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Surface roughness modeling of Ni -Co based alloy using RSM

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Abstract

This article presents the experimental data for the machining of Monel 400 on wire electrical discharge machining (WEDM). It is a nickel based alloy which possessing creep resistance and high rupture strength at high temperature (up to 950 ∘C). Four input process parameters, viz., Pulse on time (A), pulse off time (B), peak current (C), spark gap set voltage (D) were investigated and modelled for response variable namely Surface roughness utilizing Response Surface Methodology (RSM). In present experimentation, quadratic model is suggested for the response. Analysis of Variance (ANOVA) indicate that Ip, Ton, Toff and SV are significant process parameters influencing the CS.

Keywords: ANOVA; WEDM; CCD, Response surface, machining

1. Introduction

The Electrical Discharge Machining (EDM) was first introduced in the 1940's as a crude device used to cut broken machining tools from expensive in - process parts. Since that time EDM has become a sophisticated and indispensable technology, revolutionizing the tool, die, and mold making industries, and making significant inroads into the production of highly accurate, intricate and difficult to machine production parts. In electrical discharge machining, it is important to select machining parameters for achieving optimal machining performance. Usually, the desired machining parameters are determined based on experience or handbook values. However, this does not ensure that the selected machining parameters result in optimal or near optimal machining performance for that particular electrical discharge machine and environment. In earlier work to solve this task, Lin, Wang, Yan, Tarng used the Taguchi method with fuzzy logic as an efficient approach to determine the optimal machining parameters in the electrical discharge machining process. Wire-cut electrical discharge machining of Monel 400 has been considered in the present set of research work. Inconel, nickel – chromium - iron alloy Monel 400 is a standard engineering material for applications which require resistance to corrosion and heat. The alloy also has excellent mechanical properties and presents the desirable combination of high strength an d good workability. The alloy's strength and oxidation resistance at high temperatures make it useful for many applications in the heat treating industry. It is used

for retorts, muffles, roller hearths, and other furnace components and for heat treating baskets and trays. In the aeronautical field, alloy monel 400 is used for a variety of engine and airframe components, which must withstand high temperatures. Examples are lock wire, exhaust liners, and turbine seals. To obtain various structural components of Monel 400 alloy the wire cut EDM process plays a predominant role in some manufacturing sectors, because this process has the capacity to cut complex and intricate shapes of components in all electrically conductive materials with better precision and accuracy [2]It has been long recognized that cutting conditions such as pulse on time, pulse off time, servo voltage, peak current and other machining parameters should be selected to optimize the economics of machining operations as assessed by productivity y, total manufacturing cost per component or other suitable criterion. The application of DOE required careful planning, prudent layout of experiment and expert analysis of results.

The meaning of factorial design is that each complete test or replications of all the possible combinations of the levels of the factors are investigated [1]. Using RSM and 21 factorial design of experiment, mathematical model (first-order) of cutting speed as a function of speed, feeds and depth of cut have been developed with 95% confidence level. These model equations have been used to develop cutting speed contours.
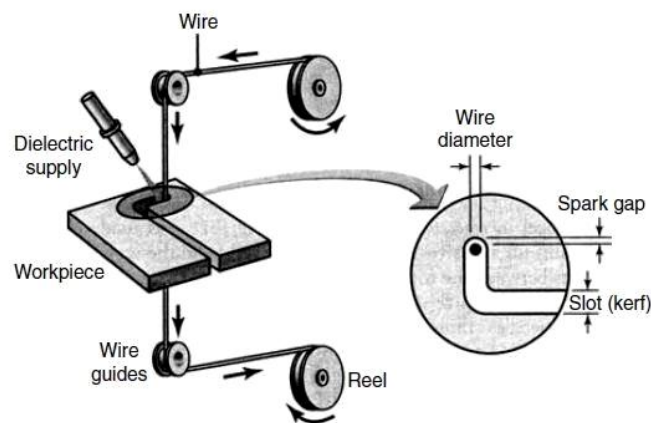

Figure 1: Schematic diagram of WEDM

2. Literature Review

Duniraj et al. [2] described the optimization of process parameters in Wire EDM with stainless steel using single objective Taguchi method and multi objective grey relation grade. For experimentation Taguchi s LI6 orthogonal array has been used. They investigated that the effect of input parameters such as gap voltage, wire feed, pulse-on-time and pulse-off-time on the surface roughness and kerf width. By using multi-objective optimization technique grey relational theory, the optimal input parametric combination has been found as 50V gap voltage, 2mm/min wire feed, 4 μs pulse on time and 4 μs pulse off time. The analysis of variance resulted that the pulse-on-time has major influence in the surface roughness and kerf width. *Hewidy et al.* [3] modeled the machining parameters of wire electrical discharge mining of *Inconel 601* using RSM. They investigated the effect of input parameters such as peak current, duty factor, wire tension and water pressure on the metal removal rate, wear ratio and surface roughness. They concluded that the volumetric metal removal rate generally increase with increase of peak current

value and water pressure This trend has been valid up to the generation of arcing, after certain limit, the increase of peak current leads to the decrease of MRR and concluded that the wear ratio increase with the increase if peak current and decrease with the increase of duty factor and wire tension. The best surface finish (Ra) that has been reached is 0.8 micron meter. Wire tension and wire speed were changed to explore their effect on machining performance, including the cutting speed, the width oil slit and surface roughness, Moreover, the wire electrode was easily broken during the machining A12O3p/606 I AI composite, so that work comprehensively investigated into the location of broken wire and the reason of wire breaking They concluded that the machining of A12O3p/6061Al composite a very low wire tension. a high flushing rate and a high wire speed were required to prevent wire breakage with an appropriate servo voltage, a short pulse-on- time and a short pulse-off-time.

Kanlayasiri and Boonmung [4] investigated influence of wire-EDM machining variables on surface roughness of newly developed DC53 die steel of width, length, and thickness 27, 65 and 13 mm, respectively. The machining variables included pulse on time, pulse off time, peak current and wire tension. The variables affecting the surface roughness were identified using ANOVA technique. Result showed that the pulse on time and peak current were significant variables to the surface roughness of wire-EDM DC53 die steel. The maximum prediction error of the model was less than 7% and average percentage error of prediction was less than 3%.

Kanlayasiri and Boonmung [4] investigated the effects of wire EDM machining parameters on surface roughness of DC53 die steel. The investigated machining parameters were pulse-on time. pulse-off time, pulse-peak current and wire tension Analysis of variance (ANOVA) technique was used to find out the parameters affecting the surface roughness. Assumptions of ANOVA were examined through residual analysis. Quantitative testing methods on residual analysis were employed in place of the typical qualitative testing techniques. Results from ANOVA showed that pulse-on time and pulse peak current are significant variables for surface roughness. The surface roughness of test specimen increased as these two variables increased. *Mgoudar and Sadashivappa* [5] investigated the effect of machining parameters on no and surface roughness in machining of ZA43/SiCp composite by WEDM. They investigated that the effect of input parameters likes current, pulse-on-time, pulse-off-time on be MMR and surface roughness. They observed a reduction in the MMR and increase in surface roughness for increased reinforcement in the composite They also observed that increment in applied current and pulse-on-time increases the MMR.

Pudand Bhattacharyya [6] An attempt has been made to model the white layer dept through response surface methodology (RSM) in WEDM process comprising a rod cut followed by a trim cut. An experimental plan of rotatable central composite desk considering of four input variables, such as the pulse off-time during rough cutting (RT on) and pulse-on-time (TT on), offset and cutting speed during cutting have been modesty. It was concluded that the white layer depth increased with increased pulse-on- structuring the first rough cut and subsequently decreased while increasing pulse-on- time during trim cutting. The white layer depth reduce with decreasing wire tool off-set during trim cutting.

Satish kumar et al. [7] reported the investigation of the machining characteristics of AI6063/SiCp composites material in WEDM. in this investigation, the effect of wire electrical discharge machining (WEDM) parameters such as pulse-on time (Ton), pulse-off time (Toff), gap voltage

(V) and wire feed (F) on material removal rate (MRR) and surface roughness (Ra) was studied. The AI6063 is reinforced with SiCp in the from of particles with 5%, 10% and 15% volume fractions. The experiments are carried out as per design of experiments approach using L9 orthogonal array. The results were analyzed using analysis of variance and response graphs. The results were also compared with the results obtained for unreinforced A16063. Generally, it was found that the increase in volume percentage of SiC resulted in decreased MRR and increased Roughness. Regression equations have been developed based on the experimental data for the prediction of output parameters for AI6063 and composites.

Shandilya et al. [8] described the parametric study along with selection of optimal solution in dry wire cut machining of cemented tungsten carbide (WC-Co), Experiments have been conducted using air as dielectric medium to investigate effect of pulse-on-time, pulse-off-time, gap set voltage, discharge current and wire tension on cutting velocity, surface roughness and oversize, A central composite rotatable method was employed to design experiments based on response surface methodology (RSM), Empirical model were developed to create relationship between process factors and response by considering to analysis of variance (ANOVA). These models were associated with optimization approaches namely desirability function and PSO. Result indicated that selection of air at inlet pressure of 1.5 bar leads to higher MRR and lower surface roughness. They concluded that the cutting velocity and surface roughness increase by increasing the discharge current and pulse-on-time. But increased pulse-on-time leads to lower oversize. Based on the results of the preliminary experiments, Cutting velocity and sure roughness were found to be decreased by increasing pulse-off-time and gap set voltage.

3. Experimental procedure

In present work, a 5 axis sprint cut WEDM is used for conducting the experiments, made by Electronica M/C Tool LTD, india,. Performance of WEDM depends on setting of process parameters. Following section discusses the work material, machining parameters and experimental design used for present study.

3.1 Work material

MONEL nickel alloy is a solid solution alloy that can be hardened by the process of cold working. MONEL is a trademark of Special Metals Corporation under which a series of nickel-copper alloys are grouped. Commercially there are many types of MONEL available, such as alloy 400, alloy 401, alloy R-405, Alloy K-500 and Monel 404. The Monel 400 alloy is also known as super alloy monel. This alloy is available in some standard shapes such as hexagon, round, tube, pipe, plate, strip, sheet and wire. The proportions of copper and nickel used to make monel are the same as that found in the nickel ore found in mines. This alloy exhibits good corrosion resistance. This datasheet will look into the chemical composition, properties and applications of MONEL 400 alloy.

Table1: The composition of Monel 400

Element	Content (%)
Nickel, Ni	Remainder
Copper, Cu	28-34
Iron, Fe	2.5 max
Manganese, Mn	2 max
Silicon, Si	0.5 max
Carbon, C	0.3 max
Sulphur, S	0.024

3.1.2 Properties of work material

Properties	Metric	Imperial
Tensile strength (annealed)	517-620 MPa	75-90 ksi
Yield strength	172-345 MPa	25-50 ksi
Modulus of elasticity	179 GPa	26000 ksi
Poisson's ratio	0.32	0.32

3.2 Machining parameters

Four discharge parameters, viz. Pulse on time (A), pulse off time (B), peak current (C), spark gap set voltage (D)are selected as input variable parameters other remaining least significant parameters are kept constant. A brass wire (zinc coated) of diameter 0.25 mm is selected as wire electrode. Wire feed rate 5 m/min is used with wire tension 10N. All experiments are performed at zero wire offset value. The distilled water having conductivity, 20mho is used as a dielectric fluid with high flow rate (i.e. 12 L/min). Selected levels and range of four variable input parameters are shown in Table 1 series of experimental trials have been conducted as per response surface methodology (RSM). The details about the work material, experimental set-up and measuring apparatus, selection of process parameters and their range, design of experiments, and reproducibility have been explained in the following sections.

3.3 Selection of process parameters and their range

In the present work, the effect of various process parameters (factors) such as viz., Pulse on time (A), pulse off time (B), peak current (C), spark gap set voltage (D) cut on cutting rate (response parameters) has been investigated. These process parameters and their range have been selected on the basis of the existing literature, pilot experimentation, manufacturer's manual, and machine capability. The independent process parameters and their levels in coded and actual values are shown in Table 2. The constant parameters and their values are indicated in Table 3.

4. Results and discussion

The present chapter gives the application of the response surface methodology. The scheme of carrying out experiments was selected and the experiments were conducted to investigate the effect of process parameters on the output parameters e.g. cutting rate. The selected process variables were varied up to four levels and central composite rotatable design was adopted to design the experiments. Response Surface Methodology was used to develop second order regression equation relating response characteristics and process variables. The process variables and their ranges are given in Table 2.

Table 2: Process parameters and their levels

Coded Factors	Real Factors	Parameters	Levels		
			(-1)	(0)	(+1)
A	Ton	Pulse on Time	105	112	130
B	Toff	Pulse off Time	35	40	45
C	SV	Spark Gap Set Voltage	30	38	45
D	IP	Peak Current	105	190	120

4.1 Experimental Results

The WEDM experiments were conducted, with the process parameter levels set as given in Table 4.1, to study the effect of process parameters over the output parameters. Experiments were conducted according to the test conditions specified by the second order central composite design (Table 2). Experimental results are given in Table 3. For cutting rate Altogether 21 experiments were conducted using response surface methodology.

Table 3: Observed Values for Performance Characteristics

		Factor 1	Factor 2	Factor 3	Factor 4	Response 1
Std	Run	A:Peak current	B:Pulse on time	C:Pulse off time	D:Servo voltage	Cutting Rate
12	1	112.5	130	40	37.5	2.48
10	2	120	117.5	40	37.5	2.9
11	3	112.5	105	40	37.5	1.14
15	4	112.5	117.5	40	30	2.31
3	5	120	105	45	45	1.35
17	6	112.5	117.5	40	37.5	1.23
7	7	105	130	45	45	2.09
2	8	120	130	35	30	1.45
14	9	112.5	117.5	45	37.5	2
19	10	112.5	117.5	40	37.5	2.12
21	11	112.5	117.5	40	37.5	1.76
8	12	105	105	35	30	2.32
16	13	112.5	117.5	40	45	2.065
4	14	105	130	35	45	1.845
18	15	112.5	117.5	40	37.5	2.12
6	16	105	105	45	30	1.88
13	17	112.5	117.5	35	37.5	1.9
5	18	120	105	35	45	1.9
1	19	120	130	45	30	2
9	20	105	117.5	40	37.5	1.98
20	21	112.5	117.5	40	37.5	2.02

4.2 Analysis And Discussion Of Results

The experiments were designed and conducted by employing response surface methodology (RSM). The selection of appropriate model and the development of response surface models have been carried out by using statistical software, "Design Expert (DX-9)".

The regression equations for the selected model was obtained for the response characteristics, viz., cutting rate. These regression equations were developed using the experimental data (Table 3.) and were plotted to investigate the effect of process variables on various response characteristics. The analysis of variance (ANOVA) was performed to statistically analyze the results.

4.2.1 Selection of Adequate Model

To decide about the adequacy of the model, three different tests viz. Pulse on time (A), pulse off time (B), peak current (C), spark gap set voltage (D)sequential model sum of squares, lack of fit tests and model summary statistics were performed for Surface roughness characteristics of WEDM process. The sequential model sum of squares test in each table shows how the terms of increasing complexity contribute to the model. It can be observed that for all the responses, the quadratic model is appropriate. The „lack of fit" test compares the residual error to the pure error from the replicated design points. The results (Tables 4.3) indicate that the quadratic model in all the characteristics does not show significant lack of fit, hence the adequacy of quadratic model is confirmed. Another test „model summary statistics" given in the following sections further confirms that the quadratic model is the best to fit as it exhibits low standard deviation, high "R-Squared" values, and a low "PRESS"

4.2.2 Effect of Process Variables on Surface Roughness

The regression coefficients of the second order equation (Equation 3.8, Chapter 3) are obtained by using the experimental data (Table 3). The regression equation for the surface roughness as a function of four input process variables was developed using experimental data and is given below. The coefficients (insignificant identified from ANOVA) of some terms of the quadratic equation have been omitted.

$$
\begin{aligned}
\text{Roughness} = &-17.80900 + 0.12760 * \text{ Peak current} + 0.022400 * \text{ Pulse on time} \\
&+ 0.13480 * \text{ Pulse off time} + 0.34140 * \text{ Servo voltage} - 2.96250E - 003 \\
&* \text{ Peak current} * \text{ Servo voltage} - 2.02667E - 003 * \text{ Pulse off time2}
\end{aligned}
$$

The above response surface is plotted to study the effect of process variables on the surface roughness and is shown in Figures 4.1 (a, b). It is clear that from Figure 4.4a the surface roughness has an increasing trend with the increase of servo voltageand peak current. The surface roughness is most affected by the amount of discharge energy which increases with increase in pulse on-time. The surface roughness depends on the size of spark crater. A shallow crater together with a larger diameter leads to a better work piece surface roughness. To obtain a flat crater, it is important to control the electrical discharging energy at a smaller level by setting a small pulse-on time (Ton). A large discharging energy will cause violent sparks resulting in a deeper erosion crater on the surface. Accompanying the cooling process after the spilling of molten metal, residues will remain at the periphery of the crater to form a rough surface. Furthermore, greater discharge energy will produce a larger crater, causing a larger surface

roughness value on the work piece. It can be seen from Figure 4.2 that all the actual values are following the predicted values. Normal probability plot has been drawn for residuals in Figure 4.3.
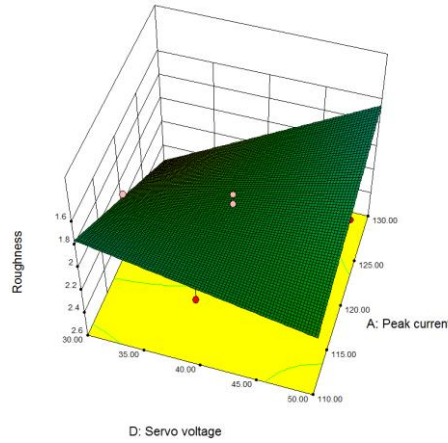

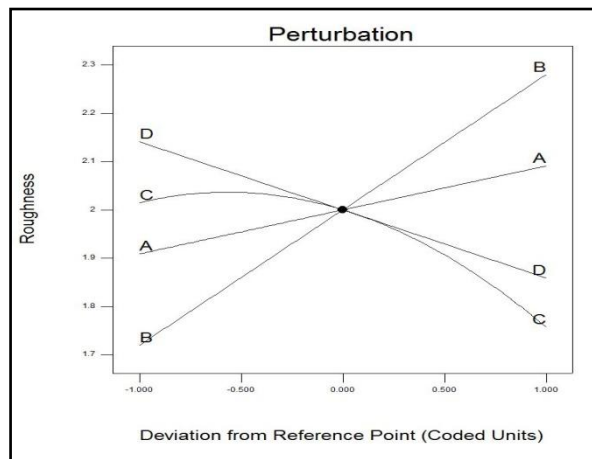**Figure 2: Combined Effect of servo voltage and peak current on Surface Roughness**

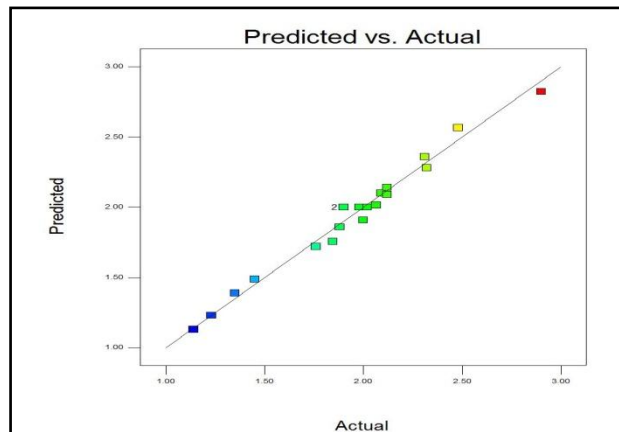**Figure 3: Overall performance of surface roughness**

Figure 4: Predicted vs. Actual for Surface Roughness

Table 4: Pooled ANOVA- SR

| Source	Sum of Squares	df	Mean Square	F Value	p-value Prob> F	
Model	3.32941679	6	0.5549028	78.42	< 0.0001	significant
A-Peak current	0.08281	1	0.08281	18.388358	0.0008	
B-Pulse on time	0.1568	1	0.1568	34.818193	< 0.0001	
C-Pulse off time	0.16641	1	0.16641	36.952139	< 0.0001	
D-Servo voltage	0.19881	1	0.19881	44.146715	< 0.0001	
AD	0.1404225	1	0.1404225	31.18149	< 0.0001	
C^2	0.06807429	1	0.0680743	15.116222	0.0016	
Residual	0.0630475	14	0.0045034			
Lack of Fit	0.0502475	10	0.0050247	1.5702344	0.3521	not significant
Pure Error	0.0128	4	0.0032			
Cor Total	3.39246429	20				
Std. Dev.	0.06710732		R-Squared	0.9814154		
Mean	1.94571429		Adj R-Squared	0.9734506		
C.V. %	3.44898138		Pred R-Squared	0.9531612		
PRESS	0.15889908		Adeq Precision	43.683697		
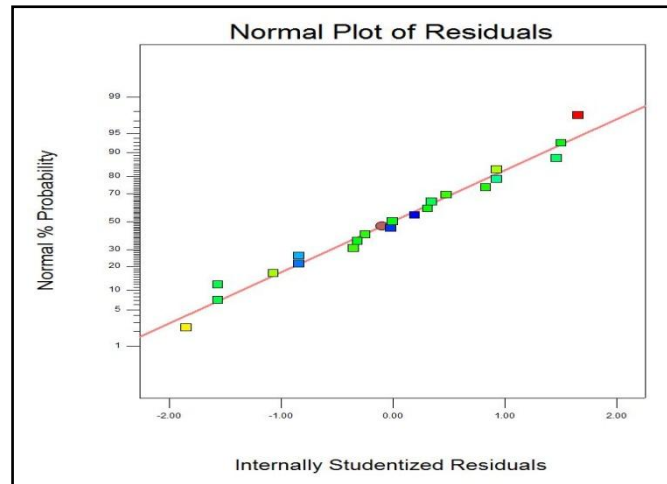
Figure 5: Normal Plot of Residuals for SR

4.3 Analysis of variance

In order to statistically analyze the results, ANOVA was performed. Process variables having p-value<0.05 are considered significant terms for the requisite response characteristics. The insignificant parameters were pooled using backward elimination method. For surface roughness the Peak current (A), the pulse on time (B), pulse off time(C), servo voltage (D), the interaction term (BD), and the quadratic terms (C^2) are significant parameters affecting its value.

5. Conclusion

In the previous chapter, the effect of machining parameters of WEDM on the response variable surface finish the material (Inconel X-750) has been discussed. Also the optimal levels of the machining parameters for each of response variables have been found out using response surface methodology (RSM), The important conclusions drawn from the present study are summarized below:

1. Pulse off time (p value 0.0002) is the most significant factor for surface roughness. Additionally, peak current (C) and spark gap set voltage (D) are also significant for their effect on SR. Surface roughness decreases with increase in voltage, and off time.

2. For surface roughness, Pulse off time (B), Peak current,) Spark gap set voltage (D) and few interactions AC and quadratic terms (A2, B2, C2) are significant

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