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Optimum WEDM Process Parameters of Incoloy®Alloy800 Using Taguchi Method

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Abstract: Studies are made on the wire electrical discharge machining (WEDM) process performance parameters such as material removal rate, kerf and surface roughness of Incoloy®Alloy800 following the Taguchi's design of experiments. ANOVA is performed to trace the statistically significance of input parameter (viz. gap voltage, pulse-on-time, pulse-off-time and wire feed) on the WEDM process parameters. A simple multi-objective optimization approach is suggested for specifying a set of optimum input parameters to achieve maximum material removal rate, and minimum surface finish and kerf width.

Keywords: ANOVA, Incoloy®Alloy800, Kerf, Material Removal Rate, Surface Roughness, WEDM

1. Introduction

Wire Electrical Discharge Machining (WEDM) has been adopted in machining high strength, high hardness and temperature as well as corrosion resistant super alloys in marine, space and other applications. There is a necessity to specify the optimum process parameters to maintain better quality and high process safety controlling manufacturing costs and time. Material removal rate (MRR), kerf width, and surface roughness (SR) are the important responses in WEDM. One of the promising techniques is the Taguchi's design of experiments to obtain the desired results with less number of experiments. Choudary and El-Baradie [1] have made a review on the machinability of nickel-base super alloys. Egugwu [2] have highlighted advances in machining techniques to enhance productivity and minimize manufacturing cost in addition to the controlling the surface finish, surface integrity, circularity and hardness of the machined component.

Muthukumar et al. [3] have transformed the original response values to S/N ratio value and carried out the multi-response optimization of WEDM process for machining of Incoloy®800 using combination of Grey- relational analysis and Taguchi methods. Jaganathan et al. [4] have conducted experiments on EN31 alloy steel and used the Taguchi's method to obtain optimum control factors (such as applied voltage, pulse width, pulse interval and speed) for maximization of MRR and minimization of SR. They have also applied the S/N ratio transformation on a single value of each test run output responses. Malik et al. [5] have utilized zinc-coated brass wire and claimed that the WEDM process parameters can be adjusted so as to achieve better material removal rate, surface finish, and electrode wear rate. Lokeswara Rao and Selvaraj [6] have applied the S/N ratio transformation on a single value of each test run output response to obtain the optimum WEDM process parameters on titanium alloy. Singh et al. [7] have identified wire-type and pulse-on-time as significant parameters and set the optimum input parameters to obtain minimum surface roughness on AISI H13. They have performed analysis of variance (ANOVA) by applying S/N ratio transformation (with lower is better) on the value of surface roughness for each test run. Mahapatra and Patnaik [8] have used a multi-objective optimization based on genetic algorithm for maximization of metal removal rate (MRR) and surface finish (SF) simultaneously. Mahapatra and Patnaik [9] have studied factors like discharge current, pulse duration, pulse frequency, wire speed, wire tension and dielectric flow rate and few selected interactions both for maximization of MRR and minimization of surface roughness (SR) in WEDM process using Taguchi method. Mahapatra and patnaik [10] have employed genetic algorithm to optimize WEDM process with multiple objectives and adjusted the process parameters to achieve better MRR, SF and cutting width simultaneously. By varying the machine feed rate with constant current, Alias et al. [11] have performed experiments on Ti-6Al-4V alloy using brass wire in the WEDM process and obtained fine surface at high level machine feed rate. Tosun et al. [12] have set optimum machining parameters to obtain maximum MRR and low kerf on AISI 4140 by adopting a multi-objective optimization approach. While optimizing the WEDM process parameters for AISI D3, Lodhi and Agarwal [13] have observed that pulse-on-time and peak current are influencing more on the surface roughness when compared to pulse-off-time and wire feed. WEDM experiments on SS304 carried out by Lingadurai et al. [14] indicate that pulse-on- time, wire feed, and input voltage are significantly influencing the kerf width, SR and MRR.

The optimal machining conditions to achieve high MRR and low SR are found to be different. It is preferable to have a set of optimum machining parameters to achieve high MRR and low SR adopting a reliable multi-objective optimization technique. To study the influence of zinc coated brass wire in the WEDM process of titanium alloy, experiments performed by Nourbaksh et al. [15] indicate that cutting speed is increased with peak current and pulse interval, whereas surface roughness increases with pulse width and pulse interval. Dhiman et al. [16] have presented optimum process parameters for S7 steel. It is noted from their findings that cutting rate is increased with pulse-on-time, pulse duration and peak current, whereas it decreases with servo gap voltage. Experiments of Sharma et al. [17] on SS100 indicate that MRR and SR increase with increase in pulse-on-time and peak current.

INCOLOY®Alloy800 is being used in a variety of applications involving exposure to corrosive environments and high temperatures. The alloy is used for heat-treating equipment such as baskets, trays, and fixtures. In chemical and petrochemical processing, the alloy is used for heat exchangers and other piping systems in nitric acid media especially where resistance to chloride stress-corrosion cracking is required. In nuclear power plants, it is used for steam-generator tubing. The alloy is often used in domestic appliances for sheathing of electric heating elements. In the production of paper pulp, digester-liquor heaters are often made of alloy800. In petroleum processing, the alloy is used for heat exchangers that air cool the process stream. (Ref: www.specialmetals.com/alloys). The signal-to-noise (S/N) ratio transformation in the Taguchi's design of experiments considered by the above researchers is on a single value of each test run output response. In fact, Taguchi has created the S/N ratio transformation to consolidate several repetitions into one value to reflect the amount of variation present. Hence, the unwanted S/N ratio transformation adopted by the previous researchers has no added advantage other than additional computational work. An appropriate multi-objective optimization technique has to be adopted to specify a set of optimum process parameters for the output responses.

Muthu Kumar et al. [3] have studied the optimization of the WEDM parameters on machining INCOLOY®Alloy800 with multiple performance characteristics such as MRR, SR and kerf based on the Grey-Taguchi method. The unwanted S/N ratio transformation adopted by them on a single value of each test run output responses has no added advantage. They have provided mathematical models to predict the output responses. Motivated by the investigations of the above researchers, studies are made on Incoloy®alloy800 to trace the optimum WEDM parameters for achieving high material removal rate and lower surface roughness and kerf width by performing ANOVA analysis on the test data from the Taguchi's design of experiments and utilizing a simple multi-objective optimization technique.

2. Taguchi's Design of Experiments and Analysis of Variance

Many factors / parameters in the processes influence the final outcome. It is possible to identify their individual contributions and their intricate relationship through design of experiments. Taguchi defined a set of orthogonal arrays and devised a standard method for analyzing the results [18-21].

The high strength temperature resistant alloy (i.e., Incoloy®alloy800) is considered as the work piece material in the present study. The chemical composition (Wt%) of Incoloy®alloy800 [3]: C-0.096; Cr-20.096; Mn-0.501; Al-0.302; Mo-0.335; Ni-34.991; Fe-42.821; Ti-0.304; W-0.066; V-0.027; and Co-0.07. Muthu Kumar et al. [3] have performed experiments on four axes Electronica Ecocut CNC WEDM machine. 0.25 mm diameter brass wire is used as the tool electrode material. 0.025 to 0.05 mm gap is maintained in between the wire and work-piece. The de-ionized water is flashed through the gap along the wire to the sparking area for removing the debris produced during the erosion. The tank at the bottom collects the wire erosions and discards later. Due to variation in dimensional accuracy, the wires are used only once.

The design of experiments involves selection of independent variables or factors (viz., gap voltage, pulse-on-time, pulse-off-time and wire feed rate); selection of number of level setting for each independent variable; selection of orthogonal array; assignment of independent variable to each column of orthogonal array; conducting experiments for measuring material removal rate (MRR), surface roughness (SR) and kerf. The surface finish value (in μm) has been obtained by measuring the mean absolute deviation, SR from the average surface level using a computer controlled surface roughness tester, whereas the kerf width has been measured using the video measuring system (VMS 2010F). The material removal rate $MRR = ktv_c\rho$. Here k is the kerf width (mm), t is the thickness of work piece (mm), v_c is the cutting speed (mm/min) and ρ is the density of the work piece material (g/mm^3).

Table 1 gives the assignment levels of process parameters and the performance output responses (viz., MRR, SR and kerf) for the assigned process parameters as per L_9 orthogonal array [3]. Analysis of variance (ANOVA) is performed to trace the optimum process parameters for obtaining maximum MRR and minimum SR and kerf.

It is noted from the ANOVA results of Table 2 that gap voltage has an immense effect on MRR with 64.8% contribution and other parameters like pulse-on-time, pulse-off-time and wire feed rate on the MRR are 24, 5.1 and 6.1% respectively. Gap voltage has 84.1% contribution on SR and other parameters like, pulse-on-time, pulse-off-time and wire feed rate on the SR are 14.6,1.2 and 0.1% respectively. Gap voltage has 85.3% contribution on kerf and other parameters like pulse-on-time, pulse-off-time and wire feed rate on the kerf are 0.8, 11.6 and 2.3% respectively.

3. Prediction Methodology and Multi-objective Approach

The process parameters for the maximum MRR are $A_1B_3C_2D_2$. Here subscripts denote the level of the parameter. The process parameters to achieve minimum surface roughness (SR) are $A_1B_1C_2D_2$, whereas for the minimum kerf width, the process parameters are $A_1B_1C_3D_3$. Conformation experiments are necessary to find output responses for the optimum process parameters. However, there is a possibility to estimate the optimal output response for the desired process parameters by means of additive law [15]:

$$\hat{\eta} = \eta_m + \sum_{i=1}^{p} (\eta_i - \eta_m) \tag{1}$$

Here $\hat{\eta}$ is the optimum value for the output response; η_m is the overall mean of η with 9 test runs; η_i is the mean of η at the optimal level for the process parameters (i); and p is the number of process parameters.

Table 1. *Performance output responses (viz., MRR, SR and kerf) for the assigned process parameters as per L_9 orthogonal array.*

Control Factors (Input parameters)	Designated Factor	Level -1	Level-2	Level-3
Gap voltage (V)	A	50	60	70
Pulse- on-time (µs)	B	6	8	10
Pulse-off-time (µs)	C	4	6	8
Wire feed (m/min)	D	6	8	10

Assignment levels of process parameters

Test Run	Levels of input parameters				Output responses [3]			ζ (Eq. 2)
	A	B	C	D	MRR (g/min)	SR (µm)	kerf (mm)	
1	1	1	1	1	0.04833	3.11	0.317	0.56862
2	1	2	2	2	0.05351	3.31	0.324	0.55147
3	1	3	3	3	0.05128	3.60	0.299	0.56631
4	2	1	2	3	0.04192	3.67	0.330	0.68154
5	2	2	3	1	0.04295	3.97	0.322	0.68577
6	2	3	1	2	0.05011	4.04	0.343	0.64618
7	3	1	3	2	0.03844	4.11	0.356	0.77796
8	3	2	1	3	0.03974	4.26	0.368	0.78342
9	3	3	2	1	0.04538	4.40	0.376	0.74134

Performance output responses

Table 2. *Analysis of variance (ANOVA) for the material removal rate (MRR), surface roughness (SR) and kerf width.*

Parameters	1-Mean	2-Mean	3-Mean	Sum of squares	% contribution
Material removal rate, MRR (g/min)					
A	0.05104	0.04499	0.04119	1.481-04	64.8
B	0.04290	0.04540	0.04892	5.488-05	24.0
C	0.04606	0.04694	0.04422	1.156-05	5.1
D	0.04555	0.04735	0.04431	1.402-05	6.1
Surface roughness, SR (µm)					
A	3.3400	3.8933	4.2566	1.27828	84.1
B	3.6300	3.8466	4.0133	0.22162	14.6
C	3.8033	3.7933	3.8933	0.01820	1.2
D	3.8266	3.8200	3.8433	8.654-04	0.1
Kerf width (mm)					
A	0.3133	0.3316	0.3667	4.411-03	85.3
B	0.3343	0.3380	0.3393	4.038-05	0.8
C	0.3427	0.3433	0.3257	6.006-04	11.6
D	0.3383	0.3410	0.3323	1.181-04	2.3

Figures 1 to 3 show the comparison of experimental and estimated output responses for the assigned levels of the input variables. The estimated output responses are in good agreement with the test results [3]. The output responses estimated from the mathematical models of Ref. 3 are reasonably in good agreement with test results.

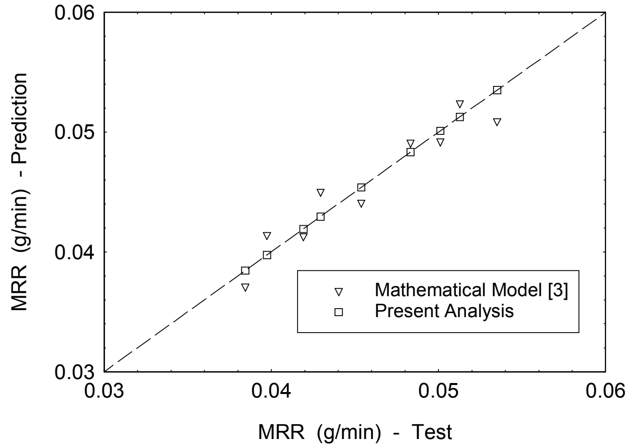

Figure 1. *Comparison of estimated material removal rate (MRR) with test results.*

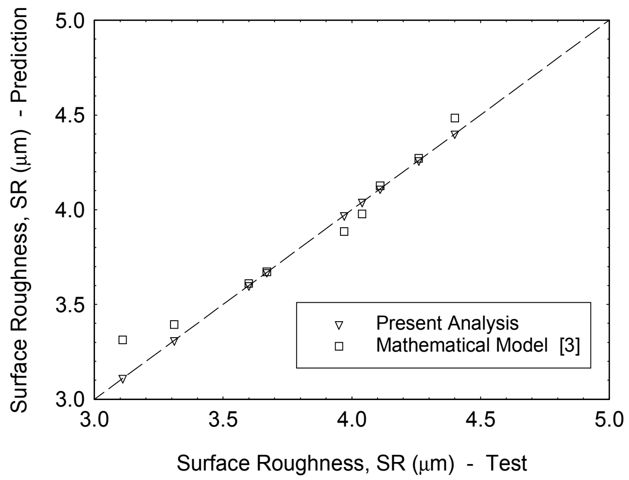

Figure 2. *Comparison of estimated surface roughness (SR) with test results.*

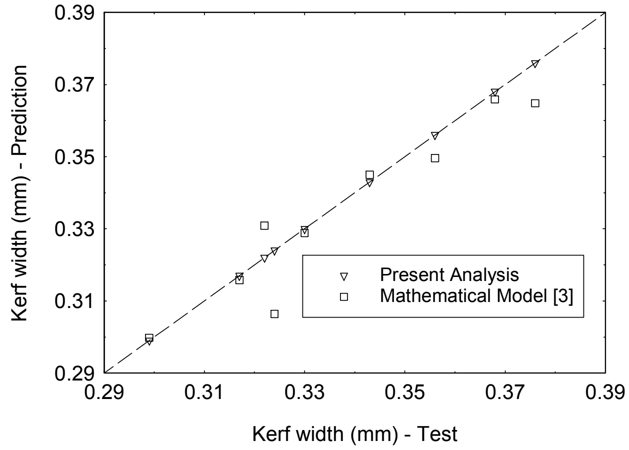

Figure 3. *Comparison of estimated kerf width with test results.*

The optimum values of MRR, SR and Kerf for the identified process parameters obtained from equation (1) are: 0.05703 g/min, 3.0933 μm and 0.29393 mm respectively. It should be noted that the optimum process parameters for the above output responses are different. There is a need to specify a set of optimal process parameters to achieve maximum MRR, minimum SR and Kerf width. For this purpose, a non-dimensional parameter ζ is introduced as

$$\zeta = \omega_1\left(\frac{(MRR)_{\max}}{MRR}-1\right)+\omega_2\frac{SR}{(SR)_{\max}}+\omega_3\frac{Kerf}{(Kerf)_{\max}} \quad (2)$$

Here ω_1, ω_2 and ω_3 are weighing factors, whose sum is unity. To have common optimum process conditions, equal weight are given (i.e., $\omega_1=\omega_2=\omega_3=1/3$). The maximum values estimated for the output responses are: $(MRR)_{max}$ = 0.05703 g/min; $(SR)_{max}$ = 4.5165 μm and $(Kerf)_{max}$ = 0.37861 mm. The ζ values for all the 9 test runs of Table 1 are generated and ANOVA is performed on ζ and obtained optimum process parameters to achieve minimum ζ. The selected process parameters are 50V gap voltage (A_1), 10μs pulse-on-time (B_3), 6μs pulse-off-time (C_2) and 8m/min wire feed rate (D_2). The corresponding output responses are: MRR=0.05703 g/min; SR=3.4766 μm; and kerf=0.32524mm. Muthukumar et al. [3] have obtained the same set of optimum process parameters for which the output responses from their mathematical models are: MRR=0.05406 g/min; SR=3.5488 μm; and kerf=0.311mm. Their Grey-theory design provides the output responses for the same optimum parameters as MRR=0.05765 g/min; SR=3.10 μm; and kerf=0.296mm, which are close to the present values (MRR=0.05703 g/min, SR=3.0933 μm and kerf=0.29393 mm) of the respective standard single objective optimization approach.

4. Concluding Remarks

This paper deals with the WEDM process performance parameters such as material removal rate (MRR), surface roughness (SR) and kerf width of Incoloy®alloy800 adopting the Taguchi's Design of Experiments. ANOVA is performed to identify the significance of the input parameters, viz. gap voltage, pulse-on-time, pulse-off-time and wire feed rate on the output response parameters (viz., MRR, SR and kerf). The maximum MRR of 0.05703 g/min can be achieved for 50V gap voltage, 10 μs pulse-on-time, 6 μs pulse-off-time and 8m/min wire feed rate. The minimum surface roughness, SR of 3.0933 μm can be achieved for 50V gap voltage, 6 μs pulse-on-time, 6 μs pulse-off-time and 8m/min wire feed rate. The minimum kerf of 0.29393 mm can be achieved for 50V gap voltage, 6 μs pulse-on-time, 8 μs pulse-off-time and 10m/min wire feed rate. Multi-objective-optimization approach is adopted and specified a set of optimum input parameters as 50V gap voltage, 10 μs pulse-on-time, 6 μs pulse-off-time and 8m/min wire feed rate. For these parameters, the output response parameters obtained from equation (1) are: MRR=0.05703 g/min; SR=3.4766 μm; and kerf=0.32524mm. The unwanted signal-to-noise (S/N) ratio transformation adopted by Muthukumar et al. [3] in the Grey-Taguchi method on a single value of each test run output response has no added advantage other than additional computational work. The prediction methodology adopted in this paper is quite simple and useful in the Taguchi's design of experiments.

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