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Optimization of Process Parameters in Wire Electrical Discharge Machining of Inconel X-750 for Dimensional Deviation Using Taguchi Technique

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Abstract**—**The effective optimization of machining process parameters affects dramatically the cost and production time of machined components as well as the quality of the final products. This paper presents the optimization aspects of a Wire Electrical Discharge Machining operation using Inconel X-750 as work material. The objective considered in this study is minimization of the dimensional deviation. Six input process parameters of WEDM namely spark gap voltage, pulse-on time, pulse-off time, wire feed rate, peak current and wire tension, were chosen as variables to study the process performance. Taguchi's design of experiments methodology has been used for planning and designing the experiments. The analysis of variance was carried out for raw data as well as for signal to noise ratio. Four input parameters and one two-factor interaction have been found to be statistically significant for their effects on the response of interest. The confirmation experiments were also performed for validating the predicted results.

Keywords**—**ANOVA, DOE, inconel, machining, optimization.

I. Introduction

Wire Electrical Discharge Machining (WEDM) is an electro thermal machining process to machine any material which is electrically conductive regardless of strength and hardness. This process utilizes thin wire (electrode), which follows a programmed path. The material removal takes place by series of electric sparks which erode away a part of material, which is vaporized and melted from the workpiece. Some of the wire electrode material is also eroded. These particles (micro-chips) are flushed away from the machining zone with a stream of de-ionized water flowing through the top and bottom flushing nozzles. The de-ionized water prevents the heat built-up in the work-piece. WEDM can machine any electrically conductive material such as tool steel, aluminum, copper, graphite, exotic space-age alloys including hastelloy, inconel, titanium, tungsten carbide, polycrystalline diamond compacts, Ni based alloys and ceramics. The process enables higher accuracy and surface finish together with reasonable cutting efficiency. It is generally used in aerospace, automobile, tool and dies industries where accuracy and surface finish have great importance. Fig. 1 represents the WEDM set up used for this research work.

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In general, WEDM is perceived to be an extremely accurate process, and there are various reasons for this perception. Firstly, in WEDM, there is no direct contact between tool and work piece; as a result, the adverse effects such as mechanical stresses, chatter and vibration normally present in the conventional machining are eliminated.

Secondly, the wire used as a cutting tool has high mechanical properties and small diameter producing very fine, precise and accurate cuts. Finally, the movements of the work piece are controlled by a highly accurate CNC system; as a result, the effects of positioning errors present in traditional machining are eliminated.

Fig. 1 WEDM Setup

II. Literature Review

There is a lot of work done on WEDM in past but there is no reported work on the optimization of parameters for Inconel X-750. Antar et al. [1] machined Udimet 720 nickel based super alloy and Ti-6Al-2Sn-4Zr-6Mo titanium alloy using Cu core coated wires (ZnCu50 and Zn rich brass) as tool on Wire EDM. The authors concluded that an increase in productivity of about 40% for Udimet 720 and about 70% for Ti6246 was possible when replacing standard uncoated brass wire with diffusion annealed coated wires under the same operating parameters. Chiang and Chang [2] presented an effective approach for the optimization of the wire electric discharge machining process of Al_2O_3 particle reinforced material (6061 alloy) with multiple performance characteristics based on the grey relational analysis. Gokler and Ozanozgu [3] investigated the effects of cutting parameters on surface roughness in the WEDM process for different steel materials. A series of experiments was performed on 1040 steel material of thicknesses 30, 60 and 80 mm, and on 2379 and 2738 steel materials of thicknesses 30 and 60 mm respectively. Hascalyk and Caydas [4] investigated the machining characteristics of AISI D5 tool steel in wire electrical discharge machining process. During experiments, parameters such as open circuit voltage, pulse duration, wire speed and dielectric fluid pressure were changed to explore their effect on the surface roughness and metallurgical structure. Optical and scanning electron microscopy, surface roughness and micro hardness tests were used to study the characteristics of the machined specimens. Hewidy et al. [5] highlighted the development of mathematical models for correlating various WEDM machining parameters of Inconel 601 material— peak current, duty factor, wire tension and water pressure— with the metal removal rate, wear ratio and surface roughness. The material was successfully machined by WEDM with a volumetric material removal rate of 8 mm^3/min and surface finish of less than 1μm. The response surface methodology (RSM) was applied for analysis of the data. Kuriakose and Shunmugam [6] investigated multi-objective optimization of wire EDM process. Titanium alloy was chosen as the work material and workpiece thickness was kept as 60 mm. The applied voltage, ignition pulse current, pulse-off time, pulse duration, servo-control reference mean voltage, servo-speed variation, wire speed, wire tension and injection pressure were taken as the input parameters. Zinc-coated brass wire of 0.25 mm diameter was used for all the experiments. The cutting speed and surface roughness were optimized by using Non-Dominated Sorting Genetic Algorithm (NSGA). Liao et al. [7] investigated the machining characteristics of Wire-EDM to achieve a fine surface finish. The traditional circuit was modified by using low power for ignition and for machining as well. Miller et al. [8] investigated the effect of spark on-time duration and spark on-time ratio on the material removal rate (MRR) and surface integrity of four types of advanced materials: porous metal foams, metal bonded diamond grinding wheels, sintered Nd-Fe-B magnets, and carbon–carbon bipolar plates. Five types of constraints on the MRR due to short circuit, wire breakage, machine slide speed limit, and spark on-time upper and lower limits were identified. Muthuraman and Ramakrishnan [9] studied the material removal rate and surface roughness of the WC-Co composite material subjected to wire electric discharge machining. Using desirability analysis, the surface roughness was improved from 2.52 μm to 1.90 μm and MRR was increased from 19.52 mm^3/min to 21.24 mm^3/min. Puri and Bhattacharyya [10] carried out an extensive study of the wire lag phenomenon in Wire-cut Electrical Discharge Machining and established the trend of variation of the geometrical inaccuracy caused due to wire lag with various machine control parameters. All the machine control parameters were considered simultaneously for the machining operation which comprised a rough cut followed by a trim cut. Taguchi's L_{27} (3^{13}) orthogonal array was selected as an experimental design. Shichun et al. [12] analyzed the Kerf width in micro-WEDM, which is composed of two main parts: breakdown distance and wire vibration amplitude. The wire lateral vibration model in micro- WEDM process was built and the relationship between the machining parameters and wire vibration amplitude analyzed. Singh and Garg [13] investigated the effects of various process parameters of WEDM like pulse on time (TON), pulse off time (TOFF), gap voltage (SV), peak current (IP), wire feed (WF) and wire tension (WT) 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. Singh and Khanna [14] investigated the effect of parameters like pulse width, time between two pulses, maximum feed rate, servo reference mean voltage, short pulse time, and wire mechanical tension, on cutting rate of cryogenic-treated D-3 in wire electrical discharge machining. An L27 orthogonal array was used to conduct experiments and statistically evaluate the experimental data by analysis of variance (ANOVA). It is seen that cutting rate decreases with the increase in pulse width, time between two pulses, and servo reference mean voltage. Cutting rate first decreases and then increases with the increase in wire mechanical tension.

In the reported literature, it has been observed that the work has been done on some selected materials but there is no work done on the machining of Inconel X-750 on WEDM. So, this current article is targeted to analyze the effect of input parameters of WEDM on dimensional deviation (DD) while machining Inconel X750.

III. Materials and Methods

Experiments were performed on Electronica sprintcut CNC wire cut EDM machine to study dimensional deviation at different settings of spark gap voltage (SV), pulse-on time (T_{ON}), pulse-off time (T_{OFF}), wire feed rate (WF), peak current (IP) and wire tension (WT). The levels of the input parameters were decided on the basis of literature survey and pilot study using one factor at a time approach. Each factor was varied over a wide range keeping all others at a fixed level and the trend of influence of the factor was obtained in the pilot study. Taguchi's L_{27} orthogonal array with six input variables and three interactions (Table I) was selected for final experimentation.

The various input parameters with their levels are reported in Table II.

A plate with dimensions 150*100*23 in mm has been taken for the experimental work. The specimens were prepared in cylindrical shape of base diameter 5 mm. The deionized water was used as the dielectric fluid.

IV. Design of Experiments (DOE) by Taguchi Method

The statistical design of experiments (DOE) is an efficient procedure for planning experiments so that the data obtained can be analyzed to yield valid and objective conclusions. DOE begins with determining the objectives of an experiment and selecting the process factors for the study. Taguchi's L_{27}

orthogonal array was used for this study. Table III gives the experimental results of the Dimensional Deviation (in µm) for different settings of parameters.

Three trials were conducted for each setting in order to minimize the chances of error. MINITAB-17 software was used for the design and analysis purpose in this study.

V. Results and Discussion

In this work, six input parameters (T_{ON}, T_{OFF}, IP, SV, WF, WT) and three interactions (T_{ON}*T_{OFF}, T_{OFF}*SV, T_{ON}*SV) have been studied. Signal to noise ratio was obtained by using MINITAB-17. The selected characteristic, DD, is of the type "Lower the Better". The S/N ratio is calculated by the logarithmic transformation of loss function as in (1) [11] and values are reported in Table III along with the raw data.

$$\text{S/N ratio} = -10 \log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} y^2\right] \quad (1)$$

The Taguchi approach for predicting the mean performance characteristic and determination of confidence intervals for the predicted mean has been applied.

TABLE I
Taguchi's L-27 Orthogonal Array

Run	1	2	3	4	5	6	7	8	9	10	11	12	13
	A	B	A*B	A*B	C	A*C	A*C	B*C	D	E	B*C	F	-
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

TABLE II
Input Parameters with Levels

Symbols	Factors	Levels			Unit
		I	II	III	
A	T_{on}	110	116	122	Machine unit
B	T_{off}	37	44	51	Machine unit
C	SV	25	45	65	Volt
D	IP	90	130	170	Ampere
E	WF	5	8	11	m/min
F	WT	5	8	11	Machine unit

The material used in this study was Inconel X750 which is a nickel based alloy. The chemical composition of the work material in wt.% is as: Ni 70, Cr 14-17, Fe 5-9, Nb 0.7-1.2, Co 1, Mn 1, Cu 0.5, Al 0.4-1, Ti 2.25-2.75, Si 0.5, C 0.08 and S 0.01.

TABLE III
EXPERIMENTAL RESULTS FOR DIMENSIONAL DEVIATION

Run	Trial1	Trial2	Trial3	S/N Ratio	Mean
1	9	11	10	-20.0289	10
2	21	20	22	-26.4509	21
3	14	16	15	-23.5347	15
4	22	23	21	-26.8544	22
5	14	16	15	-23.5347	15
6	6	4	5	-14.0937	5
7	9	11	10	-20.0289	10
8	3	5	4	-12.2185	4
9	4	3	2	-9.85277	3
10	22	24	23	-27.24	23
11	37	36	38	-31.3661	37
12	21	23	25	-27.2564	23
13	30	29	28	-29.2514	29
14	21	23	22	-26.8544	22
15	20	18	19	-25.5831	19
16	17	16	18	-24.619	17
17	17	18	19	-25.1144	18
18	12	10	11	-20.8517	11
19	41	40	42	-32.2574	41
20	36	37	38	-31.3661	37
21	39	38	40	-31.8232	39
22	36	37	35	-31.1283	36
23	39	40	38	-31.8232	39
24	33	32	34	-30.3729	33
25	34	35	33	-30.6321	34
26	28	26	30	-28.9579	28
27	8	7	9	-18.1068	8

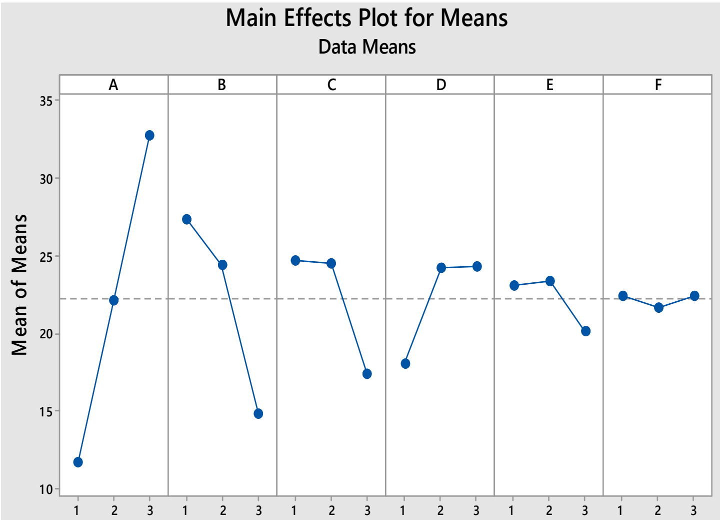

Fig. 2 Main effects plot for means

Fig. 2 represents the main effects plot of data means on DD, and Fig. 3 shows the interaction effect of means. Figs. 4 and 5 show the main effects plot and interaction plot for S/N ratios respectively.

The analysis of variance (ANOVA) was carried out in MINITAB-17 software. Tables IV and V represent the analysis of variance results for means and S/N ratios respectively. From ANOVA results it can be observed that the pulse on time (T_{ON}), pulse off time (T_{OFF}), spark gap voltage (SV) and peak current (IP) have significant effect, whereas wire feed (WF) and wire tension (WT) have little effect on dimensional deviation. Therefore, WF and WT can be neglected in future study. It can also be observed that an interaction between pulse off time and gap voltage has a significant effect on DD while the other two interactions have little effect and can thus be dispensed with in future work. The optimized condition for dimensional deviation (Figs. 2 and 4) is A1, B3, C3 and D1. Table VI gives the optimization results.

The predicted optimum value of DD is calculated as [11]:

$$\mu_{DD} = (\mu_{A1} + \mu_{B3} + \mu_{C3} + \mu_{D1}) - 3\mu \quad (2)$$

The overall mean of the population is: μ= 22.1852 μm. By putting values, the predicted value of DD is: μ_{DD}= 4.7778 μm

For calculation of confidence interval, (3) has been used [11]:

$$CI_{CE} = \sqrt{F_a(1, f_e).V_e\left\{\frac{1}{n_{eff}} + \frac{1}{R}\right\}} \quad (3)$$

Here, f_e (error degree of freedom) = 2; $F_{0.05}$ (1,2) = 18.51 (Tabulated value at 95% confidence level); V_e (error variance) = 2.93.

$$n_{eff} = \frac{N}{1 + Total\ degrees\ of\ freedom\ involved\ in\ estimation\ of\ mean}$$

N= total number of experiments = 81. Hence, n_{eff} = 81/(1+8) = 9, R = sample size = 3. Putting all values in (3): CI_{CE} = 4.912

The 95% confidence interval for μ_{DD} is:

$$0.1342 < \mu_{DD} < 9.6898$$

The confirmation experiments were conducted three times at the optimized settings of parameters. Table VII shows the confirmatory experimental results. The mean value of DD has been found to be within confidence intervals.

TABLE IV
ANOVA TABLE FOR MEANS

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	2005.63	2005.63	1002.81	342.73	0.003
B	2	778.30	778.30	389.15	133.00	0.007
C	2	317.85	317.85	158.93	54.32	0.018
D	2	236.52	236.52	118.26	40.42	0.024
E	2	58.30	58.30	29.15	9.96	0.091
F	2	3.63	3.63	1.81	0.62	0.617
A*B	4	36.15	36.15	9.04	3.09	0.259
A*C	4	30.59	30.59	7.65	2.61	0.295
B*C	4	191.26	191.26	47.81	16.34	0.058
Error	2	5.85	5.85	2.93		
Total	26	3664.07				

S = 1.711 R-Sq = 99.8% R-Sq(adj) = 97.9%

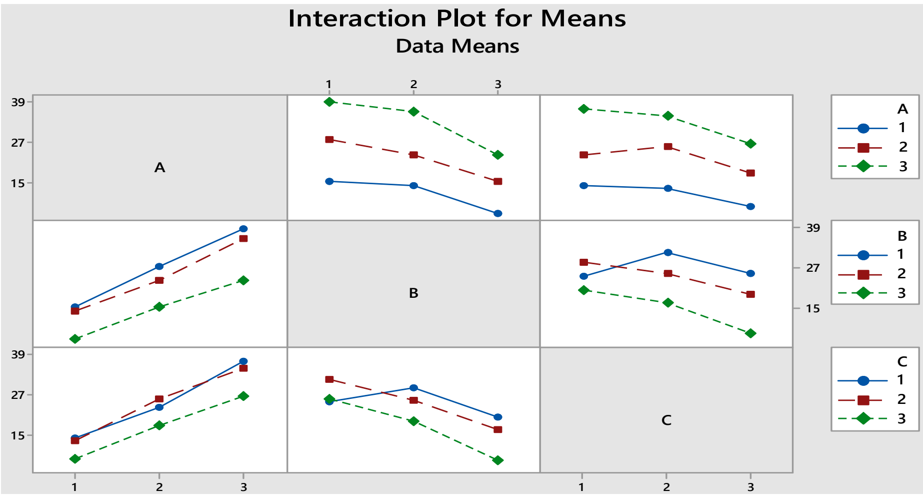

Fig. 3 Interaction plot for means

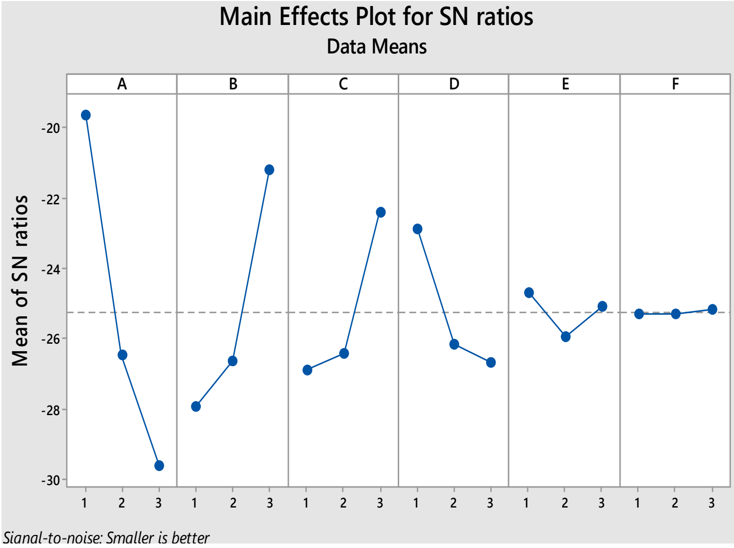

Fig. 4 Main effects plot for S/N ratios

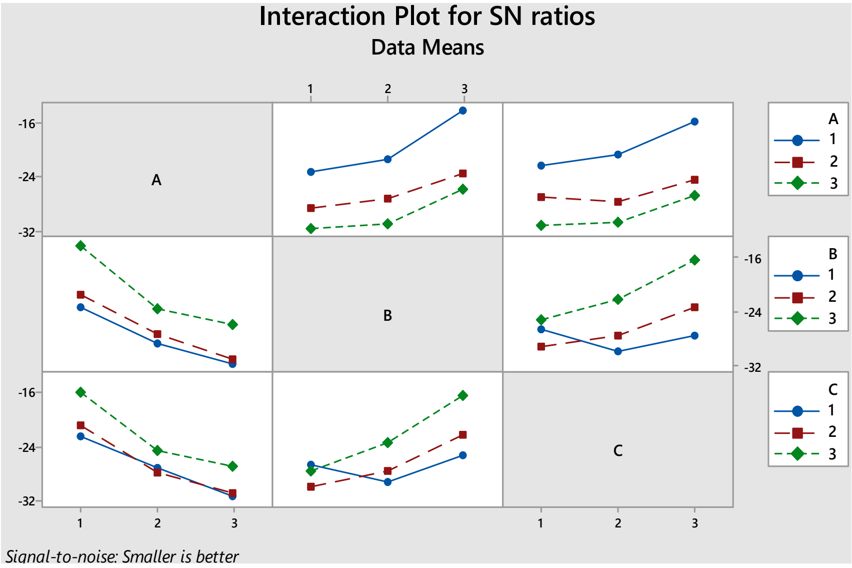

Fig. 5 Interaction plot for S/N ratios

TABLE V
ANOVA TABLE FOR S/N RATIOS

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	469.13	469.13	234.56	274.14	0.004
B	2	232.07	232.07	116.03	135.62	0.007
C	2	110.21	110.21	55.10	64.40	0.015
D	2	77.56	77.56	38.78	45.33	0.022
E	2	7.55	7.55	3.77	4.41	0.185
F	2	0.08	0.08	0.04	0.05	0.954
A*B	4	17.78	17.78	4.44	5.20	0.168
A*C	4	12.16	12.16	3.04	3.55	0.231
B*C	4	78.82	78.82	19.70	23.03	0.042
Error	2	1.71	1.71	0.856		
Total	26	1007.08				

S = 0.9250 R-SQ = 99.8% R-SQ(ADJ) = 97.8%

TABLE VI
OPTIMIZATION RESULTS

Method	Characteristic	Optimal Setting	Predicted Optimal Value
Taguchi's Technique	Dimensional Deviation	A1B3C3D1	4.7778 μm

TABLE VII
CONFIRMATORY EXPERIMENTAL RESULTS

Response (units)	Predicted Value	CI_{CE}	Experimental Value
DD (μm)	4.7778	$0.1342< \mu_{DD} <9.6898$	5.0

VI. CONCLUSIONS

The following conclusions can be drawn from this study:

1. The pulse on time (T_{ON}), pulse off time (T_{OFF}), spark gap voltage (SV) and peak current (IP) are found to be significant factors in both the ANOVAs, hence affecting both mean and variance of DD at 95% confidence level.
2. During WEDM of Inconel X750, Wire feed (WF) and Wire Tension (WT) are found to be insignificant to the response DD.
3. The analysis of results leads to conclusion that the factors at levels A1, B3, C3, and D1 can be set for the minimization of DD.
4. The optimal predicted value of dimensional deviation comes out to be 4.7778 μm and the confidence interval is $0.1342< \mu_{DD} <9.6898$.

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