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Modeling and Multi-Objective Optimization of WEDM of Commercially Monel Super Alloy considering Multiple Users Preferences

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Abstract-

In this research work, development of a multi-response optimization technique has been undertaken, using traditional desirability analysis and non-traditional particle swarm optimization techniques (for different customer's priorities) in wire electrical discharge machining (WEDM). Monel 400 has been selected as work material for experimentation. The effect of key process parameters such pulse on time (TON), pulse off time (TOFF), a peak current (IP), wire feed (WF), were investigated on material removal rate (MRR) and surface roughness in WEDM operation. Further, the responses such as MRR and SR were modeled empirically through regression analysis. The developed models can be used by the machinists to predict the MRR and SR over a wide range of input parameters. The optimization of multiple responses has been done for satisfying the priorities of multiple users by using Taguchi-desirability function method and particle swarm optimization technique. The analysis of variance (ANOVA) is also applied to investigate the effect of influential parameters. Finally, the confirmation experiments were conducted for the optimal set of machining parameters, and the betterment has been proved.

Key words: Desirability Analysis, Multi-Objective Optimization, WEDM, Monel 400 super alloy.

1. INTRODUCTION

WEDM is recognized as an effective machining technique used in a wide range of applications namely automotive, aerospace, defense, electronics, telecommunications, and healthcare, environmental, industrial and consumer products of micro-feature with good surface finish. Advanced machining has become a hotspot in the manufacturing industry with the development of MEMS systems and devices. There is a growing need for fast, direct, and mass manufacturing of miniaturized products from super alloys in many applications. To machine these materials and to meet the demands of manufacturing industry, many Unconventional machining methods have been developed in the recent years. Wire electrical discharge machining (WEDM) is one of the nonconventional machinings which uses the thermal energy generated due to the controlled discrete sparks occurring between the tool electrode and work piece. It transforms electrical energy into thermal energy for eroding the material. The electrodes are immersed in dielectric liquid or flowing pressurized dielectric medium. A very small amount of work materials melts and vaporize by a series of discharge energy between tool and workpiece. Debris materials are flushed out from the sparking area by the dielectric fluid. Due to the contactless process between tool and workpiece, any conductive material can be machined by WEDM regardless of its hardness and toughness.

WEDM can machine any electrically conductive material such as tool steel, aluminum, copper, graphite, exotic space-age alloys including Hastaloy, Inconel, titanium, tungsten carbide, polycrystalline diamond compacts, Ni-based alloys and ceramics. WEDM process enables higher accuracy and surface finish together with reasonable cutting efficiency. WEDM process is generally used in aerospace, automobile, tool and dies industries where accuracy and surface finish have great importance [1]. Figure 1 represents the WEDM set up used for this research work.

Figure 1: Ezeecut NXG CNC WEDM machine

2. LITERATURE REVIEW

Wire electrical discharge machining (WEDM) is one of the nonconventional machinings which uses the thermal energy generated due to the controlled discrete sparks occurring between the tool electrode and workpiece. A suitable dielectric is continuously supplied to the inter-electrode gap. Wire electrical discharge machining (WEDM) is a variant of WEDM technique, in which, a continuously traveling wire made of thin copper, brass, or tungsten is used as the electrode. The wire movement is controlled numerically to obtain the desired complex three-dimensional shapes on difficult to machine materials such as superalloys [2, 3]. With the advantages of micro-WEDM over the other micromachining methods, it has been widely accepted in aerospace and nuclear space industry to machine difficult to machine materials.

Nickel-based super alloys find wider applications in modern industries such as space vehicles, rocket engines, experimental aircraft, nuclear reactors, submarines, steam power plants, gas turbines, nuclear reactors, petrochemical equipment and other high-temperature applications [4,5]. However due to their properties such as high tensile strength, abrasiveness, work hardening, high hardness, low thermal conductivity, strong tendency to weld and formation of built-up edge, it is difficult to machine superalloys [6, 7].

They are known to be among the most difficult-to-cut materials. Several researchers have studied the effect of cutting conditions in machining of nickel-based superalloys [8, 9, 10, 11 and 12]. Most of the research on machining Monel alloy is concentrated mainly on the study of cutting tool wear and wear mechanism [13, 14]. Poor selection of machining parameters causes cutting tools to wear and break quickly as well as economic losses such as damaged workpiece and poor surface quality [15, 16 and 17].

WEDM is recognized as an effective machining technique used in micro-parts machining for difficult-to-cut materials using the micro-wire tool (brass, copper, and zinc coated copper wire diameter range from 0.03 mm to 0.3 mm) with advantages of high machining efficiency, precision and low cost.

WEDM is an advanced micromachining technique which can be used for machining of titanium alloys. Due to its complex and stochastic nature and the increased number of variables involved, achieving the optimal performance measures of micromachining of superalloys is still a challenging task in the manufacturing industry. Hence, the machinability of WEDM process on super alloys needs to be explored. Only a few researchers have been reported, on the machining of Monel using WEDM. But there is a need for the modeling and multiobjective optimization of WEDM process.

Balasubramanian and Ganapathy [18] investigated WEDM process using gray relational analysis. An optimal process parameter setting was found out in this paper. Lin and Lin [19] presented the use of gray relational grade to the machining parameter optimization of the EDM process. Jangra et al. [20] presented optimization of performance characteristics such as cutting speed, surface roughness and dimensional lag using Taguchi method and gray relational analysis in WEDM process.

Pradhan et al [21] optimized WEDM process by response surface approach while machining of Tie6Ale4V. The observed results reveal that the pulse on time was the most influential parameter for material removal rate, overcut and taper, whereas peak current was the factor that affected tool wear rate the most. Vijay Kumar Meena et al. [22] optimized MRR, TWR and overcut for current, voltage and frequency using Taguchi based grey scale methods. Voltage has significant effects on output performance. Somashekhar et al. [23] used artificial neural network or optimizing micro-EDM input parameters for MRR.

Aniza Alias et al. [24] performed experiments on titanium alloy for an influence of machining feed rate in the WEDM process. The results show that surface roughness and MRR were increased by increasing feed rate whereas Kerf width was decreased. Anil Kumar et al. [25] investigated the influence of aluminum powder mixed with electrical discharge machining process using Inconel alloy. The experimental results show that the size of the particle and its concentration has significant effects in additive mixed EDM process. There are significant improvements in material removal rate, reduction of tool wear and surface finish using medium mesh size 325 aluminum additive powders. Various researchers have tried to optimize and investigate the effects of various input factors and their levels on response variables like metal removal rate (MRR), tool wear rate (TWR), and surface finish in the macro-EDM and micro-EDM process [26-30].

From literature, it has been found that many researchers were focused on the developments of EDM, WEDM, and micro-WEDM. Hence, in this study, an attempt has been made to determine the effect of process parameters on the responses like MRR and surface roughness. Taguchi orthogonal array has been used for conducting the experiments. Desirability analysis was used to predict the optimum process parameters for WEDM of Monel. Experimental results confirm the feasibility of the strategy and are in good agreement with predicted results over a wide range of machining conditions.

3. METHODOLOGY

3.1 Experimental Design using Taguchi Method: Taguchi proposed the robust design based on the design of experimentation. This method provides the best tool for parameter design of response characteristics. The design of experiments consists of a selection of appropriate orthogonal array and assignment of factors and interaction in the appropriate column. Taguchi method reduces the number of experiments by using orthogonal array thus reducing the efforts of large experimentation. The statistical analysis of variance (ANOVA) method is applied to an outcome of experiments which helps to determine percentage contribution of individual process parameter on responses against the predefined level of confidence. Ishikawa cause and effect diagram was selected to identify the potential process parameters affecting the response characteristics of WEDM process.(Figure. 2). In this work, the effects of four process parameters, such as pulse on-time (Ton), pulse off time (Toff), peak current (IP), wire feed (WF) and wire tension (WT) have been investigated on two response characteristics –material removal rate (MRR) and surface roughness (SR) using L9 orthogonal array. ANOVA and mean effect plot were determined using Minitab16 Software.

3.2 Experimentation: The experiments were performed on Ezeecut NXG CNC WEDM Machine setup with RC circuit positional accuracy of 1µ. The experimental setup of WEDM process is shown in Fig. 1. Different settings of a pulse on-time (Ton), pulse off-time (Toff), the peak current (IP) and wire feed (WF) were used in the experiments (TABLE 1). Sensitivity and gap width were kept constant throughout the experiments.

Cu-Zn37 master brass wire with 0.25 mm diameter (900 N/mm^{2,} tensile strength) was used in this work. As workpiece material, commercial Monel 400 in the form of a rectangular slab (size 200 x 200 x 10.5 mm) was used. During the experiments, a punch of 20mm x 8mm x 10.5mm was cut during each trial (Fig 3), for this purpose the WEDM machine was programmed accordingly. The chemical composition of Monel 400 was given in TABLE 2.

Cutting speed was obtained directly from the display panel of CNC WEDM set up during the experiment. Material removal rate was calculated by using the following formula.

MRR (mm^3/min)

= (Average machining rate)X (thickness of plate x width of cut)

Width of cut = (2 x Spark gap) + Wire Diameter

Experiments were repeated two times to minimize the experimental error induced by the action of noise factors. MAHR Surface Testing tester (Figure. 4) was used for measurement of the surface roughness (Ra) of the machined surface. Two independent readings were taken on each surface of machined surface and average was then taken to reduce the variability caused by the measurement error. TABLE 3 represents Taguchi’s L-9 orthogonal array with assigned factor the various experimental results for the material removal rate and surface roughness responses (**TABLE 4.)** as per designed L9orthogonal array.

4. RESULTS AND DISCUSSIONS

This section discusses an experimental finding of the parametric influences on the response characteristics and optimization of WEDM characteristics using Desirability analysis and Particle Swarm Optimization techniques.

4.1 Influence of process parameters on MRR and SR: Single response optimization was carried out to investigate the effects of machining parameters on MRR and SR. According to the Taguchi method, S/N ratios were calculated for each experiment. The objective of optimization was to maximize the MRR and minimize the SR. The response table for S/N ratios of MRR was calculated considering the fact that MRR was a larger-the-better performance characteristic; the maximization of the quality characteristic of interest is sought and is expressed as:

$$\text{S/N Ratio } = -\log_{10}\left(1/n\right)\sum_{i=1}^{n}\frac{1}{\mathrm{y}_{\mathrm{ij}}^{2}} \qquad (1)$$

yij = observed response value

i=1, 2... ....n; j = 1, 2...k

n = number of replications

The surface roughness was the lesser-the-better performance characteristic and the S/N ratio for SR was calculated by:

$$\text{S/N Ratio } = -\log_{10}\left(1/n\right)\sum_{i=1}^{n} y_{ij}^{2} \qquad (2)$$

The S/N ratio values are presented in TABLE 5.

Single response optimization values for MRR and SR can be identified through main effect plots for MRR and SR. The response table for MRR and SR was presented in TABLE 6. The ANOVA for MRR and SR was performed with the help of Minitab software. TABLE 7 summarizes the effect of individual process parameters on MRR and SR through ANOVA. Figure 5 shows the impact of each input parameter on MRR. The influence of process parameters on SR was given in Figure 6.

The experimental results were used to obtain the mathematical relationship between process parameters and machining outputs. The coefficients of mathematical models were computed using a method of multiple regressions. In this study, MINITAB 16 (Software Package for Statistical Solutions) was used for the regression analysis. Quadratic models were developed by using regression analysis to determine the relation of process parameters with MRR and SR. These models were developed at 95 % confidence level.

Regression equation of MRR is

MRR = 6.33 – 0.101(Ton) – 1.06 (Toff) – 1.02 (Ip) + 0.364 (WF)--- (3)

The correlation coefficient, R^2 has a value of 85.2% which tells us that the equation models MRR quite accurately.

Regression equation of SR

SR = 12.5 + 0.590 (Ton) – 0.646 (Toff) – 0.879 (Ip) + 0.006 (WF) ---- (4)

The correlation coefficient is 80.5%.

4.2 Multi-objective optimization of response parameters by desirability approach: The main aim of the present study was finding the optimal machining conditions of WEDM process. The Taguchi optimization based on desirability analysis was an ideal technique for finding the optimal machining condition of WEDM process. Here the goal was to maximize the material removal rate and minimize the surface roughness. Desirability approach helps us to map between the predicted response ‘y’ and desirability function'. The desirability value varies from 0 to 1. If the desirability value was zero it indicates that predicted value was completely undesirable and the desirability value of one was idle. The desirability of corresponding response increases as the value of d increases. The one-sided transformation desirability function of maximization for MRR as shown in Eq. (5) and minimization of surface roughness as shown in Eq. (6).

$$d_i = \left\{\left(\frac{y - y_{\min}}{y_{\max} - y_{\min}}\right)^{wt}, \left\{\begin{matrix} 0 \rightarrow y \le y_{\max} \\ y_{\min} \le y \le y_{\max} \\ 1 \rightarrow y \ge y_{\max} \end{matrix}\right\}\right\} ------------(5)$$

$$d_i = \left\{\left(\frac{y - y_{\max}}{y_{\min} - y_{\max}}\right)^{wt}, \left\{\begin{matrix} 1 \rightarrow y \le y_{\min} \\ y_{\min} \le y \le y_{\max} \\ 0 \rightarrow y \ge y_{\max} \end{matrix}\right\}\right\} -----(6)$$

Where, d was a desirability function of y, $y_{\min}$ and $y_{\max}$ are lower and upper limits of response value of ‘y', respectively, it was weight, which can be varied from 0.1 to 10 to adjust the shape of desirability function. An overall desirability function D (0 _ D _ 1) was defined as the geometric mean of individual desirability functions. The multi-objective function was a geometric mean of all transformed responses of single objective problem shown in Eq. (7). The higher the D value was the better desirability of the combined response levels

$$D = (d_1 \times d_2 \times .... \times d_n)^{1/n} \text{ ----------------- (7)}$$

Multi-response optimization was carried out using desirability function in conjunction with Taguchi method. The ranges of input parameters viz pulse on time, pulse off time, current and wire feed rate.

The goal was to maximize the material removal and minimize the surface roughness. The weight values are assigned for MRR and SR as one and equal importance is given to each response.

A set of 9 optimal solutions were derived for the specified design space constraints for material removal rate and surface roughness using Minitab statistical software. The set of conditions possessing highest desirability value was selected as the optimum condition for the desired responses. TABLE 8 shows the optimal set of condition with higher desirability function required for obtaining desired response characteristics under specified constraints.

Figure 7 shows the main effects plot for the composite desirability for the different levels of the processing parameters. Basically, the larger the composite desirability, the better was the multiple performance characteristics. However, the relative importance of the parameters for the multiple performance characteristics will still need to be known so that the optimal combinations of the process parameter levels can be determined more accurately.

From the Figure 7, it was showing that the optimal set of process parameters from desirability analysis was TON 1-T OFF 1-IP 2-WF 1.

4.3 Analysis of Variance for Composite Desirability: The results obtained from the experiments were analyzed using Analysis of Variance to find the significance of each input factor on the measures of process performances, Material Removal Rate, and surface roughness. Using the composite desirability value, ANOVA was formulated for identifying the significant factors. The results of ANOVA were presented in TABLE 10.

The results of the ANOVA were represented in the TABLE 10.and from the table it was clear that pulse off time was the major influencing factor contributing 48.182% to performance measures, followed by peak current contributing 34.411%, and wire feed contributing 10.7% and pulse on time contributing 6.723%.

After the optimal settings have been obtained, verification of the results with the predicted results has done. The formulae for estimated composite desirability was given by

$$\boxed{y = y_m + \sum_{i=1}^{q} (y_j - y_m)} \textbf{........(8)}$$

Where y_m is the total mean of the composite desirability, ‘j’ is the mean of the composite desirability at the optimum levels and ‘q’ is the number of machining parameters that affect the machining process. After substituting the values in the formula, we get the predicted desirability as 0.5815.

From desirability analysis, TON 1-T OFF 1-IP 2-WF 1 was found as the set of optimal process parameters. These settings were used for confirmation experiments. There was a reduction in surface roughness of the job when compared to the base experiment. A 0.891 % reduction in surface roughness was achieved. Also, an increase of 19.568 % was also obtained in MRR after the confirmation experiment. There is also an increase in the composite desirability of the setting. The results are definitely satisfactory and show an improved response value.

TABLE 1. Process parameters with their levels

Factors	Symbol	Range	Levels		
			1	2	3
Pulse on time (μs)	(T_{on})	0-99	70	80	90
Pulse off time (μs)	(T_{off})	0-10	4	6	8
Peak current (A)	(I_p)	0-8	3	4	5
Wire feed (mm/min)	WF	0-99	70	80	90

TABLE 2. Chemical composition of Monel 400

Element	Percentage Composition
Carbon	0.3 max
Silicon	0.5 max
Manganese	2.0 max
Sulphur	0.024 max
Iron	2.5 max
Copper	28.0-34.0
Nickel (plus Cobalt)	63.0 min

TABLE 3. L9 orthogonal array

Exp No.	T ON	T OFF	IP	WF
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

TABLE 4. Experimental Data

Exp Run	Surface Roughness(μm)		MRR(mm^3/min)	
	Trail-I	Trail-II	Trail-I	Trail-II
1	11.3641	11.0412	4.0026	4.1258
2	10.0482	10.9169	2.9048	3.2196
3	8.7453	7.5854	0.6327	0.6488
4	11.1998	10.9003	4.5174	4.7117
5	10.6030	8.9557	1.1956	1.1252
6	12.5158	11.1335	3.6166	3.6112
7	11.9223	11.2912	2.9628	2.9349
8	11.7762	11.8151	3.0499	3.3154
9	9.9571	10.0241	0.8186	1.2402

TABLE 5. S/N ratios of experimental data

Exp. Run	Average SR(μm)	S/N Ratios of SR(db)	Average MRR (mm^3/min)	S/N Ratios of MRR(db)
1	11.20265	-20.9864	4.0642	12.1795
2	10.4825	-20.4093	3.0622	9.720
3	8.16535	-18.2395	0.64075	-3.8662
4	11.05005	-20.8673	4.61455	13.2826
5	9.77935	-19.8062	1.1604	1.2922
6	11.82465	-21.4558	3.6139	11.1595
7	11.60675	-21.2942	2.94885	9.3931
8	11.79565	-21.4344	3.1827	10.0559
9	9.9906	-19.9918	1.0294	0.2517

TABLE 6. Response table of MRR and SR

Response Table of MRR				
Level	**T ON**	**T OFF**	**IP**	**WF**
1	2.589	3.876	3.620	2.085
2	3.130	2.468	2.902	3.208
3	2.387	1.761	1.583	2.813
Delta	0.743	2.115	2.037	1.124
Rank	4	1	2	3
Response table of SR				
Level	**T ON**	**T OFF**	**IP**	**WF**
1	9.950	11.286	11.608	10.324
2	10.885	10.686	10.508	11.305
3	11.131	9.994	9.850	10.337
Delta	1.181	1.293	1.757	0.980
Rank	3	2	1	4

TABLE 7. Analysis of variance (ANOVA) for response characteristics

ANOVA for Response Variables				
ANOVA for Material Removal Rate(MRR)				
Source	**DF**	**Sum of Squares**	**Mean sum of Squares**	**%Contribution**
TON	2	0.8845	0.44227	5.46
TOFF	2	6.9520	3.47601	42.94
IP	2	6.4039	3.20197	39.55
WF	2	1.9491	0.97456	12.04
Error	0	0		
Total	8	16.1896		
ANOVA for Surface Roughness(SR)				
Source	**DF**	**Sum of Squares**	**Mean sum of Squares**	**%Contribution**
TON	2	2.3284	1.16418	20.3
TOFF	2	2.5118	1.25589	21.9
IP	2	4.7294	2.36472	41.24
WF	2	1.8977	0.94885	16.55
Error	0	0		
Total	8	11.4673		

TABLE 8. Set of Optimal Solutions for WEDM process

Run	Desirability MRR	Desirability SR	Composite Desirability	Rank
1	0.92817	0.41228	0.38267	2
2	0.60935	0.60562	0.36903	3
3	0	1	0	8
4	1	0.46008	0.46008	1
5	0.36162	0.74762	0.27035	4
6	0.86498	0	0	8
7	0.76212	0.24402	0.18597	6
8	0.7998	0.08902	0.071198	7
9	0.31273	0.70796	0.2214	5

TABLE 9. Response Table of Composite Desirability

Process Parameters	Average Composite Desirability			
	Level 1	**Level 2**	**Level 3**	**Rank**
TON	0.2506	0.2435	0.1595	4
TOFF	0.3429	0.2369	0.0738	1
IP	0.1513	0.3502	0.1521	2
WF	0.2915	0.185	0.1771	3
Mean value of composite desirability , y_m = 0.2179				

TABLE 10. ANOVA of Composite Desirability

Source	Degree of Freedom	Sum of Squares	Mean of Squares	Percentage Contribution
TON	2	0.01539	0.007694	6.723
TOFF	2	0.1103	0.01978	48.182
IP	2	0.07878	0.03939	34.411
WF	2	0.02448	0.01224	10.694
Error	0	0		
total	8	0.22891		

TABLE 11. Comparison of Initial Settings with Optimised Experimental Results

	Initial machining parameters	Optimal machining parameters	Percentage change in responses
Setting level	$A_1B_1C_1D_1$	$A_1B_1C_2D_1$	
(SR) µm	11.20265	11.1028	0.891% Decrease
(MRR) mm^3/min	4.0642	4.8595	19.568 % Increase
Composite Desirability	0.38267	0.5815 (Predicted)	51.96 %Increase
Improvement in desirability index = 0.19883			

5. CONCLUSIONS

In this paper the multi-objective optimization of process parameters of WEDM on Monel 400 superalloy was done. Based on the results and discussions, the following conclusions were drawn.

- Monel 400 can be easily machined using WEDM process with a reasonable cutting speed and surface finish. Because of work hardening, it was difficult to machine Monel using traditional methods. In order to improve MRR response characteristics using Taguchi analysis, pulse off-time and peak current must be adjusted as they have the highest impact on it. Pulse on-time and wire feed have the least impact on the process.
- Desirability approach was used to optimize multi-responses of WEDM process. The parameter combination obtained from this technique was T ON 1- T OFF 1- IP 2- WF 1. After the confirmation experiment, a decrease of 0.891 % in surface roughness and an increase of 19.568% in material removal rate were observed. Overall, there was 51.96 % increase in desirability of the settings after optimization.
- Desirability doesn't depend on any equation and instead measures the desirability index of each parametric setting. It was very suitable for work and was, therefore, satisfactory and reliable.

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