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SELECTION OF OPTIMAL PROCESS PARAMETERS IN WIRE-ELECTRICAL DISCHARGE TURNING WHILE MACHINING TI-6AL-4V ALLOY

Naresh Baki[1]*, A. Chennakesava Reddy[2], Thella Babu Rao[1]
[1]Assistant,Department of Mechanical Engineering, GITAM University, Hyderabad - 502329, India.
[2]Professor, Department of Mechanical Engineering, JNTU, Hyderabad – 500085, India.

Abstract: Wire electrical discharge turning (WEDT) is one of the novel configurations of wire electrical discharge machining (WEDM) process developed to produce cylindrical components. A precise rotary spindle is designed and added to the WEDM configuration to enable the generation of free-form cylindrical geometries. In WEDT, the turning process parameters such as spindle rotational speed, feed, depth of cut and the usual WEDM parameters play a significant role on the process performance. Therefore, this further increased complexity of understanding the process variables against the process performance. However, the right selection of WEDT conditions become the most important aspect while producing the precise turned components. This investigation presents an experimental study on the effects of machining parameters on material removal rate (MRR)and surface roughness (R_a) in WEDT process. The machining experiments were conducted on Ti-6Al-4V super alloy by using statistical design of experiment (DOE) method. The experimentally measured responses were analyzed for individual and interaction effects by adopting analysis of variance (ANOVA). Since the machining responses are found with correlation between them, the problem was formulated as a multi-objective optimization problem and is solved to obtain the solutions.An integrated statistical multi-response optimization approach, gray relational analysis was implemented on the experimental results to derive the optimal WEDT conditions. Consequently, the derived optimal process responses are confirmed by the validation experiments and the results are found with good correlation.

Keywords: Wire electrical discharge turning, Ti-6Al-4V alloy, ANOVA, modeling, multi-responseoptimization.

Address all correspondence to: flytonaresh@gmail.com

1. INTRODUCTION

Wire electric discharge machining (WEDM) is considered as one of the configurations of conventional EDM process. WEDM is evidenced as one of the most extensively used non-traditional thermoelectric process used to manufacture components with intricate shapes. WEDM utilizes a continuously traveling wire electrode of diameter 0.05-0.3 mm for attaining very small corner radii [1]. During the WEDM process, the material is eroded ahead of the wire due to the thermoelectric sparks generated between the work piece and the electrode. In this process the work piece experiences no mechanical stresses due to no direct contact between the work piece and the wire makes the process widely employed to cut the electrically conductive hard-to-cut material with irrespective of its hardness and strength [2]. Wire electrical discharge turning (turning with WEDM) is one of the emerging area, developed to generate cylindrical form on hard and difficult to cut super alloys such as Titanium and Nickel. In WEDT process the electrical discharge takes place between the traveling wire and the rotating workpiece (a rotary axis is added to WEDM) to be machined. In this process the desired cylindrical forms can be obtained by controlling the electrically charged wire in X and Y directions to remove the unwanted work material [3,4].

2. LITERATURE REVIEW

Several research works that solely study the characteristics of the WEDT process considering various input and output parameters. The turning of small diameter pins of size 5 mm using WEDM works have been reported by Masuzawa and Tonshoff [5-7]. Qu et al. [3] reported the turned automobile components like diesel injector plungers with WEDM. The results of Liao et al., 1997 [8] showed that the MRR and surface finish are easily influenced by the table feed rate and pulse on time. Mohammadi et al. [9] investigated the WEDT process to evaluate the effects of machining parameters on MRR by using the Taguchi approach in design of experiments (DOE). K. Ponappa et.al [10] investigated the influence of EDM parameters on various aspects of the surface integrity of Ti-6Al-4V with different electrode materials. Farnaz Nourbakhsh et al. [11] experimentally investigated the WEDM performance parameters such as cutting speed, surface roughness and wire rupture of Ti-6Al-4V in relation to process parameters and different wire electrode materials. Shajan Kuriakose et al. [12] investigated the surface characteristics of Ti-6Al-4V during WEDM process by employing the Taguchi method and analysis of variance. They found that time between two pulses, pulse duration, injection pressure, wire speed and wire tension are the most influencing parameters and the formation of layer consisting of mixture of oxides is influenced by the time between two pulses.

Recently Aravind Krishnan and Samuel [13] has attempted to optimize the process parameters by considering the MRR and surface roughness as output parameters of wire electrical discharge turning process. Lin et al. [14] reported the use of the grey relational analysis based on an orthogonal array and fuzzy-based Taguchi method for optimizing the multi-response EDM process. Experimental results showed that both approaches can optimize the machining parameters effectively. Grey relational analysis can be recommended as a method for optimizing [15, 16] the complicated conflicting multiple performance parameters. Moreover, Lin et al. Showed grey relational analysis is more straightforward than the fuzzy-based

Taguchi method for optimizing the EDM process with multiple process responses [12].From the above Literature it is found that several researchers have attempted previously to improve the performance of the WEDT process such as surface roughness, cutting speed, dimensional accuracy and material removal rate (MRR). However, because of its stochastic nature and several variables are involved in this process, the full potential utilization of this process is not completely solved. In addition to that these performance parameters are conflicting in nature so it is difficult to find the single optimal combination of process parameters for the performance parameters.

The present paper deals with the experimentalanalysis of measuredresponses such as MRR and Ra for individual and interaction effects by adopting analysis of variance (ANOVA). Gray relational analysis (GRA) integrated Taguchi's S/N ratio optimization approach has been implemented to maximize the MRR and to minimize the surface roughness.

3. MATERIALS AND METHODS

This section discusses the experimental procedure and design of experiments based on Taguchi method.

Figure 1: The experimental setup of turning with wire EDM

3.1 Experimental Procedure

In this research, the experiments are conducted on ROBOFIL 100 high precision 5- axis CNC WEDM shown in figure1. The wire EDM machine was equipped with a rotary axis in order to produce cylindrical forms. Ti-6Al-4Vwork piece of 20mm diameter with 150mm length was used to perform the turning experiments on WEDM. The surface finish was measured using a Talysurf (MITUTOYO) with a 0.8mm cut off length (according to DIN EN ISO 3274:1998). Eq. (1) can be derived to describe the calculation for MRR:

$$MRR = \pi(R^2 - r^2)V_f \tag{1}$$

where, R is the original radius of the work piece, r the final radius of the work piece after machining, and V_f is the machining cutting speed or feed rate.

Table 1: Machining parameters and their levels.

S.No.	Parameter	Units	Notation	-1	0	+1
1.	Spindle speed	Rpm	X_1	14	22	30
2.	Pulse-on time	µs	X_2	110	115	120
3.	Pulse-off time	µs	X_3	50	55	60
4.	Peak current	A	X_4	100	150	200
5.	Wire feed	mm/min	X_5	1	2	3
6.	Servo	V	X_6	30	60	90

Table 2: Experimental analysis using Taguchi method

Exp. No.	X_1 (rpm)	X_2 (µs)	X_3 (µs)	X_4 (A)	X_5 (mm/min)	X_6 (V)	R_a (µm)	MRR (mm^3/min)
1.	14	110	50	100	1	30	0.80	2.553
2.	14	110	55	150	2	60	1.06	2.355
3.	14	110	60	200	3	90	1.43	1.762
4.	14	115	50	150	2	90	1.79	4.406
5.	14	115	55	200	3	30	1.67	5.812
6.	14	115	60	100	1	60	1.02	4.792
7.	14	120	50	200	3	60	2.57	6.208
8.	14	120	55	100	1	90	1.99	5.253
9.	14	120	60	150	2	30	1.72	9.756
10.	22	110	50	100	3	90	1.84	2.816
11.	22	110	55	150	1	30	1.18	4.077
12.	22	110	60	200	2	60	1.46	4.710
13.	22	115	50	150	1	60	1.88	5.463
14.	22	115	55	150	2	90	2.04	3.742
15.	22	115	60	100	3	30	1.58	5.356
16.	22	120	50	200	2	30	2.64	8.536
17.	22	120	55	100	3	60	2.51	6.070
18.	22	120	60	150	1	90	2.34	5.253
19.	30	110	50	200	2	60	2.49	2.626
20.	30	110	55	100	3	90	2.39	3.959
21.	30	110	60	150	1	30	1.70	5.812
22.	30	115	50	100	3	30	2.61	6.829
23.	30	115	55	150	1	60	2.43	7.805
24.	30	115	60	200	2	90	2.74	4.478
25.	30	120	50	150	1	90	3.37	4.406
26.	30	120	55	200	2	30	3.19	5.938
27.	30	120	60	100	3	60	3.03	4.553

3.2 Design of ExperimentsBased on Taguchi Method

The WEDM process consists of three operations, a roughing operation, a finishing operation, and a surface finishing operation. Usually, performance of various types of cutting operations is judged by different measures. In case of finish cutting operation, the surface finish is of primary importance whereas both metal removal rate and surface finish are of primary importance for rough cutting operation. Therefore, the rough cutting phase is investigated in the present approach considering two performance goals such as surface roughness (R_a) and metal removal rate (MRR) while spindle speed, pulse-on time, pulse-offtime, peak current, wire feed and servo are considered as the process control variables. Factors and their levels are shown in table 1. In order to reduce the number of experimental runs, experiments were planned based on design of experiments (DoE). Table 2 represents the matrix of experimental design and experimentally measured responses.

4. RESULTS AND DISCUSSION

The effect of process variables on the surface roughness, material removable rate is discussed.

4.1 Analysis of Surface Roughness

Equation 2 presents the linear relationship between factors, factors effects and surface roughness (response) which is the result of regression analysis.

$$R_a = -10.274 + 0.068X_1 + 0.101X_2 - 0.033X_3 + 0.003X_4 + 0.162X_5 + 0.006X_6 \quad (2)$$

The R-Sq (R^2) value in the table 3 indicates that the predictors explain 98.19% of the variance in R_a. The R-Sq (adj) (R^2adj) is 97.65%, which accounts for the number of predictors in the model. Both values indicate that the model fits the data well. Table indicates that the model estimated by regression procedure is significant at an α-level of 0.05. This implies that at least one coefficient is different from zero. The predicted machining parameters performance was compared with the actual machining performance and a good agreement was obtained between these performances. The above mathematical model for surface roughness of WEDT is of great importance to the proper selection of machining parameters during the machining of the cylindrical parts.

4.2Analysis of Metal Removal Rate

Eq. 3 presents the linear relationship between factors, factors effects and MRR (response) which is the result of regression analysis.

$$MRR = -27.508 + 0.024X_1 + 0.281X_2 + 0.029X_3 + 0.002X_4 - 0.113X_5 - 0.034X_6 \quad (3)$$

The R-Sq (R^2) value in the Table 4 indicates that the predictors explain 78.23% of the variance in MRR. The R-Sq (adj) (R^2adj) is 77.56%, which accounts for the number of predictors in the model. Both values indicate that the model fits the data well. Table 4 indicates that the model estimated by regression procedure is significant at an α-level of 0.05. This implies that at least one coefficient is different from zero.The predicted machining parameters performance was compared with the actual machining performance and a good agreement was obtained between these performances.The mathematical model for metal removal rate of WEDT is of great importance to the proper selection of machining parameters during the machining of the cylindrical parts. Figure 2 & 3shows that spindle speed, pulse-on time, pulse-off time, peak current, wire feed and servo have the most significant effect on MRR. Pulse-on time has direct proportion to the R_a; that is, by increasing this factor, MRR increases significantly. Also it is indicated from this figure that servo has a significant effect on MRR, because at decreasing servo MRR increases strongly.

Table 3: ANOVA Table for regression model for R_a

Source	DF	Seq SS	Adj SS	Adj MS	F	P
X_1	1	5.4450	5.4450	5.44500	502.684	0
X_2	1	4.5100	4.5100	4.51001	416.365	0
X_3	1	0.4900	0.4900	0.49005	45.2420	0.0000015
X_4	1	0.3610	0.4098	0.40980	37.8330	0.0000052
X_5	1	0.4737	0.4737	0.47369	43.7310	0.0000019
X_6	1	0.4969	0.4969	0.49693	45.8770	0.0000014
Error	20	0.2166	0.2166	0.01083		
Total	26	11.9933				
R-Sq : 98.19%		R^2 (adj): 97.65%		R^2(pred): 96.75%		

Table 4: ANOVA Table for regression model for MRR

Source	DF	Seq SS	Adj SS	Adj MS	F	P
X_1	1	0.6841	0.6841	0.6841	0.4022	0.533152
X_2	1	35.569	35.569	35.569	20.9122	0.000185
X_3	1	0.384	0.384	0.384	0.2258	0.639837
X_4	1	0.4962	0.2064	0.2064	0.1214	0.731215
X_5	1	0.2332	0.2332	0.2332	0.1371	0.715041
X_6	1	18.9178	18.9178	18.9178	11.1224	0.0033
Error	20	34.0174	34.0174	1.7009		
Total	26	90.3017				
R-Sq : 78.23%		R^2(adj): 77.56%		R^2(pred): 76.25%		

5. Implementation of Gray Relational Analysis

In the procedure of GRA, the responses are normalized as the first step using the equations 4 and 5 as shown in Table 5. As a part of the estimation of grey relational coefficients, the quality loss estimates of each individual has been calculated and listed in Table 5. Then the individual gray relational grades and the overall gray relational grade have been calculated by using Eq. 6 and are shown in Table 5.Here, the value of distinguishing coefficient is assumed as 0.5. The overall gray relational grade represents the quality index of multiple responses of the process; hence, the multi-objective optimization problem has been converted in to single-objective optimization problem.

Lower-the-better (LB) is the criterion: $x_i(k) = \dfrac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)}$ (4)

Higher-the-better (HB) is the criterion: $x_i(k) = \dfrac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)}$ (5)

where, $x_i(k)$ is the normalised value of k^{th} response, $\min y_i(k)$ is the smallest value of $y_i(k)$ for k^{th} response and max y_i(k)is the largest value of $y_i(k)$ for k^{th} response.x is the normalised array.

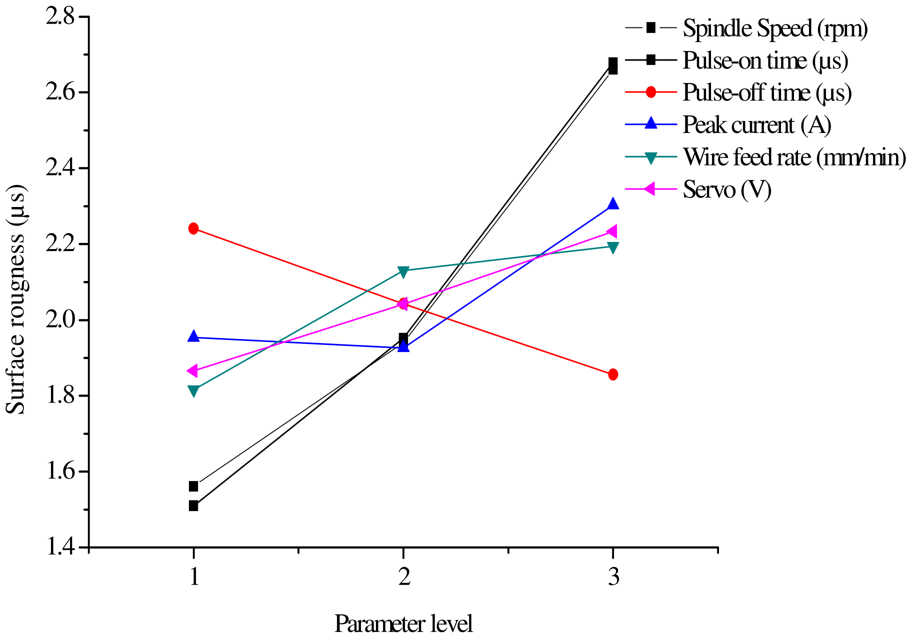

Figure 2: Effects of factors on R_a

Grey relational coefficient calculated from the normalised matrix.

$$\xi_i(k) = \frac{\Delta_{\min} + \varsigma\Delta_{\max}}{\Delta_{0i}(k) + \varsigma\Delta_{\max}} \tag{6}$$

Where, $\Delta_{0i} = \left\| x_0(k) - x_i(k) \right\|$: is the deviation of absolute value $x_0(k)$ and $x_i(k)$.

ς is the distinguishing coefficient $0 \le \psi \le 1$.

$$\Delta_{\min} = \min_{\forall j \in i} \min_{\forall k} \left\| x_0(k) - x_j(k) \right\| \tag{7}$$

$$\Delta_{\max} = \max_{\forall j \in i} \max_{\forall k} \left\| x_0(k) - x_j(k) \right\| \tag{8}$$

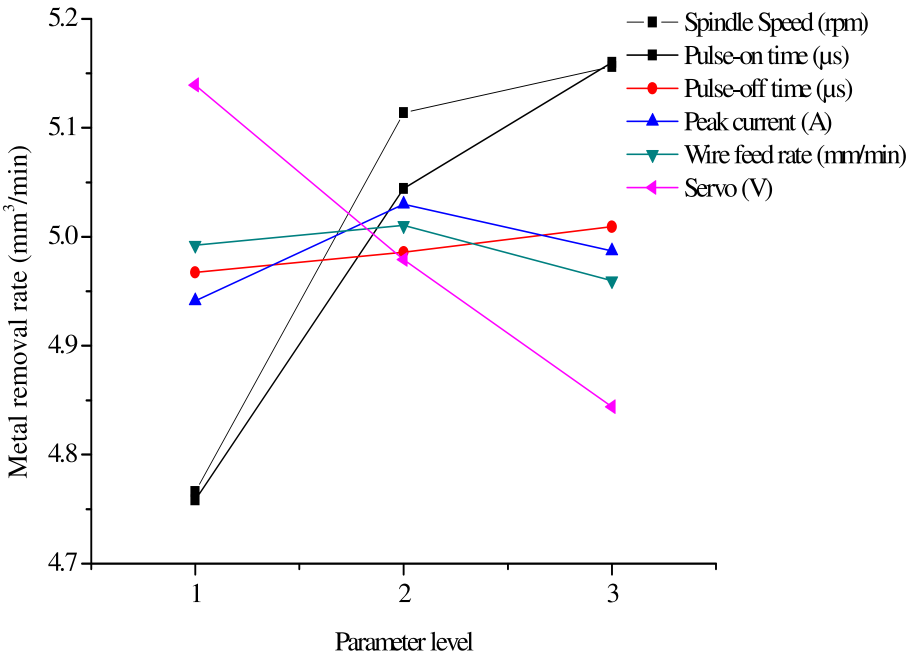

Figure 3: Effects of factors on MRR

The calculated gray relational grade values in the Table 5 serve as an overall quality index for each individual run which represents all the measures multiple responses of the WEDT process. The S/N ratios corresponding to the values of the GRG are then calculated and are tabulated Table 5. Hence, the problem with multi-response optimization has been converted in to single-response optimization with the aim of maximization of GRG. On the basis of maximization of S/N ratio of GRG, the optimal set of WEDT process parameter has been calculated using the Taguchi's maximization criterion which is:

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{9}$$

These optimal process parameters are depicted in Figure 3. This figure reveals the set of optimal parameter levels as: Spindle speed: 30 rpm, Pulse-on Time: 110µs, Pulse-off Time: 50 µs, Peak Current: 150 A, wire Feed: 3 mm/min and Servo: 90 V. Consequently, the conformation experimental runs have been conducted at the obtained levels of process variables and the comparisons have been made between the predicted and experimental runs at the optimum levels of process parameters and are presented in Table 6.The results in the Table 6 reflect the reasonable result of confirmatory experiment.

Table 5: Procedure of GRA

Normalized values					GRG			S/N ratios of GRG	
	Experimentally measured values		Normalized values		$\xi_i(k)$		γ_i		
Exp. No	Ra(μm)	MRR (mm³/min	Ra	MRR	Ra	MRR		GRG	S/N ratio (HB)
1	0.80	2.55	1.00	0.00	0.33	0.83	0.58	0.58	-4.67
2	1.06	2.36	0.90	0.03	0.36	0.87	0.61	0.61	-4.24
3	1.43	1.76	0.75	0.18	0.4	1.0	0.7	0.70	-3.11
4	1.79	4.41	0.61	0.19	0.45	0.6	0.53	0.53	-5.60
5	1.67	5.81	0.66	0.26	0.43	0.5	0.46	0.46	-6.67
6	1.02	4.79	0.91	0.41	0.35	0.57	0.46	0.46	-6.73
7	2.57	6.21	0.31	0.59	0.62	0.47	0.54	0.54	-5.27
8	1.99	5.25	0.54	0.69	0.48	0.53	0.51	0.51	-5.88
9	1.72	9.76	0.64	0.88	0.44	0.33	0.39	0.39	-8.27
10	1.84	2.82	0.60	0.09	0.46	0.79	0.62	0.62	-4.10
11	1.18	4.08	0.85	0.15	0.37	0.63	0.5	0.50	-5.99
12	1.46	4.71	0.74	0.28	0.40	0.58	0.49	0.49	-6.21
13	1.88	5.46	0.58	0.25	0.46	0.52	0.49	0.49	-6.18
14	2.04	3.74	0.52	0.33	0.49	0.67	0.58	0.58	-4.73
15	1.58	5.36	0.70	0.48	0.42	0.53	0.47	0.47	-6.52
16	2.64	8.54	0.28	0.63	0.64	0.37	0.5	0.50	-5.95
17	2.51	6.07	0.33	0.73	0.6	0.48	0.54	0.54	-5.35
18	2.34	5.25	0.40	0.92	0.56	0.53	0.54	0.54	-5.29
19	2.49	2.63	0.34	0.26	0.59	0.82	0.71	0.71	-3.00
20	2.39	3.96	0.38	0.31	0.57	0.65	0.61	0.61	-4.35
21	1.70	5.81	0.65	0.44	0.43	0.5	0.47	0.47	-6.63
22	2.61	6.83	0.30	0.39	0.63	0.44	0.53	0.53	-5.43
23	2.43	7.81	0.37	0.46	0.58	0.4	0.49	0.49	-6.23
24	2.74	4.48	0.25	0.62	0.67	0.6	0.63	0.63	-3.97
25	3.37	4.41	0.00	0.74	1	0.6	0.8	0.80	-1.93
26	3.19	5.94	0.07	1.00	0.88	0.49	0.68	0.68	-3.31
27	3.03	4.55	0.13	0.97	0.79	0.59	0.69	0.69	-3.22

6. CONCLUSIONS

Gray relational analysis integrated with Taguchi method implemented on the experimental values of WEDT to find the optimal levels of process parameters. Results of confirmatory experiment. The results are summarized as follows:

1. The performance of the integrated approach is effective while handling with the multiple responses and while converting in to single – response problem with minimum effort.
2. The optimal combination process variable obtained from the proposed methods is the set with Spindle speed: 30 rpm, Pulse-on time: 10μs, Pulse-off time: 50 μs, Peak current: 150 A, wire feed: 3 mm/min and servo: 90 V.
3. Ther esults of ANOVA reveals the major controllable parameters significantly affecting the process responses are spindle speed, pulse-on time and servo.
4. The proposed methodology can effectively deals with the multi-response optimization problems to determine the optimal WEDT process variables while cutting Ti-6Al-4V.

5.The present work provides the optimal WEDT conditions to produce Ti-6Al-4V based cylindrical component and also helps to automate the process.

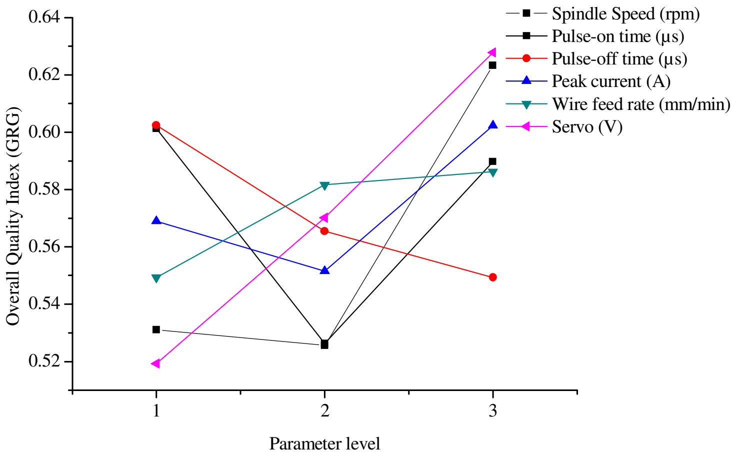

Figure 3: Effects of factors on GRG

Table 6: Results of confirmatory experiment

	Optimal Settings	
	Prediction	Experimental
Level of variables	Spindle speed :30 rpm Pulse-on time :110µs Pulse-off time :50 µs Peak current :150 A Wire feed :3 mm/min Servo :90 V	Spindle speed :30 rpm Pulse-on time :110µs Pulse-off time :50 µs Peak current :150 A Wire feed :3 mm/min Servo :90 V
S/N of GRG	-4.79442	-4.8104
GRG	0.7367	0.6910

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