HSLA steels are widely used in different applications, its machining to produce complex components with intricate shapes is a challenging task to accomplish. Non-conventional machining processes such as WEDM have the potential to machine this special category of alloy steel. However, it is important to select optimum combination of machining parameters including WEDM for achieving optimal machining performance [2]. Keeping this in view, an attempt has been made in this study to obtain optimum combination of machining parameters using the Taguchi method.

II. LITERATURE SURVEY

In the past a lot of work has been published on the effect of WEDM machining parameters on various performance parameters. Scott et al. [3] presented a formulation and solution of a multi-objective optimization problem for the selection of the best parameter settings on a WEDM machine. The measures of performance for the model were MRR and surface quality. Liao et al. [4] performed an experimental study to determine the variation of the machining parameters on the MRR, gap width and surface roughness. In their work, although an attempt was made to determine the level of importance of the machining parameters on the MRR, the level of importance of gap width and surface roughness were not introduced. Tosun et al. [5] introduced a statistical approach to determine the optimal machining parameters for minimum size of wire craters in WEDM. Anish et al. [6] made an attempt to model the response variable i.e. surface roughness in WEDM process using response surface methodology. Rao et al.[7] optimized the surface roughness using multi-response optimization through desirability. They presented, the parametric optimization method using Taguchi's robust design for WEDM machining of Aluminum BIS-24345 alloy. Optimal combinations of parameters were obtained by this method. They also developed mathematical and artificial neural network (ANN) models relating the machining performance and process parameters. Mu-Tian Yan et al. [16] performed the experiment on monitoring and control of the micro wire-EDM process. They investigated the effect of pulse interval, machining feed rate and work piece thickness on the variations of the proportion of normal spark, arc discharge and short circuit in the total sparks (defined as normal ratio, arc ratio and short ratio, respectively). Radzi et al. [17] optimized the process parameters in the cutting of Tungsten Carbide ceramic using electro-discharge machining (EDM) with a graphite electrode by using Taguchi methodology. In their study, they reported that EDM parameters such as peak current, voltage, pulse duration and interval time have a significant influence on machining characteristic such as metal removal rate (MRR), electrode wear rate (EWR) and surface roughness (SR). The analysis of the Taguchi method used by them reveals that, in general the peak current significantly affects the EWR and SR, while, the pulse duration mainly affects the MRR. Manoj et al.[8] optimized the process parameter of WEDM using zinc coated brass electrode. Their study included three factors i.e. metal removal rate, electrode wear rate, and Surface roughness. Manna and Bhattacharya[9] developed a dual response approach for the hard SiC particles of Al/SiC-MMC which intermittently comes in contact with the hard surface during conventional machining and act as small cutting edges like those of a grinding wheel on the cutting tool edge that, in due course, are worn out by abrasion. Mahapatra and Patnaik[10] optimized the WEDM parameters. Sachin Maheshwari et al. [11] presented an investigation on the optimization of process parameters for the Electric Discharge Machining (EDM) of 6061Al/Al2O3p/20p work specimens by employing the Taguchi Design of Experiment (DOE) methodology. They selected one noise factor, aspect ratio (with two levels), and five control factors, viz. pulse current, pulse ON time, duty cycle, gap voltage and tool electrode lift time (three levels each), and employed an L_{18} (21 × 35) fractional factorial design to perform experiment to obtain the optimal settings of factors and the effect of these factors on multiple performance characteristics, namely, Material Removal Rate (MRR), Tool Wear Rate (TWR) and Surface Roughness (SR). Yih-fong Tzeng et al. [12] performed an experimental study to optimize the precision and accuracy of the high-speed electrical discharge machining (EDM) process. Their paper describes the application of the fuzzy logic analysis coupled with Taguchi methods to optimize the precision and accuracy of the high-speed electrical discharge machining (EDM) process.

Literature survey revealed that there are published works on the effect of machining parameters on MRR, surface roughness, cutting speed, wire rupture and wire craters. It appears from the available literature that studies focused on the effect of machining parameters on micro-hardness, an important surface integrity parameter, have not yet been conducted by researchers. In this study, the effect and significance of the machining parameters on micro-hardness is statistically evaluated by using analysis of variance (ANOVA).

Experiments were conducted under different machining parameters, namely, pulse on time, pulse off time and current. The settings of machining parameters were determined by using Taguchi experimental design method. Taguchi's robust design is an important tool for design of experiments which offers a simple and systematic approach to optimize design for performance, quality and cost. The plan of experiments consisted of acquiring data in a controlled way, executing these experiments and analyzing the data, in order to obtain information about the behavior of a given process.

III. EXPERIMENT

The experimental runs were performed on a Steer Corporation DK7712 NC WEDM machine. This machine can cut work piece in accordance with the predetermined locus (The schematic of the experimental setup is shown in Fig. 1). Different settings of pulse on time, pulse off time and current were used in the experiments. Frequency and voltage settings were kept constant throughout the study. ASTM A572-grade 50 HSLA (composition given in Table 1) with 200mm × 40mm × 10mm size was used as work-piece material. During the experiments 100 mm long cuts with 10 mm depth were made. Micro-hardness testing was performed as per ASTM E-384 and micro-hardness was measured using the micro-hardness testing machine (Mitutoyo, Japan). The micro-hardness testing machine used in the present study is shown in Fig. 2.

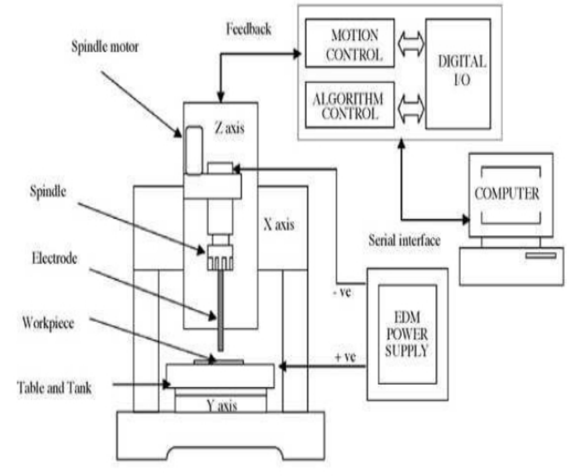

Fig. 1 Experimental setup

Table-1 Material Composition (% by weight)

Element	Concentration	Element	Concentration
Iron	98.31	Aluminum	.004
Carbon	0.187	Copper	.011
Silicon	0.039	Tin	.000
Manganese	1.35	Niobium	.001
Sulphur	0.025	Cobalt	.002
Phosphorous	0.027	Boron	.000
Nickel	0.012	Lead	.0001
Chromium	0.010	Vanadium	.0001
Molybdenum	0.014	Zirconium	.0001

The experimental setup details are given below.

- Machine type/make: Steer Corporation DK7712 NC WEDM machine
- Wire material: Molybdenum wire
- Wire diameter: 0.18 mm
- Dielectric fluid: Demineralized water
- Work piece specification: ASTM A572-grade50 HSLA
- Micro-hardness measuring device: Micro-hardness testing machine (Mitutoyo, Japan) .

Micro-hardness testing is a method for measuring the hardness of a material on a microscopic scale. A precision diamond indenter is impressed into the material at loads from a few grams to 1 kilogram. The impression length is measured microscopically, and the test load is used to calculate a hardness value.

Fig 2. Mitutoyo Micro-hardness testing machine.

The term micro-hardness test usually refers to static indentations made with loads not exceeding 1 kgf.

The load value of 0.2N was used on the Vickers micro hardness indenter in present study. The resulting indentation was measured and converted to a hardness value. Fig. 3 shows a sample indentation of a diamond indenter. Vickers hardness is also sometimes called Diamond Pyramid Hardness (DPH) owing to the shape of the indenter.

The test samples should have a smooth surface and be held perpendicular to the indenter. All things being equal, a lighter indenter load will require a smoother surface for a satisfactory test.

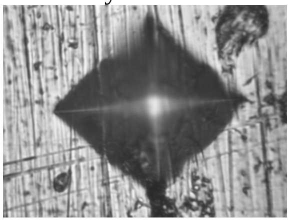

Fig 3. Sample indentation.

3.1 Taguchi Method

Experimental design methods were developed originally by Fisher [13]. However, classical experimental design methods are too complex and not easy to use. Furthermore, a large number of experiments have to be carried out as the number of the machining parameters increases. To solve this important task, Dr.Genichi Taguchi, a Japanese engineer has developed a method based on orthogonal arrays (OA) to study the entire parameter space with only a small number of experiments. In this method quality is measured by the deviation of a characteristic from its target value.

To evaluate the effects of machining parameters on performance characteristics (micro hardness in the present study), and to identify the performance characteristics under the optimal machining parameters, a specially designed experimental procedure is required [11]. In this study, Taguchi method, a powerful tool for parameter design of performance characteristics, was used to determine optimal WEDM machining parameters for micro-hardness. In Taguchi method, machining parameters which influence the products are separated into two main

groups : control factors and noise factors [12]. The control factors are used to select the best conditions for stability in design of manufacturing process, whereas the noise factors denote all factors that cause variation. According to the Taguchi quality design concept, a L_9 orthogonal array with 9 rows (corresponding to the number of experiments) was chosen for the experiments. Selection of parameters is done to maximize the S/N ratio. S/N ratio is the ratio of the mean to standard deviation. Signal represents the square of the mean value of the quality characteristic while noise is the measure of the variability of the characteristics. Usually, there are three categories of performance characteristics in the analysis of the S/N ratio: the lower-the better, the higher-the-better, and the nominal-the-better. Regardless of the category of the performance characteristic, a larger S/N ratio corresponds to better performance characteristic. Therefore, the optimal level of the machining parameters is the level with the highest S/N ratio. Furthermore, a statistical analysis of variance (ANOVA) is performed to identify the machining parameters that are statistically significant. In Taguchi method, a loss function is used to calculate the deviation between the experimental value and the desired value. This loss function is further transformed into a signal-to-noise (S/N) ratio. In WEDM, the higher micro-hardness is the indication of better performance. Therefore, higher-the-better characteristic for the micro-hardness was selected for obtaining optimum machining performance and S/N ratio was obtained as:

$$\eta = -10\log\frac{1}{n}\sum_{i=1}^{n}\left(\frac{1}{y^2}\right) \qquad (1)$$

where:

η = S/N ratio value.
y = micro-hardness value.
n= number of experiments.

3.2 Parameters and their Levels

The WEDM machining parameters and their levels used in the present study for the optimization based of Taguchi method are given in Table-2

Table-2 WEDM process parameters and their levels

Parameters	Levels			units
	Level 1	Level 2	Level 3	
Pulse on time	15	20	25	µs
Pulse of time	3	4	5	µs
Current	2	3	4	A

3.3 Orthogonal Array

To select an appropriate orthogonal array for the experiments, the total degrees of freedom need to be computed. The degrees of freedom are defined as the number of comparisons between design parameters that need to be made to determine which level is better and specifically how much better it is. For example, a three-level design parameter counts for two degrees of freedom. The degrees of freedom associated with the interaction between two design parameters are given by the product of the degrees of freedom for the two design parameters. In the present study, the interaction between the machining parameters is neglected. Therefore, there are six degrees of freedom owing to there being three machining parameters in the WEDM operations.

Once the required degrees of freedom are known, the next step is to select an appropriate orthogonal array to fit the specific task. Basically, the degrees of freedom for the orthogonal array should be greater than or at least equal to those for the design parameters. In this study, an L9 orthogonal was used. This array has eight degrees of freedom and it can handle three-level design parameters. Each machining parameter is assigned to a column, nine machining-parameter combinations being available. Therefore, only nine experiments are required to study the entire parameter space using the L9 orthogonal array. The experimental layout for the three machining parameters using the L9 orthogonal array is shown in Table 3. In addition, Table 3 also shows the measured values of micro-hardness and S/N ratio obtained from Eqn. (1).

Table-3 Experimental design using L_9 orthogonal array

S no.	A(pulse on time)	B(pulse off time)	C(current)	Micro-hardness	S/N ratio
1	15	3	2	173.46	44.784
2	15	4	3	219.4	46.824
3	15	5	4	206.8	46.311
4	20	3	4	140.1	42.928
5	20	4	2	179.5	45.081
6	20	5	3	181.9	45.196
7	25	3	3	167.9	44.501
8	25	4	4	152.3	43.653
9	25	5	2	155.1	43.812

3.4 ANOVA

The importance of machining parameters was investigated to determine the optimum combinations of the machining parameters by using ANOVA. F-test provides a decision at some confidence level as to whether these estimates are significantly different. Larger percentage contribution indicates that the variation of the machining parameter makes a big change on the response. The results of ANOVA given in Table 4 shows that the parameter ***Pulse on time*** is the most dominant factor that affects the micro-hardness as its percentage contribution is 48.304%.

Table 4 Result of ANOVA for micro hardness:

Machining parameter	Sum of square (SS)	Degree of freedom (dof)	Mean Square	Contribution% (ρc)
A	6.038	2	3.019	48.304
B	2.057	2	1.028	16.456
C	2.164	2	1.082	17.312
Error	2.241	2	1.120	17.928
Total	12.50	8		

3.5 Graphs

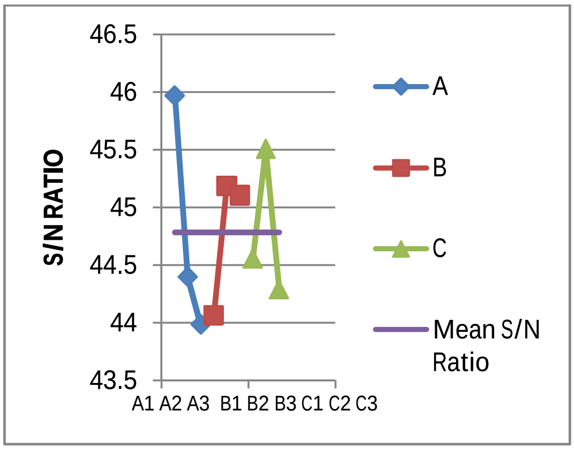

Fig 4. The effect of machining parameter on micro hardness

The graph for the S/N ratio of micro-hardness for all the machining parameters (Pulse on time A, Pulse off time B, Current C) is shown in Fig 4. Based on Fig. 4 and the analysis of variance, the maximum value of micro-hardness was obtained at 15 µs pulse on time (Level 1), 4 µs pulse off time (Level 2) and 4 ampere current (level 2).Further, the effect of machining parameters on micro-hardness is shown in Fig. 4

4. Confirmation experiment

The purpose of the confirmation experiment is to validate the conclusions drawn during the analysis phase. The confirmation experiment is performed by conducting a test with specific combination of the factors and levels previously evaluated. In this study, after determining the optimum conditions and predicting the response under these conditions, a new experiment was designed and conducted with the optimum levels of the machining parameters. The final step is to predict and verify the improvement of the performance characteristic. The predicted *S/N* ratio $\hat{\eta}$ using the optimal levels of the machining parameters can be calculated as:

$$\hat{\eta} = \eta_m + \sum_{i=1}^{p} (\bar{\eta}_i - \eta_m) \qquad \text{……………………} (2)$$

Where η_m is total mean of *S/N* ratio, η_i *is* the mean of *S/N* ratio at the optimal level, and *p* is the number of main machining parameters that significantly affect the performance.

Table 5 Result of the confirmation experiment

	Optimal machining parameters	
	Prediction	Experiment
Levels	A1B2C2	A1B2C2
Micro hardness	214.89	219.4
S/N ratio	46.644	46.824

Table 5 shows the comparison of the predicted micro-hardness with the actual micro-hardness using the optimal machining parameters. It can be seen from Table 5 that there is almost negligible difference between the predicted and experimental values of S/N ratio. Thus, it confirms that the optimum combination of the machining parameter is A1B2C2.

CONCLUSION

The effects of pulse on time, pulse off time, peak current, are experimentally investigated in machining of HSLA steel using WEDM process based on Taguchi method. The combination of machining parameters A1B2C2 i.e. pulse on time at 15 µs, pulse off time at 4 µs and current at 3 A is found to be optimum for micro-hardness. In addition, it is also found that pulse on time is most dominant factor for micro-harness as its percentage contribution is maximum i.e. 48.304%. The level of importance of pulse off time and current, indicated by percentage contribution, on the micro hardness is observed to be 16.458% and 17.315% respectively. The experimental results are also validated using confirmation test and it is found that the predicted and experimental values of S/N ratio are in close agreement. This paper also demonstrates the effectiveness of the Taguchi approach to optimize machining parameters with minimum number of experiments.

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