Implementation of the Taguchi Method for Optimizing Surface Roughness in the Aluminum Drilling Process

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Abstract

Drilling is one of the important machining processes in the manufacturing industry, especially for lightweight materials such as aluminum. However, drilling aluminum poses significant challenges, including the generation of surface roughness and elevated temperatures in the cutting zone, which can accelerate tool wear. This study aims to optimize drilling parameters for aluminum 7075 (Al7075) under Minimum Quantity Lubrication (MQL) conditions, with surface roughness selected as the primary quality characteristic where lower values indicate better performance. The cutting tool used in the drilling process was HSS with a point angle of 118°. The investigated process parameters include spindle speed, feed rate, and type of cutting fluid. The experiments were designed using the Taguchi method with an L18 orthogonal array. Data were analyzed through signal-to-noise (S/N) ratio and analysis of variance (ANOVA) to identify the influence of each parameter. The results indicated that feed had the most significant effect on surface roughness, followed by spindle speed and the type of cutting fluid. The optimal combination of parameters, which includes a feed rate of 0.05 mm/rev, a spindle speed of 1500 rpm, and sunflower oil as the cutting fluid, yielded the lowest surface roughness and demonstrated the effectiveness of the Taguchi method in improving machining performance in aluminum drilling processes.

Kata kunci: Drilling, Taguchi, ANOVA, Surface Roughness

Abstrak

Drilling merupakan salah satu proses pemesinan yang penting dalam industri manufaktur, khususnya pada material ringan seperti aluminium. Tantangan dalam proses *drilling* aluminium antara lain kekasaran permukaan yang tinggi dan peningkatan suhu di zona potong yang dapat menyebabkan keausan pahat. Penelitian ini bertujuan untuk mengoptimalkan parameter proses *drilling* aluminium 7075 (AL7075) dengan kondisi pemesinan menggunakan Minimum Quantity Lubrication (MQL). Pahat yang digunakan dalam proses *drilling* adalah HSS dengan sudut ujung pahat 118°. Kekasaran permukaan sebagai karakteristik kualitas utama dimana semakin kecil nilainya semakin baik. Parameter yang divariasikan meliputi jenis cairan pemotongan, kecepatan spindel, dan gerak makan. Rancangan eksperimen menggunakan metode Taguchi dengan ortogonal array L18, dan data dianalisis menggunakan *signal to noise ratio* (S/N ratio) serta analisis variansi (ANOVA) untuk menentukan pengaruh masing-masing faktor. Hasil penelitian menunjukkan bahwa gerak makan merupakan parameter paling signifikan berpengaruh terhadap kekasaran permukaan, selanjutnya adalah kecepatan spindel dan jenis cairan pemotongan. Kombinasi parameter optimal yang menghasilkan kekasaran permukaan minimum yaitu dengan mengatur nilai gerak makan 0.05 mm/rev, kecepatan spindel 1500 rpm, dan cairan pemotongan minyak bunga matahari.

Kata kunci: Drilling, Taguchi, ANOVA, Kekasaran Permukaan

1. Introduction

Drilling is the most widely utilized process in most manufacturing industries. It is a necessary step in the production of mechanical components with hole making operation [1]. Aluminum is widely used in various industries, including automotive, construction, electrical and electronics, transportation, marine, and aerospace sectors. As a lightweight metal, aluminum offers good machinability, making it suitable for a range of manufacturing applications. However, the drilling process of aluminum presents several challenges, such as burr formation, built-up edge on the cutting tool, and elevated temperatures in the cutting zone. These issues can negatively impact hole quality, reduce tool life, and lead to longer production times and higher manufacturing costs [2].

Surface roughness is a critical parameter in evaluating the quality of machined components [3]. In drilling processes, surface roughness plays a crusial role in determining the functional performance of parts, especially in high-precision industries such as aerospace. The surface roughness of drilled hole directly affects dimensional accuracy, assembly fit, and fatigue performance of the component. Poor surface roughness of drilled hole can compromise mechanical properties, including fatigue strength and wear resistance, when components are subjected to operational loads [4]. Surface roughness is strongly affected by machining parameters, including feed rate, spindle speed, and tool type. Among these, feed rate and spindle speed are known to have the most significant influence on surface roughness, with higher spindle speeds generally leading to smoother drilled surface [5]. A smaller surface roughness value indicates a smoother surface and commonly corresponds to the better functional performance of the component [6].

In addition to machining parameters, cutting fluids play a vital role in metal cutting operations by enhancing workpiece quality through effective lubrication and cooling at the tool and workpiece interface. Proper lubrication reduces friction, minimizes tool wear, and contributes to improved surface finish and overall machining performance. One widely adopted technique is Minimum Quantity Lubrication (MQL), which delivers a fine mist of cutting fluid mixed with compressed air directly to the cutting zone [7]. MQL offers a cost-effective and environmentally friendly alternative to conventional flood cooling methods, as it significantly reduces fluid consumption while maintaining efficient heat dissipation and lubrication [8].

To obtain the optimal parameter combination systematically, experimental approaches such as the Taguchi method are widely used. This method allows the analysis of the influence of each parameter on the output response with an efficient number of experiments, and is able to identify the most dominant factors that affect the quality of the results. The Taguchi method is very suitable for solving optimization problems. The Taguchi method is a robust statistical approach for designing experiments, utilizing orthogonal arrays to systematically evaluate the effects of multiple parameters and their interactions. A key feature of this method is the use of the signal-to-noise (S/N) ratio, which serves as an indicator for assessing the robustness and consistency of product performance under varying conditions. By analyzing experimental data, the Taguchi method enables the identification of optimal parameter combinations that are not only resistant to disturbances but also easy to implement and capable of delivering stable, reliable outcomes. Furthermore, by precisely defining parameter tolerance limits, this method helps achieve high product quality at minimal production cost, offering significant technical and economic advantages [9].

Given these considerations, a systematic experimental approach is essential to evaluate the influence of machining parameters on the quality of drilling on aluminum. The Taguchi method is adopted in this study due to its efficiency in identifying optimal parameter combinations through robust statistical analysis. Moreover, the research aligns with the principles of sustainable manufacturing by incorporating Minimum Quantity Lubrication (MQL), an environmentally friendly lubrication technique. Therefore, this study aims to optimize drilling parameters with a focus on surface roughness as the primary quality indicator, striving to enhance machining performance while supporting sustainable and high-quality production.

2. Materials and Method

The machining process was performed using a CNC Vertical Machining Center, specifically the Hartford S-Plus 10 model. The workpiece material used was aluminum 7000 series, namely Al7075. The dimensions of the workpiece material were 250 mm × 30 mm with a thickness of 20 mm. The cutting tool used was HSS twist drill with point angle 118°. Drilling operations were conducted under near-dry conditions utilizing Minimum Quantity Lubrication (MQL). The process parameters investigated included cutting fluid type, spindle speed, and feed, with their respective values and levels presented in Table 1. The response variable measured was the surface roughness of the drilled holes, evaluated using a Mitutoyo SJ-310 surface roughness tester. The experimental setup for the drilling process is illustrated in Figure 1.

Table 1. Drilling Parameters and Their Levels

Process Parameters	Unit	Symbol	Level 1	Level 2	Level 3
Cutting fluid type	-	A	Palm oil	Sunflower oil	-
Spindle speed	rpm	B	500	1500	2500
Feed rate	mm/rev	C	0.05	0.10	0.15

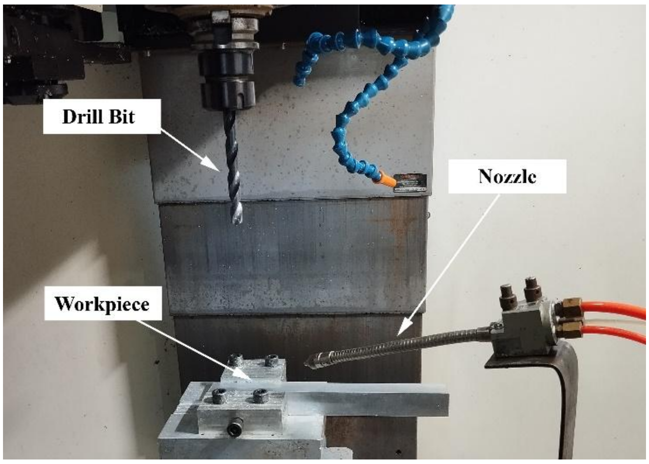

Figure 2. Experiment setup

Taguchi method is an experimental design method that is widely used in engineering analysis. This method provides a very efficient and systematic approach to determine optimal cutting parameters during production. This method significantly reduces the number of experiment and minimizes the impact of uncontrollable factors by using orthogonal arrays. This method calculates the deviation between the experimental value and the desired value using a loss function which is then converted into a signal to noise ratio (S/N). In general, there are three types of quality characteristics used in the S/N ratio analysis including the smaller the better, the larger the better, and the nominal the best [10].

The lower the value of the quality characteristic, the better the quality. The optimum surface roughness in the machining process is the smaller the surface roughness, the better the surface quality. The S/N value for the type of characteristic is the smaller the better according to Equation 1 [11].

$$S/N\ ratio = -10 \log \left[\sum_{i=1}^{n} \frac{{y_i}^2}{n} \right] \quad (1)$$

Experimental design based on Taguchi method with L18 orthogonal matrix. Table 2 shows the L18 orthogonal matrix with 18 experimental combinations.

Table 2. L18 Orthogonal Array

No	Cutting Fluid (A)	Spindle Speed (B)	Feed (C)
1	1	1	1
2	1	1	2
3	1	1	3
4	1	2	1
5	1	2	2
6	1	2	3
7	1	3	1
8	1	3	2
9	1	3	3
10	2	1	1
11	2	1	2
12	2	1	3
13	2	2	1
14	2	2	2
15	2	2	3
16	2	3	1
17	2	3	2
18	2	3	3

3. Result and Discussion

The experiment was designed using an L18 mixed-level Taguchi orthogonal array with three levels for selected parameters based on Table 1. This design configuration resulted in a total of 36 experimental data as illustrated in Figure 2, providing a comprehensive dataset for evaluating the influence of each parameter on the machining result.

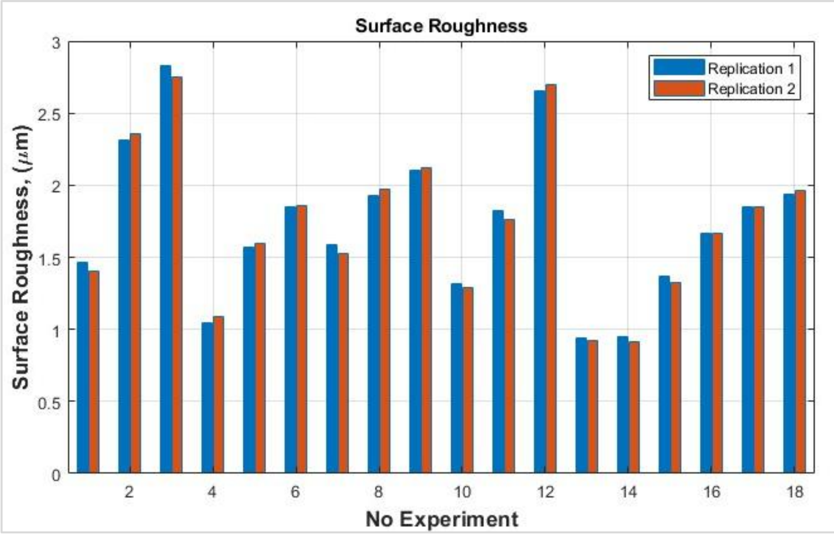

Figure 2. Experimental result

3.1 Analysis of Variance

Analysis of variance (ANOVA) at 95% confidence interval was performed to determine the effect of cutting process parameters on the response [9]. The results are tabulated in Table 3. A p-value of less than 0.05 indicates the significance (most influential) of the cutting process parameters. The ANOVA results revealed that the most influential cutting process parameters for the surface roughness (SR) profile were feed, followed by spindle speed. In contrast, the type of cutting fluid did not show a statistically significant effect. These findings are consistent with previous studies, which also reported that surface roughness is primarily influenced by feed rate and spindle speed [12]. Feed is a parameter that significantly affects surface roughness. Therefore, proper feed setting can improve the quality of the drilling hole [13].

Table 3. ANOVA for Surface Roughness

Parameter	DF	Adj SS	Adj MS	F-Value	P-Value
Cutting Fluid	1	0.2780	0.27804	4.32	0.060
Spindle Speed	2	1.9035	0.95177	14.78	0.001
Feed	2	1.8901	0.94505	14.67	0.001
Error	12	0.7730	0.06442		
Total	17	4.8447			

3.2 Response optimization based on Taguchi SN ratios

In the Taguchi method, data means and signal-to-noise (S/N) ratios are used to analyze how process parameters affect the result, such as surface roughness. The data mean shows the average outcome for each parameter level, helping to find out which settings give better results. However, it does not show how consistent those results are. The S/N ratio combines the average and the variation in the data to find the most stable and reliable settings. For surface roughness, where smaller values are better, the "smaller the better" formula is used. A higher S/N ratio means better quality with less variation, so it is useful for finding the best and most consistent parameter combination.

The measured surface roughness (SR) was analyzed using the Taguchi method based on the experimental design for each combination of process parameters. Optimization of the control factors was carried out using the signal-to-noise (S/N) ratio, which helps identify the most robust settings against variability. Since achieving lower surface roughness is critical for enhancing product quality and reducing manufacturing costs, the "smaller-is-better" criterion was applied in the S/N ratio calculation. The resulting S/N values for surface roughness are presented in Table 4.

The level that gives the optimum value is the combination A2B2C1. Similarly, the option where S/N gives the greatest response is also shown in Figure 3. Each point marked for each parameter in the graph indicates a different level. The highest value of the point on the graph indicates the level that meets the optimum condition [10].

Table 4. Response Table for S/N Ratio

Level	Cutting Fluid (A)	Spindle Speed (B)	Feed (C)
1	-5.055	-5.892	-2.284
2	-3.652	-1.882	-4.495
3		-5.286	-6.283
Delta	1.403	4.010	3.999
Rank	3	1	2

Table 5. Response Table for Data Means

Level	Cutting Fluid (A)	Spindle Speed (B)	Feed (C)
1	1.854	2.056	1.327
2	1.605	1.286	1.741
3		1.847	2.121
Delta	0.249	0.770	0.794
Rank	3	2	1

Table 5 shows the responses for the average values taken from the experimental results. The lowest value of surface roughness means good surface quality, the smallest response (the smaller the better) is selected. The lowest value for each individual parameter indicates the level that meets the optimum conditions as shown in Figure 3. In this result, it is clear that the optimum level is A2B2C1. From both results, it shows that the S/N ratio and the average data of the experimental results produce the same optimum level.

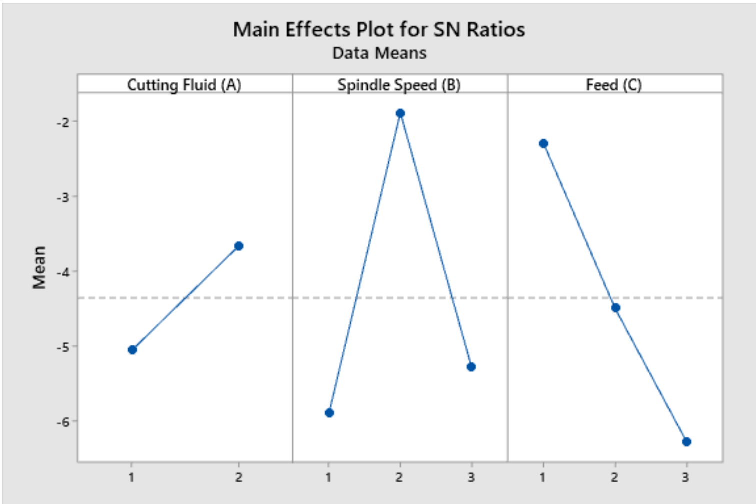

Figure 3. Main effect plot for S/N ratios

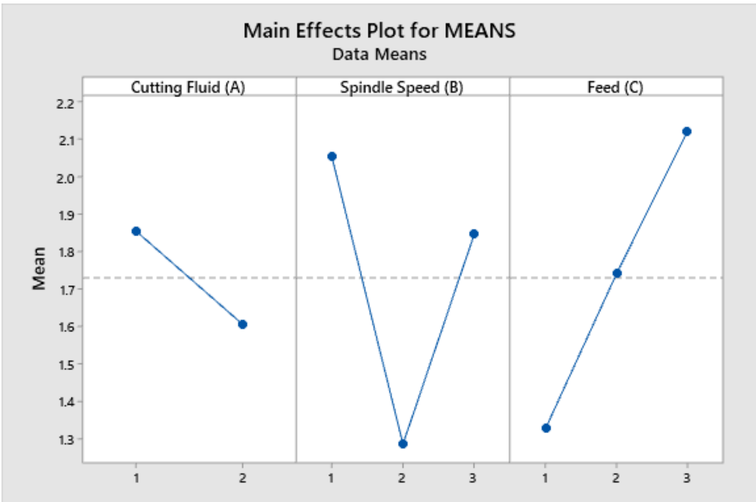

Figure 4. Main effect plot for data means

Figure 4 illustrates that lower surface roughness can be achieved by using a low feed rate. This occurs because a lower feed rate results in thinner chip formation, leading to reduced material deformation along the hole wall, which in turn improves surface finish [12, 14]. Additionally, increasing spindle speed enhances heat generation and transfer to the workpiece, which softens the material. This softening effect promotes the formation of more stable chips and reduces burr formation, thereby contributing to a smoother surface [15].

4. Conclusion

This experimental study was conducted to determine the optimal combination of process parameters for aluminum drilling using the Minimum Quantity Lubrication (MQL) technique, applying the Taguchi method as the analytical approach. The analysis showed that machining parameters such as spindle speed and feed significantly affect the surface roughness of the drilled holes, while cutting fluid type did not significantly affect the response. By using the Taguchi experimental design and signal-to-noise (S/N) ratio analysis, the best parameter combination was identified. The optimal setting consisted of a spindle speed of 1500 rpm, a feed rate of 0.05 mm/rev, and sunflower oil as the cutting fluid, which produced the lowest surface roughness.

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