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Application of Taguchi design method to optimize the electrical discharge machining

D.C. Chen*, J.J. Jhang, M.W. Guo
Department of Industrial Education and Technology,
National Changhua University of Education, Changhua 500, Taiwan
* Corresponding e-mail address: dcchen@cc.ncue.edu.tw

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Properties

ABSTRACT

Purpose: The current study utilizes the Taguchi design methodology to optimize the EDM processing parameters for the machining of A6061-T6 aluminum alloy. The experimental trials consider four EDM parameters, namely the pulse current (PC), the pulse-on duration (ON), the duty cycle (DC), and the machining duration (MD).

Design/methodology/approach: The machined specimens are observed using the surface roughness is measured using a commercial profilometer. The optimal machining parameters and the relative influence of each parameter on the surface roughness are determined by analyzing the experimental data using the analysis of means (ANOM) and analysis of variance (ANOVA) techniques.

Findings: The results show that the magnitude of the surface roughness is determined primarily by the pulse current (PC) and duty cycle (DC) parameters. A CuZn40 brass alloy specimen is machined using the optimal processing parameters and is found to have a lower mean surface roughness than the A6061-T6 workpiece.

Research limitations/implications:

Practical implications: The general applicability of the optimal machining parameters is investigated by machining a CuZn40 alloy specimen under the optimal conditions and then comparing the surface roughness characteristics of the machined surface with those of the A6061-T6 specimen.

Originality/value: It is inferred that the optimal machining parameters established using the Taguchi design methodology have a good general applicability to the EDM machining of both aluminum and brass alloys.

Keywords: Mechanical properties; Electrical properties; Electrical discharge machining (EDM); Surface roughness

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1. Introduction

Electrical discharge machining (EDM) is a non-conventional machining technique which provides the means to fabricate highly complex geometrical forms in materials with even very high hardness and toughness properties. As a result, EDM is widely applied throughout the modern metal-working industry and has emerged as the method of choice for the fabrication of high-precision dies and molds. In the EDM process, material is removed from the workpiece by generating high-frequency electrical sparks through a thin dielectric layer between the electrode and the workpiece surface. However, the gap between the electrode and the workpiece is very small (typically 5~100 μm), and thus debris tends to accumulate in the machining area. Unless this debris is efficiently removed, it causes a breakdown of the insulating properties of the dielectric layer and therefore induces a secondary discharge phenomenon, i.e. multiple electrical sparks within the same region of the machined surface. The secondary discharge phenomenon leads to a serious degradation of the surface roughness of the machined component and must therefore be suppressed by assigning suitable values to the EDM machining parameters to maintain the gap size at its designated value throughout the entire machining operation.

The literature contains many numerical and experimental investigations aimed at optimizing the EDM processing conditions for a variety of common engineering materials. For example Tzeng and Chen [1] utilized the Taguchi robust design method to optimize the processing conditions for the high-speed EDM process of material parameters. Haron et al. [2] performed a series of EDM investigations using AISI 1045 tool steel and copper electrodes of various diameters to establish the correlation between the pulse current and the corresponding material removal rate and electrode wear rate, respectively. Simao et al. [3] utilized an L8 fractional factorial Taguchi design to identify the effects of key processing conditions such as the peak current, the electrode polarity and the pulse-on time on the electrode wear and workpiece surface hardness, respectively, in the EDM machining of AISI H13 hot work tool steel. Ghanem et al. [4] performed finite element simulations to establish the temperature and residual stress distributions generated during the EDM machining of X2CrNiMo17-12-02 steel and showed that the calculated value of the residual stress was higher than that measured experimentally. Lin et al. [5] applied the Taguchi design method to improve the surface integrity of workpieces machined using a combination of EDM and ball burnish machining. Su et al. [6] optimized the machining performance of an EDM process using a neural network integrated with a genetic algorithm (GA). Das et al. [7] utilized DEFORM^{TM} finite element software to simulate the residual stress, deformation and microstructure induced by a single-pulse discharge in the EDM process. Lee and Tai [8] applied a full factorial design method to investigate the effects of the pulse current and pulse-on duration on the formation of surface cracks in the EDM machining of D2 and H13 tool steels.

Schulze et al. [9] simulated the thermal-affected zones of workpieces subjected to single and multiple electrical discharges, respectively, and compared the numerical results obtained for the crater morphology with the corresponding experimental observations. Putyra et al. [10] studied Si_3N_4 matrix materials with the addition of titanium diboride are characterized by low electrical resistance with high physical and mechanical features maintained. Kuc and Cebulski [11] conducted tests on high-manganese steels with aluminium, the part of which is presented with test results. Szajnar and Wrobel [12] investigated into reduction of grain size and unification of structure for pure Al casting by introduction of small amount of inoculant. Kim et al. [13] investigated into feasible experiments involving the BOP welding of an Al 5052 thick plate were using a disk laser. Jiang et al. [14] developed a pulse generator capable of shutting off harm-full pulses, such as arc pulses. A series of experiment are carried out to investigate the performance of the pulse control techniques, including shutting off harmful pulses and applying sweep pulses. Weingartner et al. [15] evaluated the influence of high-speed rotating workpieces on WEDM. Kanagarajan et al. [16] performed the experiments to observe the fracture strength between thr un-machined WC-Co cemented carbides and electric discharge machined cemented carbides.

The current study utilizes the Taguchi design methodology to optimize the EDM processing parameters for the machining of A6061-T6 aluminum alloy. Experimental trials are performed to examine the correlation between the surface roughness of the machined workpieces and four fundamental EDM parameters, namely the pulse current (PC), the pulse-on duration (ON), the duty cycle (DC), and the machining duration (MD). The surfaces of the machined specimens are observed using a CCD image processing system and the surface roughness is measured using a commercial profilometer. Utilizing the analysis of means (ANOM) and analysis of variance (ANOVA) techniques, the optimal EDM parameters for the machining of A6061-T6 alloy are determined and the machining parameters having the greatest influence on the surface roughness are identified. The general applicability of the optimal machining parameters is investigated by machining a CuZn40 alloy specimen under the optimal conditions and then comparing the surface roughness characteristics of the machined surface with those of the A6061-T6 specimen.

2. Overview of Taguchi method

All products have certain characteristics which describe their performance relative to the requirements or expectations of their customers. For example, the fuel economy of a car, the weight of a package of breakfast cereal, the power losses of a domestic hot water heater, and the breaking strength of fishing line are all items of concern to their respective customers when making a purchase decision [17]. The Taguchi method is one of the most widely applied robust design methods and enables a comprehensive understanding of the individual and combined effects of various design parameters to be obtained from a minimum number of experimental or simulation trials. By utilizing the Taguchi approach, product manufacturers and process designers can greatly improve the likelihood of the product (or process) satisfying the desired specification on a consistent basis. The basic principle of the Taguchi design method is to identify the parameter settings which render the quality of the product or process robust to unavoidable variations in external noise. The relative "quality" of a particular parameter design is evaluated using a generic signal-to-noise (S/N) ratio. Depending on the particular design problem, different S/N ratios are applicable, including "lower is better" (LB), "nominal is best" (NB), or "higher is better" (HB). In problems such as that considered in the current study, the objective is to identify the EDM machining conditions which minimize the surface roughness, and hence the lower-is-better S/N ratio is applicable. According to William & Creveling [18] and Belavendram [19] the lower-is-better S/N ratio can be formulated as:

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

where n is the number of trials carried out under the same design parameter conditions, y_i indicates the obtained results, and subscript i denotes the number of design parameters arranged in the Taguchi orthogonal array (OA).

Having carried out the trials prescribed in the OA, the resulting S/N data are analyzed using the analysis of means (ANOM) statistical method. The ANOM results are then used to produce S/N response tables and S/N response graphs from which the optimal design parameters can be obtained.

In performing the ANOM analysis, the mean S/N ratio of Factor A at level m is given by

$$M_{Am} = \frac{1}{n_A} \sum_{m=1}^{L_A} \left(S/N \right)_{Am} , \tag{2}$$

where n_A is the number of appearances of Factor A in the OA and $(S/N)_{Am}$ is the S/N ratio of Factor A at level m.

In the Taguchi method, a design parameter is considered to be significant (i.e. to have a significant effect on the experimental outcome) if its influence on the design solution is large compared to the experimental error, as estimated by the analysis of variance (ANOVA) method. The ANOVA analysis is performed using the following formula:

$$SS_{total} = \sum_{i=1}^{n} \sum_{j=1}^{r} n_{ij}^2 - nr\eta_m^2 , \tag{3}$$

$$SS_{factor} = \frac{nr}{L} \sum_{k=1}^{L} \left(\eta_k - \eta_m \right)^2 , \tag{4}$$

$$DOF = L - 1 , \tag{5}$$

$$V_{factor} = \frac{SS_{factor}}{DOF} , \tag{6}$$

$$F_{factor} = \frac{V_{factor}}{V_{error}} , \tag{7}$$

where SS_{total} is the total sum of squares, SS_{factor} is the factorial sum of squares, n is the number of trials configured in the OA, r is the number of specimens taken, DOF is the number of degrees of freedom, V_{factor} is the variance of the factor, F_{factor} is the F ratio of the factor, η_m is the mean S/N ratio of the factor at level m, and η is the mean of the factor.In this section it is necessary to present in details assumptions and course of own researches to such an extent that a reader could repeat those works if he was going to confirm achieved results. In short papers those information should be given in as short a version as possible.

3. Application of Taguchi design method to optimization of EDM process

In the present study, the Taguchi method is applied to establish the EDM machining parameters which minimize the surface roughness of A6061-T6 aluminum alloy specimens. As discussed earlier, the experimental trials consider four machining parameters, namely the pulse current (PC), the pulse-on duration (ON), the duty cycle (DC), and the machining duration (MD). The machining trials are performed using the EDM system shown in Figure 1 and the surface roughness of each machined specimen is evaluated using the profilometer shown in Figure 2. To ensure the reliability of the surface roughness results, each specimen is scanned twice in order to obtain an average surface roughness value. Table 1 summarizes the elemental composition of the current A6061-T6 specimens.

Fig. 1. Photograph of electrical discharge machine used in experimental trials

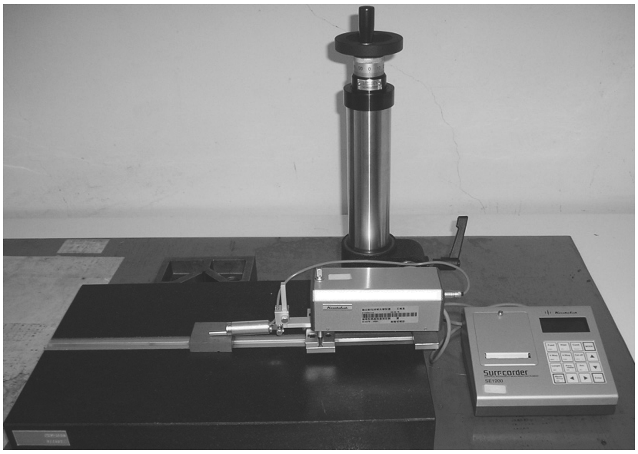


Fig. 2. Photograph of profilometer used to measure surface roughness of machined specimens

3.1. Factor selection

The current Taguchi trials considered four design factors, each with three levels. Accordingly, the machining experiments were configured using an L9(34) Taguchi OA. As shown in Table 2, the level settings of the design factors were assigned as follows: Factor A: pulse current (PC): 1.5 A, 2.0 A and 2.5 A; Factor B: pulse-on duration (ON): 12.8 µs, 25 µs and 50 µs; Factor C: duty cycle (DC): 20, 30 and 40; and Factor D: machining duration (MD) machining duration: 300 ms, 500 ms and 750 ms.

Table 1.
Elemental composition of A6061-T6 aluminum alloy

Alloy	Cu	Si	Fe	Mn	Mg	Zn	Cr	other
A6061 T6	0.27	0.6	0.7	0.15	1.0	0.25	0.25	Ti 0.15

Table 2.
Design parameters and level settings for EDM machining of A6061-T6 specimens

Factors	Description	Level 1	Level 2	Level 3
A	Pulse current (PC)	1.5	2.0 A	2.5 A
B	Pulse-on duration (ON)	12.8 µs	25 µs	50 µs
C	Duty cycle (DC)	20	30	40
D	Machining duration (MD)	300 ms	500 ms	750 ms

3.2. Analysis of means results

Table 3 presents the S/N response table for the surface roughness characteristics of the machined A6061-T6 specimens, while Tables 4 and 5 present the corresponding factor response data for the S/N ratio and surface roughness characteristic, respectively. The factor response data presented in Table 4 is plotted in graphical form in Figure 3. In accordance with the principles of the Taguchi method, a higher value of the S/N ratio indicates an improved processing condition. Therefore, Figure 3 shows that for the EDM machining of the current A6061-T6 aluminum alloy, the optimal parameter settings are as follows: a pulse current of 1.5 A (Factor A1), a pulse-on duration of 50 µs (Factor B3), a duty cycle of 20 (Factor C1), and a machining duration of 500 ms (Factor D2).

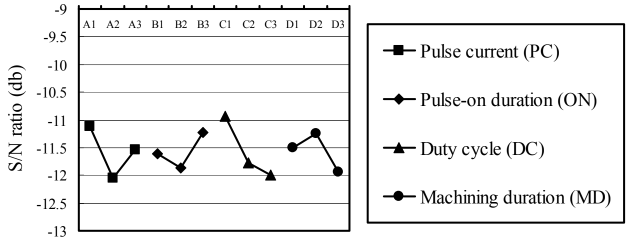


Fig. 3. S/N response graph for surface roughness characteristic, Ra (µm)

Table 3.
S/N ratio for surface roughness of machined A6061-T6 specimens

Exp.	A	B	C	D	Mea. 1 Ra (µm)	Mea. 2 Ra (µm)	Average 1 Ra (µm)	S/N ratio (dB)
1	1	1	1	1	3.668	2.976	3.322	-10.47
2	1	2	2	2	3.431	3.920	3.675	-11.32
3	1	3	3	3	3.787	3.798	3.793	-11.57
4	2	1	2	3	3.803	4.776	4.289	-12.70
5	2	2	3	1	4.239	4.405	4.322	-12.71
6	2	3	1	2	3.724	3.148	3.436	-10.75
7	3	1	3	2	4.060	3.613	3.836	-11.69
8	3	2	1	3	3.863	3.719	3.791	-11.57
9	3	3	2	1	3.692	3.688	3.690	-11.34
Mean of the total sum							3.794	-11.57

Table 4.
Factor response table for S/N ratio

Control factor	A	B	C	D
Level 1	-11.12	-11.62	-10.93	-11.50
Level 2	-12.05	-11.86	-11.78	-11.25
Level 3	-11.53	-11.22	-11.99	-11.94
Effects	0.93	0.64	1.06	0.69
Rank	2	4	1	3

Table 5.
Factor response table for surface roughness, Ra (µm)

Control factor	A	B	C	D
Level 1	3.59	3.81	3.51	3.77
Level 2	4.01	3.92	3.88	3.64
Level 3	3.77	3.64	3.98	3.95
Effects	0.42	0.28	0.47	0.31
Rank	2	4	1	3

3.3. Analysis of variance results

Table 6 summarizes the ANOVA results obtained for the experimental surface roughness data. The high confidence (> 95%) and variance values of Factors A and C indicate that the pulse current and the duty cycle have a significant influence upon the surface roughness of the machined specimen. However, it is apparent that the pulse-on duration and the machining duration have a relatively lower influence.

Table 6.
Ra (μm) analysis of variance (ANOVA)

Factor	Description	SS	DOF	Variance	F	Probability	Confidence	Significant?*
A	Pulse current (PC)	0.533	2	0.266	4.29	4.91%	95.09%	Yes
B	Pulse-on duration (ON)	0.239	2	0.120	1.93	20.06%	79.94%	No
C	Duty cycle (DC)	0.735	2	0.367	5.92	2.28%	97.72%	Yes
D	Machining duration (MD)	0.291	2	0.145	2.34	15.19%	84.81%	No
	Error	0.561	9	0.062				
	Total	2.424	17		*NOTE：At least 95% confidence			

3.4. Confirmation experiment

In accordance with the Taguchi methodology, a machining experiment was performed using the optimal parameter settings (i.e. A1B3C1D2) to confirm that the processing conditions do indeed yield a reduction in the roughness of the machined surface. Figure 4 presents a photograph of the machined specimen. The corresponding surface roughness was found to have a mean value of 3.078 μm with a S/N ratio of -9.76(dB). These results represent a considerable improvement upon the original results (see Table 3) and therefore confirm the effectiveness of the Taguchi design method in optimizing the EDM machining of A6061-T6 aluminum alloy.

Fig. 4. Surface of A6061-T6 specimen machined using optimal EDM parameter settings (A1B3C1D2)

The general applicability of the optimal machining parameters was investigated by machining a brass alloy specimen (CuZn40 (C-2800B)) using the same set of processing conditions (i.e. A1B3C1D2). Figure 5 presents a photograph of the machined brass alloy specimen. The corresponding surface profile (as measured using the profilometer shown in Figure 2) is presented in Figure 6. From inspection, the surface roughness is found to have a mean value of 2.420 μm with a S/N ratio of -7.68 (dB). In other words, the CuZn40 specimen has a lower surface roughness than the A6061-T6 workpiece when machined using the same set of processing conditions. This finding implies that the optimal machining parameters established using the Taguchi design methods have a good general applicability to the EDM machining of aluminum and brass alloys. Figure 7 shows surface roughness of experimental product using CCD machine (A3B3C3D3) for (a) A6061 T6 and (b) CuZn40 (C-2800B). It is clear that the A6061 is bad than CuZn40 for surface roughness using CCD machine.

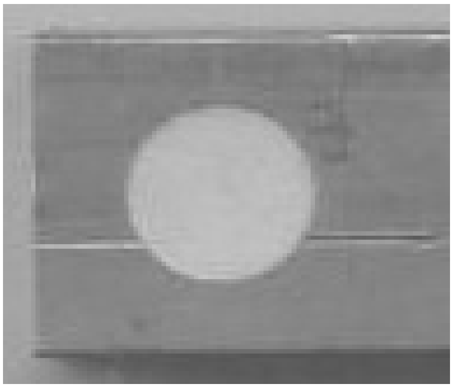


Fig. 5. Surface of CuZn40(C-2800B) specimen machined using optimal EDM parameter settings (A1B3C1D2)

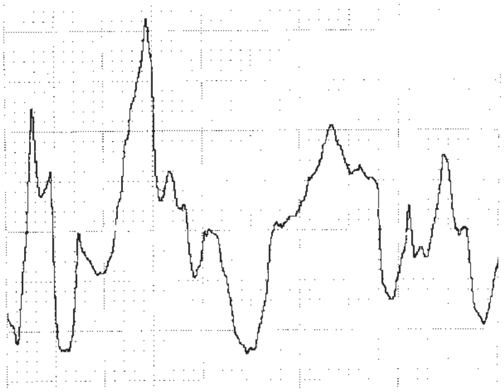
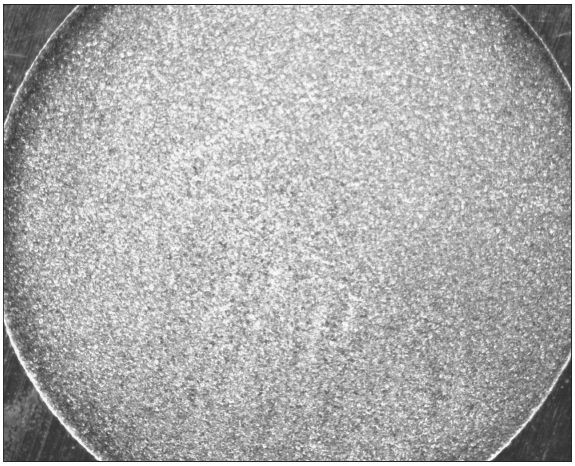


Fig. 6. Surface roughness profile of CuZn40(C-2800B) specimen machined using optimal EDM parameter settings (A1B3C1D2)

a) A6061 T6 (x24)



b) CuZn40 (C-2800B) (x24)

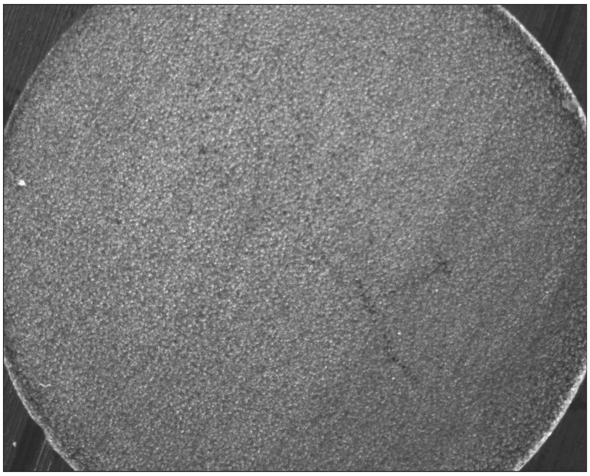


Fig. 7. Surface roughness of experimental product using CCD machine (A3B3C3D3)

4. Conclusions

This study has utilized the Taguchi robust design methodology to optimize the EDM processing conditions for the machining of A6061-T6 aluminum alloy specimens. The experimental investigations have considered four fundamental EDM parameters, namely the pulse current (PC), the pulse-on duration (ON), the duty cycle (DC), and the machining duration (MD). The results have shown that: (1) the optimal parameters for the EDM machining of A6061-T6 aluminum alloy are as follows: a pulse current of 1.5 A (Factor A1), a pulse-on duration of 50 µs (Factor B3), a duty cycle of 20 (Factor C1), and a machining duration of 500 ms (Factor D2); (2) the surface roughness of the machined specimen is determined primarily by the values assigned to the pulse current and the duty cycle parameters, respectively and (3) the optimal parameter settings established for the A6061-T6 machining process also result in a low surface roughness when applied to the machining of CuZn40 brass alloy specimens, and thus the general applicability of the Taguchi design solution is confirmed.

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