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RESEARCH ARTICLE

# Milling of Al 6060 Alloy with DLC Coated Cutting Tools

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## HIGHLIGHTS

> It is seen that the Taguchi optimization technique is a useful technique in the design of the workability test of Al 6060 alloy material, optimization of parameters, and obtaining the desired rates of response values.

> With Grey relational optimization technique, surface roughness and cutting force were optimized and reached when the revolution was 3500 rpm, the feed rate was 450 mm/min, and MQL ratio was 30.

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## ABSTRACT

In this study, the effects of rotation, feed rate, and MQL cooling system flow on surface roughness and cutting forces in milling Al 6060 alloy with DLC coated cutting tools are investigated. Taguchi method was used in the test design. Thus, time and cost are saved in the tests. The results obtained from the tests were optimized and improved. Surface roughness and performance were improved with the Taguchi method. In this study, optimal workability of Al 6060 material with DLC coated end mill was tried to be determined with grey relational analysis and surface roughness and cutting force optimization was made. Ideal values were obtained when the revolution was 3500 rpm; the feed rate was 450 mm/min. Moreover, the MQL rate was 30 l/h.

**Contents**



## 1. Introduction

By the mechanical properties of aluminum alloys, they are increasingly used in aviation, aerospace, weapons and defense industries, and this has led to an increase in researches on the workability of the materials [1]. Smearing behavior of aluminum during machining is different from other metallic materials. Smearing behavior of aluminum alloys during machining makes them adhere to cutting tools and negatively affect the working parameters such as cutting force and chatter [2]. It is seen that 6XXX series aluminum alloys come into prominence in defense and aviation industries along with 2XXX and 7XXX series Al alloys due to their manufacturing properties. There were some experimental studies in this respect. For instance, Deepak

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and Rajendra [3] have investigated the effect of various turning operations performed with cast Al 6061 alloy on the surface roughness and observed that surface roughness is reduced by 31.44% when cutting speed is increased by 39.29%. Pridhvijit and Binu [4] have conducted an experimental study on machining parameters such as chip depth, feed rate, and cutting rate when the Al 2014 alloy is machined with carbide and TiN coated carbide tools and their effects on surface roughness. The Taguchi method was used to find optimum results and orthogonal sequence, signal-noise ratio, and ANOVA methods were used to determine the performance characteristics during turning. The best surface quality was obtained with low feed rate and high cutting speed values. Ranganath et al. [5] have used Taguchi test design method in their study conducted to examine the effect of rotation, feed rate and chip depth in turning of Al 6061 alloy on surface roughness and analyzed the effect of turning parameters on surface quality. The analysis of variance has revealed that the most effective parameter on surface roughness was cutting speed [5]. Rogov and Siamak [6] have investigated the effect of cutting parameters on surface quality and natural frequency in turning of AA2024 aluminum alloy. In turning tests made with two types of cutting tool bits made of TiC coated cemented carbide and AISI 50140 by using cutting parameters such as chip depth, feed rate, revolution per minute and tool's approach angle, it was found that the active factors on the value of surface roughness (Ra) was revolution per minute and feed rate. List [7] has examined some critical reasons for tool wear such as adhesion and diffusion when the aluminum alloy is dry machined with cemented carbide cutting tool. For this purpose, orthogonal cutting was performed on 2024 aluminum alloy with uncoated cemented carbide cutting tool. When SEM images of cutting tools are examined, it was seen that BUE and adhesive wear mechanism was formed on the rake face of the tool during machining. Diamond materials are highly anti-adhesive materials [7–10]. However, diamond cutting tools are damaged due to the impacts in batch operation, and tool life is negatively affected. Therefore, it is suggested that diamond-like carbon DLC coatings are more suitable than using cutting tools with many uncrystallized films in batch operations. DLC films resemble diamond in many aspects such as hardness, excellent wear and slipperiness, chemical stability, high electrical resistance, and high optical visibility. DLC coatings are highly applicable to many machining methods [11–15].

In this study, the metal was removed from Al 6060 alloy material by using diamond-like carbon DLC coated cutting tools suggested by numerous researchers in the machining of aluminum alloys. Test conditions were determined by taking the current literature researches and the machining conditions of the companies in the industry into consideration. Cutting force was observed in the experimental study. The surface quality of the end product was examined, and a relationship between the change in cutting parameters and surface quality was tried to be found.

The test results (surface roughness and cutting force) were optimized by using the Taguchi method, which is one of the optimization techniques commonly used in literature, and the parameters were optimized. Surface roughness and cutting force were optimized with grey relational analysis.

## 2. The Experiment Study

### 2.1. The Experiment Method

The samples used in the test study were Al 6060 alloy material, and Al 6060 aluminum alloy, chemical ratios of which are given in Table 1 and mechanical properties of which are given in Table 2 was used as the test sample. In the tests, x-y-x axial JOHNFORD VMC-850/550+APC CNC Fanuc 0T CNC Milling Machine with 30 HP engine power was used.

Table 1 Chemical properties of A1 6060

| Get | Cu | Mn | Si | Ti | Zn | Cr |
|---|---|---|---|---|---|---|
| Remaining | 0.1 | 0.10 | 0.45 | 0.10 | 0.15 | 0.05 |

Table 2 Mechanical properties of Al 606

| Tensile Strength (Mpa) | Yield Strength (Mpa) | Elongation (%) | Density (g/cm$^3$) | Hardness (HB) |
|---|---|---|---|---|
| 160 | 120 | 6 | 2.70 | 60 |

In this experimental study, a 10 mm diameter DLC 10 end-mill cutter was used. Surface roughness was measured with MAHR-Perthometer device. KISTLER 9265B dynamometer, KISTLER 5019B amplifier, and DynaWare analysis program were used for measuring the force (Figure 1).

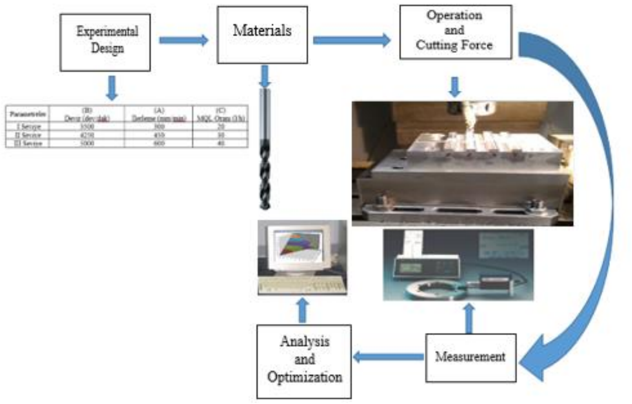


Figure 1 Schematic illustration of the test arrangement

### 2.2. The Experimental Design

The experimental design was made with the Taguchi technique. Consequently, extensive results were reached with a limited number of tests. Thus, time and cost savings were achieved [3, 16–18]. It is desired for quality values, surface quality, and cutting force to be minimum. The principle of quality at the end of the tests is "the lowest is the best."

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

n is in equation 1 represents test conditions, and the number of tests and y represents the dependent variable measured.

The parameters were selected in this study as revolution (A), feed rate (B), and MQL flow rate (C). DLC coated DL10 end mills were used in all tests. The parameters and levels to be used in the test are presented in Table 3, and the test design of L9 is presented in Table 4. Schematic illustration of the test arrangement is given in Figure 1.

Table 3 Experiment parameters

| Parameters | (A) Revolution (rpm) | (B) Feed (mm/min) | (C) MQL Ratio (l/h) |
|---|---|---|---|
| Level I | 3500 | 300 | 20 |
| Level II | 4250 | 450 | 30 |
| Level III | 5000 | 600 | 40 |

Table 4 Taguchi L9 Test design

| Test No. | Variables | (A) S (rpm) | (B) f (mm/min) | (C) d (l/h) |
|---|---|---|---|---|
| 1 | $A_1B_1C_1$ | 1 | 1 | 1 |
| 2 | $A_1B_2C_2$ | 1 | 2 | 2 |
| 3 | $A_1B_3C_3$ | 1 | 3 | 3 |
| 4 | $A_2B_1C_2$ | 2 | 1 | 2 |
| 5 | $A_2B_2C_3$ | 2 | 2 | 3 |
| 6 | $A_2B_3C_1$ | 2 | 3 | 1 |
| 7 | $A_3B_1C_3$ | 3 | 1 | 3 |
| 8 | $A_3B_2C_1$ | 3 | 2 | 1 |
| 9 | $A_3B_3C_2$ | 3 | 3 | 2 |

### 2.3. Grey Relational Analysis (GRA)

Grey Relational Analysis; In the grey system which shows the level of information between white and black, some information is known while some information is not known and the factors between the relationships within the system are not specified [15].

Grey relational analysis (GRA) is one of the sub-steps of grey modeling and is the method that determines the degree of relationship between the factor series compared to each factor in the system. Each factor is defined as an index (horizontal or vertical), and the degree of effect between factors is called grey relational degree [19–21].

Calculation steps of grey relational analysis method are as follows [19–21]:

**1. Step:** Reference series in length n (Equation 2).

$$x_0 = (x_0(1), x_0(2), x_0(3), ..., x_0(n)) \quad (2)$$

**2. Step:** Normalization of data

In the case of "the higher, the better", normalization is like in Equation 3.

$$x_i(k) = \frac{x_i^0(k) - \min x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \quad (3)$$

$x^0$ (k), i series the original value in sequence k,

$x_i$ (k) after normalization i. the value in series k

the minimum value in min $x^0$ (k) i series is the maximum value in max $x^0$ (k) i series.

For "the lower, the better" it is like in Equation 4;

$$x_i(k) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \quad (4)$$

For "the ideal value, the better" it is like in Equation 5;

$$x_i(k) = 1 - \frac{\left|x_i^0(k) - x^0\right|}{\max x_i^0(k) - x^0} \quad (5)$$

Here $x^0$ shows the desired ideal value.

**3. Step:** m number of series to be compared with $x_0$ series, Equation 6.

$x_i$= ($x_i$ (1), $x_i$ (2), $x_i$ (3),..., $x_i$ (n)) i = i i i i i = 2,1 ,...,m (6)

**4. Step:** k, is the sequence k. in length n, show the order n is the grey relational coefficient in point ε(x0(k),xi (k)) and is calculated in accordance with equalities 7, 8, 9 and 10.

$$\varepsilon(x_0(k), x_i(k)) = \frac{\Delta_{\min} + \xi\Delta_{\min}}{\Delta_{0i}(k) + \xi\Delta_{\max}} \quad (7)$$

$$\Delta_{0i}(k) = \left|x_0(k) - x_j(k)\right| \quad (8)$$

$$\Delta_{\min} = \min_j \min_k \left|x_0(k) - x_j(k)\right| \quad (9)$$

$$\Delta_{\max} = \max_j \max_k \left|x_0(k) - x_j(k)\right| \quad (10)$$

**5. Step:** Finally, the grey relational degree is calculated with equality 11:

$$\gamma(x_0, x_i) = \frac{1}{n}\sum_{k=1}^{n} \varepsilon(x_0(k), x_i(k)) \quad (11)$$

*γ(x₀,xᵢ)*, $x_i$ $x_0$ similarity is a measure of n. The size of the GRA degree shows that there is a strong relationship between $x_i$ and $x_0$.

This is calculated according to Equation 12.

$$\gamma(x_0, x_i) = \frac{1}{n}\sum_{k=1}^{n} \varepsilon(x_0(k), x_i(k).(W_i(k))) \quad (12)$$

The factor series with the highest grey relational degree (alternative) will show the best decision making alternative in decision-making problem.

## 3. Findings and Evaluation

### 3.1. Findings

Revolution, feed, and MQL flow rate parameters are used as variables on CNC milling machine for Al 6060 material with DLC coated DL10 end-mill tools and metal is removed. The effects of these machining parameters on surface roughness were examined.

Table 5 shows the surface roughness values and cutting force values obtained after the tests.

In general, obtained roughness value was between 0.327 - 0.82 µm and cutting forces were between 241.2-332.36 N.

Table 5 Surface roughness and cutting force values measured at the end of the tests.

| Test No. | Variables | Surface Roughness (µm) | Cutting Force (N) |
|---|---|---|---|
| 1 | $A_1B_1C_1$ | 0.327 | 281.96 |
| 2 | $A_1B_2C_2$ | 0.48 | 241.2 |
| 3 | $A_1B_3C_3$ | 0.562 | 332.36 |
| 4 | $A_2B_1C_2$ | 0.582 | 267.3 |
| 5 | $A_2B_2C_3$ | 0.397 | 279.2 |
| 6 | $A_2B_3C_1$ | 0.415 | 308.56 |
| 7 | $A_3B_1C_3$ | 0.82 | 284.73 |
| 8 | $A_3B_2C_1$ | 0.633 | 275.46 |
| 9 | $A_3B_3C_2$ | 0.387 | 299.23 |

### 3.2. Results of Grey Relational Analysis

It is desired to have low surface roughness and cutting force in the machining of Al 6060 series aluminum.

Normalized state of all measurement results and the calculated coefficient matrix results are presented in Table 6. Matrix coefficients are calculated, and their degrees are determined according to Equation 12. Following the tests, the highest and most suitable GRA degrees were obtained in test 2 as seen in Table 6 and Figure 2. Minimum cutting range slope, according to Grey Relational Degree, is seen in the machining conditions used in test 2.

Table 6 Grey relational analysis values

| | Normalization | | Coefficient Matrix | | Grey Relational Degree | |
|---|---|---|---|---|---|---|
| | Surface Roughness | Cutting Force | Surface Roughness | Cutting Force | Grey Degree | GRA Ranking |
| 1 | 0.000 | 0.605 | 1.000 | 0.452 | 0.726 | 2 |
| 2 | 0.310 | 0.000 | 0.617 | 1.000 | 0.809 | 1 |
| 3 | 0.477 | 1.353 | 0.512 | 0.270 | 0.391 | 8 |
| 4 | 0.517 | 0.387 | 0.492 | 0.563 | 0.527 | 6 |
| 5 | 0.142 | 0.564 | 0.779 | 0.470 | 0.624 | 3 |
| 6 | 0.178 | 1.000 | 0.737 | 0.333 | 0.535 | 5 |
| 7 | 1.000 | 0.646 | 0.333 | 0.436 | 0.385 | 9 |
| 8 | 0.621 | 0.509 | 0.446 | 0.496 | 0.471 | 7 |
| 9 | 0.122 | 0.861 | 0.804 | 0.367 | 0.586 | 4 |

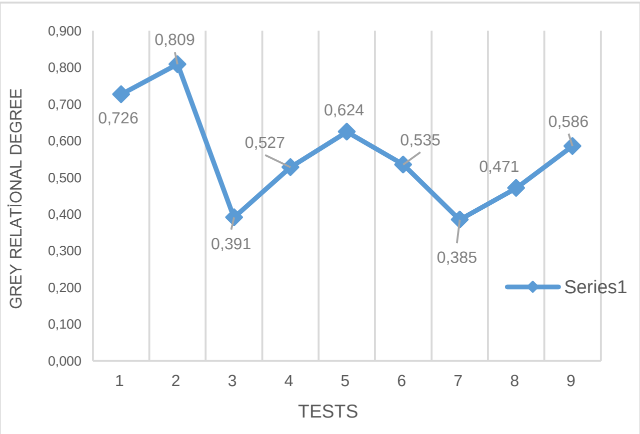


Figure 2 Grey Relational Degree

## 4. Conclusions

Useful conclusions were obtained in this study conducted on the investigation of the workability of Al 6060 alloy material with DLC coated end-mill. Workability criteria were taken as surface roughness and cutting formation. Three control factors (revolution, feed rate, and MQL rate), which are considered to be useful in the realization of this criterion under ideal conditions, were chosen at three different levels and applied in the experimental study. The results are summarized below.

In machining of Al 6060 alloy material with DLC coated cutting tools, the best surface roughness value was obtained when the rotation was 3500 rpm, the feed rate was 300 mm/min, and MQL ratio was 20.

All three control factors (feed rate, cutting speed, and MQL ratio) were also effective in the formation of cutting force. The lowest cutting force value was obtained when the revolution was 3500 rpm, the feed rate was 450 mm/min, and MQL ratio was 30.

It is seen that the Taguchi optimization technique is an effective technique in the design of the workability test of Al 6060 alloy material, optimization of parameters and obtaining the desired rates of response values.

With Grey relational optimization technique, surface roughness and cutting force were optimized and reached when the revolution was 3500 rpm, the feed rate was 450 mm/min, and MQL ratio was 30.

When the results are evaluated in consideration of the literature it is found out that DLC coatings contribute positively to the workability of Aluminum 6060 alloy material and particularly accelerates the improvement in the performance of the cutting tool.

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