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Optimization of 6061T6 CNC Boring Process Using the Taguchi Method and Grey Relational Analysis

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Abstract: This study investigated the optimization of computer numerical control (CNC) boring operation parameters for aluminum alloy 6061T6 using the grey relational analysis (GRA) method. Nine experimental runs based on an orthogonal array of Taguchi method were performed. The surface properties of roughness average and roughness maximum as well as the roundness were selected as the quality targets. An optimal parameter combination of the CNC boring operation was obtained via GRA. By analyzing the grey relational grade matrix, the degree of influenced for each controllable process factor onto individual quality targets can be found. The feed rate is identified to be the most influence on the roughness average and roughness maximum, and the cutting speed is the most influential factor to the roundness. Additionally, the analysis of variance (ANOVA) was also applied to identify the most significant factor; the feed rate is the most significant controlled factor for the CNC boring operations according to the weighted sum grade of the roughness average, roughness maximum and roundness.

INTRODUCTION

Boring is a precision machining process for generating internal cylindrical forms by removing metal with single-point tools or tools with multiple cutting edges. This process is most commonly performed with the workpiece held stationary and the cutting tool both rotating and advancing into the work. Common applications for boring include the enlarging or finishing of cored, pierced, or drilled holes and contoured internal surfaces. Related operations sometimes performed simultaneously with boring include turning, facing, chamfering, grooving, and threading. Precision boring can be performed on machines specifically designed for this purpose. In general, these machines relatively use light cuts, maintain close tolerances, and are often capable of high production rates. Additionally, machining centers (MC) have been defined as CNC machines with automatic tool-changing capabilities and rotating cutting tools. Increased productivity and versatility are major advantages of MC.

The ability to perform drilling, turning, reaming, boring, milling, contouring, and threading operations on single machine eliminates the need for a number of individual machine tools, thus reducing capital equipment and labor requirements. Therefore, aluminum alloy 6061T6 boring process is done on the various cutting parameters of MC and is discussed in this study. The current boring operation can increase productivity if compared with a grinding operation. The boring process parameters such as cutting tool geometry and materials, depth of cut, feed rates, cutting speeds impact the material removal rates and the machining quality such as surface roughness and roundness has been studied intensively.

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Recently, Deng (1989) [1] proposed a grey relational analysis (GRA). The GRA is a method for measuring the degree of approximation among the sequences using a grey relational grade. Theories of the GRA have attracted considerable interest among researchers. Some other researchers have also examined the optimization of process parameters. For example, Huang and Lin (2002) [2] applied the GRA to design the die-sinking EDM machining parameters. Fung *et al.* (2003) [3] studied the GRA to obtain the optimal parameters of the injection molding process for mechanical properties of yield stress and elongation in polycarbonate/acrylonitrile-butadiene-styrene (PC/ABS) composites. Shen *et al.* (2004) [4] studied different polymers (such as PP, PC, PS, POM) with various process parameters of the micro-gear. The simulation used Taguchi method and GRA was provided. An employed the Taguchi method and the GRA to optimize the turning operations with multiple performance characteristics by Lin (2004) [5]. A used the GRA to optimize of the wire electric discharge machining process of particle-reinforced material with multiple performance characteristics by Chiang and Chang (2006) [6]. Yang *et al.* (2006) [7] also applied the Taguchi method and the GRA to optimize the dry machining parameters for high-purity graphite in end milling process, etc.

Planning the experiments through the Taguchi orthogonal array has been used quite successfully in process optimization by Chen and Chen (2007) [8], Fung and Kang (2005) [9], Tang *et al.* (2007) [10], Vijian and Arunachalam (2006) [11], Yang (2007) [12] as well as Zhang *et al.* (2007) [13], etc. Therefore, this study applied a Taguchi L_9 (3^4) orthogonal array to plan the experiments on CNC boring operations. Three controlling factors including the cutting speed, the feed rate, and the depth of cut with three levels for each factor were selected. The GRA is then applied to examine how the CNC boring operation factors influence the quality targets of roughness average, roughness maximum and roundness. An optimal parameter combination was then

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obtained. Through analyzing the grey relational grade matrix, the most influential factors for individual quality targets of the CNC boring operations can be identified. Additionally, the ANOVA was also utilized to examine the most significant factors for the CNC boring process as the roughness average, roughness maximum and roundness are simultaneously considered.

GREY RELATIONAL ANALYSIS

Data Preprocessing

Grey data processing must be performed before grey correlation coefficients can be calculated. A series of various units must be transformed to be dimensionless. Usually, each series is normalized by dividing the data in the original series by their average.

Let the original reference sequence and sequence for comparison be represented as $x_0(k)$ and $x_i(k)$, i=1, 2, ..., m; k=1, 2, ..., n, respectively, where m is the total number of experiment to be considered, and n is the total number of observation data. Data preprocessing converts the original sequence to a comparable sequence. Several methodologies of preprocessing data can be used in grey relation analysis, depending on the characteristics of the original sequence (Deng, 1989 [1]; Gau *et al.*, 2006 [14]; You *et al.*, 2007 [15]). If the target value of the original sequence is ''the-larger-the-better'', then the original sequence is normalized as follows,

$$x_i^*(k) = \frac{x_i^{(0)}(k) - \min . x_i^{(0)}(k)}{\max . x_i^{(0)}(k) - \min . x_i^{(0)}(k)} \tag{1}$$

If the purpose is ''the-smaller-the-better'', then the original sequence is normalized as follows,

$$x_i^*(k) = \frac{\max . x_i^{(0)}(k) - x_i^{(0)}(k)}{\max . x_i^{(0)}(k) - \min . x_i^{(0)}(k)} \tag{2}$$

However, if there is ''a specific target value'', then the original sequence is normalized using,

$$x_i^*(k) = 1 - \frac{\left| x_i^{(0)}(k) - OB \right|}{\max . \left\{ \max . x_i^{(0)}(k) - OB, OB - \min . x_i^{(0)}(k) \right\}} \tag{3}$$

where OB is the target value.

Alternatively, the original sequence can be normalized using the simplest methodology that is the values of the original sequence can be divided by the first value of the sequence, $x_i^{(0)}(1)$.

$$x_i^*(k) = \frac{x_i^{(O)}(k)}{x_i^{(O)}(1)} \tag{4}$$

where

$x_i^{(O)}(k)$: the original sequence

$x_i^*(k)$: the sequence after the data preprocessing

$\max . x_i^{(0)}(k)$: the largest value of $x_i^{(O)}(k)$

$\min . x_i^{(0)}(k)$: the smallest value of $x_i^{(O)}(k)$

Grey Relational Coefficients and Grey Relational Grades

Following the data preprocessing, a grey relational coefficient can be calculated using the preprocessed sequences. The grey relational coefficient is defined as follows.

$$\gamma\left(x_O^*(k), x_i^*(k)\right) = \frac{\Delta_{\min .} + \zeta \Delta_{\max .}}{\Delta_{Oi}(k) + \zeta \Delta_{\max .}}$$

$$0 < \gamma\left(x_O^*(k), x_i^*(k)\right) \le 1 \tag{5}$$

where

$\Delta_{Oi}(k)$ is the deviation sequence of reference sequence $x_O^*(k)$ and comparability sequence $x_i^*(k)$, namely

$$\Delta_{Oi}(k) = \left| x_O^*(k) - x_i^*(k) \right|$$

$$\Delta_{\max .} = \underset{\forall j \in i}{\max .} \ \underset{\forall k}{\max .} \left| x_0^*(k) - x_j^*(k) \right|$$

$$\Delta_{\min .} = \underset{\forall j \in i}{\min .} \ \underset{\forall k}{\min .} \left| x_0^*(k) - x_j^*(k) \right|$$

ζ : distinguishing coefficient, $\zeta \in [0,1]$

A grey relational grade is a weighted sum of the grey relational coefficients, and is defined as follows.

$$\gamma\left(x_O^*, x_i^*\right) = \sum_{k=1}^{n} \beta_k \gamma\left(x_O^*(k), x_i^*(k)\right)$$

$$\sum_{k=1}^{n} \beta_k = 1 \tag{6}$$

Here, the grey relational grade $\gamma\left(x_O^*, x_i^*\right)$ represents the level of correlation between the reference and comparability sequences. If the two sequences are identical, then the value of the grey relational grade equals to one. The grey relational grade also indicates the degree of influence exerted by the comparability sequence on the reference sequence. Consequently, if a particular comparability sequence is more important to the reference sequence than other comparability sequences, the grey relational grade for that comparability sequence and the reference sequence will exceed that for other grey relational grades. The GRA is actually a measurement of the absolute value of data difference between the sequences, and can be used to approximate the correlation between the sequences.

EXPERIMENTAL PROCEDURES AND TEST RESULTS

Material

Aluminum alloy 6061T6 is one of the most widely used alloys in the 6000 Series. This standard structural alloy, one of the most versatile of the heat-treatable alloys, is popular for medium to high strength requirements and has good toughness characteristics. Applied range from transportation

components to machinery and equipment applications to recreation products.

Schematic of Machining

Fig. (**1**) shows the machining setup of the boring process via a machining center. The experiments were carried out on a rigid computer numerical control (CNC) machine center with an 11 kW spindle motor at 8000rpm (machine type of VM–32S, manufactured by Fair Friend Group in Taiwan). At the same time, the boring cutting bar is manufactured by Maho Enterprise Ltd., Taiwan, part number BJ1614-60, and the cutter tool is used number TPGH090204L. In this study, in order to properly control the depth of cut, first the internal diameter of the workpieces has been fixed to 14mm via end milling cutting and the cutting depth of workpiece is 20 mm. Furthermore, the cutting speed (m/min), the feed rate (mm/rev) and the depth of cut (mm) can be regulated in this experiment of theCNC boring operations. Additionally, Fig. (**2**) also shows the range of surface roughness (Ra) to obtain in various processes [16].

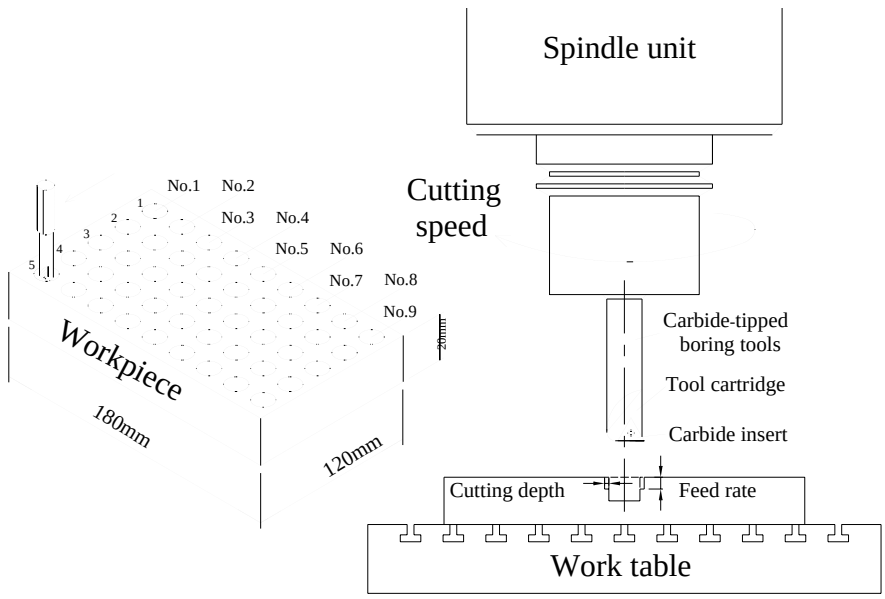

Fig. (1). Scheme of CNC boring operation.

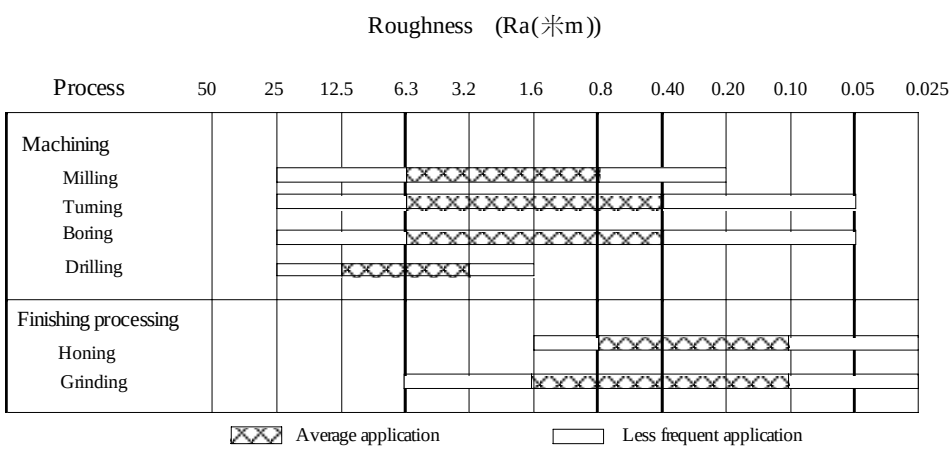

Fig. (2). The range of surface roughness (Ra) obtained in various processes.

Experimental Parameters and Design

The effects of CNC boring parameters on the surface roughness had been less discussion by research. Usually, the desired boring operation parameters can be determined from experience, a handbook or recommendation from the manufacturer. In this study, the experiment is conducted with three controllable 3-level factors and three response variables. Nine experimental runs based on the orthogonal array $L_9(3^4)$ are required. Table **1** presents three controlled factors of the cutting speed (i.e., A (m/min)), the feed rate (i.e., B (mm/rev)), and the depth of cut (i.e., C (mm)) with three levels for each factor. Table **2** shows the nine cutting experimental runs according to the selected orthogonal table. After CNC boring operations, three quality objectives of the

workpieces are chosen, including the roughness average (i.e., Ra (μm)), roughness maximum (i.e., Rt (μm)) and roundness (i.e., ψ (μm)).

Table 1. Experimental Factors and Factor Levels

Levels of Experimental Factors	Experimental Control Factors		
	A/ Cutting Speed (m/min)	B/ Feed Rate (mm/rev)	C/ Cut Depth (mm)
1	70	0.05	0.4
2	85	0.10	0.5
3	100	0.15	0.6

Measuring Apparatus

The roughness average (Ra) and roughness maximum (Rt) of the surface after the CNC boring process were measured by a surface analyzer from

Form Talysurf 50 (Taylor Hobson Ltd., UK) and Form Talyrond 250 for the roundness (ψ) of the circumference surface.

Table 2. Orthogonal Array $L_9(3^4)$ of the Experimental Runs and Results

Run no.	A	B	C	Ra(μm)	Rt(μm)	ψ(μm)
1	1	1	1	0.1362	1.1126	2.76
2	1	2	2	0.5912	3.6129	2.32
3	1	3	3	1.6178	8.3246	1.52
4	2	1	3	0.1260	1.1460	0.68
5	2	2	1	0.6376	5.2558	0.88
6	2	3	2	1.7736	13.0625	1.36
7	3	1	2	0.1605	2.1328	0.60
8	3	2	3	0.6318	2.1968	1.68
9	3	3	1	1.5866	8.1710	2.48

RESULTS AND DISCUSSION

Table **2** shows the nine cutting experimental runs according to the L_9 orthogonal table. Every experimental run by way of five CNC boring operations, three quality objectives of the fifth workpieces is measured, including the roughness average (i.e., Ra (μm)), roughness maximum (i.e., Rt (μm)), and roundness (i.e., ψ (μm)).

Best Experimental Run

The experimental results for the Ra, the Rt and the ψ are listed in Table **2**. Typically, smaller values of the Ra, the Rt and the ψ are desirable. Thus, the data sequences have a the-smaller-the-better characteristic, the "smaller-the-better" methodology, i.e. Eq. (2), was employed for data preprocessing. The values of the Ra, the Rt and ψ are set to be the reference sequence $x_0^{(0)}(k)$, k=1~3. Moreover, the results of nine experiments were the comparability sequences $x_i^{(0)}(k)$, i=1,2,…,9, k=1~3. Table **3** listed all of the sequences after implementing the data preprocessing using Eq. (2). The reference and the comparability sequences were denoted as $x_0^*(k)$ and $x_i^*(k)$, respectively. Also, the deviation sequences Δ_{0i}, $\Delta_{\max.}(k)$ and $\Delta_{\min.}(k)$ for i=1~9, k=1~3 can be calculated.

Table 3. The Sequences After Data Preprocessing

Reference/Comparability Sequence		Ra	Rt	ψ
Reference Sequence		**1.000**	**1.000**	**1.000**
Comparability Sequences	No. 1	0.9938	1.0000	0.0000
	No. 2	0.7176	0.7908	0.2037
	No. 3	0.0946	0.3965	0.5741
	No. 4	1.0000	0.9972	0.9630
	No. 5	0.6895	0.6533	0.8704
	No. 6	0.0000	0.0000	0.6481
	No. 7	0.9791	0.9146	1.0000
	No. 8	0.6930	0.9093	0.5000
	No. 9	0.1135	0.4093	0.1296

Table 4. The Calculated Grey Relational Coefficient and Grey Relational Grade for Nine Comparability Sequences

Experimental Run (Comparability Sequences)	Orthogonal Array $L_9(3^4)$			Grey Relational Coefficient			Grey Relational Grade
	A	B	C	Ra	Rt	ψ	
1	1	1	1	0.9878	1.0000	0.3333	0.7737
2	1	2	2	0.6391	0.7050	0.3857	0.5766
3	1	3	3	0.3558	0.4531	0.5400	0.4496
4	2	1	3	1.0000	0.9944	0.9310	0.9752
5	2	2	1	0.6169	0.5905	0.7941	0.6672
6	2	3	2	0.3333	0.3333	0.5870	0.4179
7	3	1	2	0.9598	0.8542	1.0000	0.9380
8	3	2	3	0.6196	0.8464	0.5000	0.6553
9	3	3	1	0.3606	0.4584	0.3649	0.3946

The distinguishing coefficient ζ can be substituted for the grey relational coefficient in Eq. (5). If all the process parameters have equal weighting, ζ is set to be 0.5. Table **4** listed the grey relational coefficients and the grade for all nine comparability sequences.

This investigation employs the response table of the Taguchi method to calculate the average grey relational grades for each factor level, as illustrated in Table **5**. Since the grey relational grades represented the level of correlation between the reference and the comparability sequences, the larger grey relational grade means the comparability sequence exhibiting a stronger correlation with the reference sequence. Based on this study, one can select a combination of the levels that provide the largest average response. In Table **5**, the combination of A_2, B_1, and C_3 shows the largest value of the grey relational grade for the factors A, B, and C, respectively. Therefore, $A_2B_1C_3$ with a cutting speed of 85m/min, a feed rate of 0.05mm/rev, and depth of cut of 0.6 mm is the optimal parameter combination of the CNC boring operations.

Table 5. The Response Table for Grey Relational Grade

Levels	Factors		
	A	B	C
1	0.6000	0.8956	0.6118
2	0.6867	0.6330	0.6442
3	0.6627	0.4207	0.6934

Most Influential Factor

In this study, the GRA is applied to examine how the boring operation parameters influence the quality targets of workpieces. The values of the factor level in nine experimental runs are set to the comparability sequences for three controllable factors. Table **6** listed all of the sequences.

Table 6. The Sequences After Data Preprocessing for the Reference Sequences and Comparability Sequences

Exp. Run	Comparability Sequences			Reference Sequences		
	A	B	C	Ra	Rt	ψ
1	1.00	1.00	1.00	1.000	1.000	1.0000
2	1.00	2.00	1.25	4.3407	3.2473	0.8406
3	1.00	3.00	1.50	11.8781	7.48213	0.5507
4	1.21	1.00	1.50	0.9251	1.0300	0.2464
5	1.21	2.00	1.00	4.6814	4.7239	0.3188
6	1.21	3.00	1.25	13.0220	11.7405	0.4928
7	1.43	1.00	1.25	1.1784	1.9170	0.2174
8	1.43	2.00	1.50	4.6389	1.9745	0.6087
9	1.43	3.00	1.00	11.6491	7.3441	0.8986

Data preprocessing was performed based on Eq. (4), and Table **6** listed the normalized results. Subsequently, the deviation sequences were calculated using the method mentioned above. The deviation sequences and the distinguishing coefficient then were substituted into Eq. (5) to obtain the grey relational coefficients. Additionally, the grey relational coefficients are averaged using an equal weighting to obtain the grey relational grade. Table **7** listed the grey relational coefficients and the grade of the Ra of the reference sequence and comparability sequences. Table **8** gives the grey relational coefficients and the grade of the Rt for the reference sequence and the comparability sequences. Similarly, Table **9** shows the grey relational coefficients and the grade of the ψ for the reference sequence and the comparability sequences.

The grey relational grades in Tables **7**, Tables **8** and **9** can be further arranged in a matrix form shown as follows:

$$\gamma = \begin{bmatrix} \gamma(Ra,A) & \gamma(Ra,B) & \gamma(Ra,C) \\ \gamma(R_t,A) & \gamma(R_t,B) & \gamma(R_t,C) \\ \gamma(\psi,A) & \gamma(\psi,B) & \gamma(\psi,C) \end{bmatrix} = \begin{bmatrix} 0.6534 & 0.6921 & 0.6531 \\ 0.7217 & 0.7682 & 0.7166 \\ 0.9052 & 0.8155 & 0.9008 \end{bmatrix} \quad (7)$$

By comparing Row 1, Row 2 and Row 3, some conclusion can be drawn from this matrix. In the first row, γ (Ra, B) $>\gamma$ (Ra, A) $>\gamma$ (Ra, C), it means that the order of importance for the controllable factors to the Ra, in sequence, is the factor B, A, and C. From the second row, γ(Rt, B) $>\gamma$(Rt, A) $>\gamma$(Rt, C), the order of importance for the controllable factors to the Rt, in sequence, is the factor B, A, and C. Similarly, based on the third row, γ(ψ, A) $>\gamma$(ψ, C) $>\gamma$(ψ, B), the order of importance for the controllable factors to the ψ, in sequence, is the factor A, C, and B. Additionally, in the matrix, it also shows that the sequences for the γ(Ra) and the γ(Rt) are similar.

The most influential factors that affect the output variables are determined by identifying the maximum values in each row. Hence, base on the maximum values in the matrix of the grey relational $(\gamma(Ra,B), \gamma(Rt,B), \gamma(\psi,A))$= (0.6921, 0.7682, 0.9052), it can be found that the factor A, cutting speed, has the most influence on the ψ with γ value of 0.9052. The factor B, the feed rate, is the most influential factor to the Ra and the Rt with γ values of 0.6921 and 0.7682, respectively.

Additionally, Table **10** gives the results of the analysis of variance (ANOVA) for the Ra, the Rt, and the ψ using the calculated values from the grey relational grade of Table **4** and the response table of Table **5**. According to Table **10**, the factor B, the feed rate with 90.09% of contribution, is the most significant controlled parameters for the CNC boring operations; the cutting speed is with 1.31% contribution, and the depth of cutting with 0.79% of contribution if the minimization of the roughness average, roughness maximum and roundness are simultaneously considered.

Confirmation Test

After identifying the most influential parameters, the final phase is to verify the Ra, Rt, and the ψ by conducting the confirmation experiments. The $A_2B_1C_3$ is an optimal parameter combination of the CNC boring process via the GRA. Therefore, the condition $A_2B_1C_3$ of the optimal parameter combination of the CNC boring process was treated as a confirmation test. If the optimal setting with a

Table 7. The Calculated Grey Relational Coefficient and Grey Relational Grade for Experimental Factors to Experimental Result of the Ra

	A	B	C
Grey Relational Coefficient	1.0000	1.0000	1.0000
	0.6386	0.7161	0.6564
	0.3518	0.3994	0.3626
	0.9533	0.9875	0.9113
	0.6300	0.6877	0.6159
	0.3333	0.3707	0.3340
	0.9594	0.9707	0.9880
	0.6478	0.6911	0.6529
	0.3661	0.4057	0.3567
Grey Relational Grade	0.6534	0.6921	0.6531

Table 8. The Calculated Grey Relational Coefficient and Grey Relational Grade for Experimental Factors to Experimental Result of the Rt

	A	B	C
Grey Relational Coefficient	1.0000	1.0000	1.0000
	0.7243	0.8256	0.7472
	0.4767	0.5684	0.4967
	0.9697	0.9949	0.9263
	0.6272	0.6843	0.6132
	0.3593	0.4031	0.3601
	0.9236	0.8656	0.8985
	0.9154	0.9957	0.9256
	0.4995	0.5761	0.4820
Grey Relational Grade	0.7217	0.7682	0.7166

cutting speed of 85 m/min, 0.05mm/rev of the feed rate, and a cut depth of 0.6mm is used, the final workpiece gives the roughness average (i.e., Ra) of 0.1368μm, the roughness maximum (i.e., Rt) of 1.1250μm, and the roundness (i.e., ψ) of 0.6428μm.

Table 9. The Calculated Grey Relational Coefficient and Grey Relational Grade for Experimental Factors to Experimental Result of the ψ

	A	B	C
Grey Relational Coefficient	1.0000	1.0000	1.0000
	0.9737	0.8359	0.9351
	0.9293	0.7068	0.8615
	0.8591	0.8868	0.8249
	0.8683	0.7784	0.8966
	0.8911	0.7019	0.8863
	0.8298	0.8830	0.8511
	0.8781	0.8093	0.8688
	0.9176	0.7375	0.9831
Grey Relational Grade	0.9052	0.8155	0.9008

CONCLUSIONS

The GRA based on an orthogonal array of the Taguchi method was a way of optimizing the CNC boring operations for aluminum alloy 6061T6. The analytical results are summarized as follows.

1. From the response table of the average grey relational grade, it is found that the largest value of the grey relational grade for the cutting speed of 85 m/min, the feed rate of 0.05 mm/rev, and the depth of cutting of 0.6 mm. It is the recommended levels of the controllable parameters of the CNC boring operations as the minimization of the roughness average, roughness maximum and roundness are simultaneously considered.
2. The order of the importance for the controllable factors to the roughness average, in sequence, is the feed rate, the cutting speed, and the depth of cut. Similarly, the order to the roughness maximum, in sequence, is the feed rate, the cutting speed, and the depth of cut. Additionally, the order to the roundness, in sequence, is the cutting speed, the depth of cut, and the feed rate.

Table 10. ANOVA Results for Ra, Rt, and ψ

Factor	Level 1	Level 2	Level 3	Degree of Freedom	Sum of Squares	Mean Square	F value	Excepted Sum of Square	Contribution (%)
A	0.6000	0.6868	0.6626	2	0.0120	0.0060	1.671	0.005	1.31
B	0.8956	0.6330	0.4207	2	0.3396	0.1698	47.114	0.332	90.09
C	0.6118	0.6442	0.6934	2	0.0101	0.0051	1.403	0.003	0.79
Error				2	0.0072	0.0036		0.029	7.81
Total				8	0.3690	0.0461		0.369	100.00

3. Through ANOVA, the percentage of contribution to the CNC boring process, in sequence, is the feed rate, the cutting speed, and the depth of cut. Hence, the feed rate is the most significant controlled factor for the CNC boring operation when the minimization of the roughness average, the roughness maximum and the roundness are simultaneously considered.
4. Via experimental runs of the CNC boring operation can be gained finishing processing for the roughness average, namely, the roughness average is about 0.13μm by CNC boring process for aluminum alloy 6061T6.

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