

# Experimental Investigation of Aluminium Alloy-2024 during Drilling Operation

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**Abstract** — This research investigates the influence of cutting parameters (spindle speed, feed rate, and depth per pass) on the drilling performance of Al 2024 alloy using a Taguchi-based design of experiments (DOE) approach. The study focuses on three key responses: material removal rate (MRR), cylindricity, and surface roughness. Analysis revealed that feed rate exerted the most dominant influence on MRR, exhibiting a positive correlation with material removal. Lower values of all three cutting parameters have influential effect for achieving better cylindricity. For Surface roughness, higher depth per pass plays important role with higher spindle speed and moderate feed rate as contributing parameter. The study highlights the importance of considering the interactive effects of cutting parameters when selecting optimal combinations for specific drilling applications.

**Keywords:** CNC (Computer Numeric Control), MRR (Material Removal Rate), RPM (Revolution per Minute), SNR (Signal to Noise Ratio), Ra (Roughness Average)

## I. INTRODUCTION

Aluminum alloys have witnessed a surge in usage across various industries, including aerospace, automotive, marine, and electrical appliance manufacturing due to their high strength, ductility, and fatigue resistance. Within the aerospace sector, alloy Al2024 is widely employed for the fabrication of critical structural components like fuselage and wing skins. During this manufacturing process, drilling remains the most prevalent machining operation. However, achieving precise hole quality is paramount to prevent detrimental effects like edge cracks, high surface roughness, and misalignment with mating parts. These imperfections not only compromise structural integrity but also lead to increased production costs and material waste.

Several studies have focused on identifying the optimal drilling parameters to achieve the desired hole quality in Al2024. These investigations consistently reveal that a combination of lower cutting speed and feed rate yields superior results across various metrics, including hole size, surface roughness, roundness, and radial deviation [1]. Interestingly, research suggests that achieving a desired surface finish hinges primarily on the selection of cutting fluid and drill diameter, with cutting parameters playing a less significant role in aluminum machining[2]. Furthermore, it has been established that increasing spindle speed while maintaining a low feed rate results in elongated chips, ultimately compromising hole quality[3], [4].

Considering the significant impact of hole surface integrity on the final component's performance and quality, design of experiments (DOE) emerges as a powerful tool to systematically investigate the relationship between drilling parameters and this crucial aspect. By employing this statistically driven approach, researchers can gain valuable

insights into the complex interplay between various factors, paving the way for the development of optimized drilling strategies that ensure impeccable hole quality in Al2024 components.

## II. DESIGN OF EXPERIMENT

### A. Selection of Material:

The chosen material for this study is Aluminum 2024, a heat-treatable alloy known for its exceptional strength-to-weight ratio and superior fatigue resistance. This makes it highly suitable for applications demanding structural integrity and optimal performance under cyclic loading.

Key Properties:

- 1) Brinell hardness number: 120
- 2) Density: 2780 Kg/m<sup>3</sup>
- 3) Tensile strength: 460 MPa
- 4) Yield strength: 324 MPa
- 5) Modulus of Elasticity: 73.1 GPa

### B. Selection of Control Parameters:

The chosen drilling parameters were strategically determined based on the capabilities of the CNC machine and the inherent properties of the aluminum material. Spindle speed, feed rate, and depth per pass were identified as the key parameters influencing the characteristics of the drilled parts, namely cylindricity, surface roughness, and material removal rate. These parameters were carefully selected for investigation due to their significant impact on the drilling process outcomes. To ensure robust experimental findings, uncontrolled factors like tool wear were intentionally excluded from the study, allowing for focused analysis of the selected parameters' influence on the desired outcomes.

For HSS drill diameter of 10 mm

Spindle speed (RPM)	1592	1910	2229
Feed (mm/min)	3	3.6	4.2
Depth per pass(mm)	2	3	4

Table 1: Cutting parameters.

### C. Selection of Orthogonal Array:

To ensure efficient process optimization, the selection of experimental runs plays a crucial role. The Taguchi method provides a strategic approach to this selection through the use of recommended orthogonal arrays. In this study, considering three control parameters, we have opted for an L9 orthogonal array. This powerful tool allows us to conduct a comprehensive experimental analysis with just nine test runs, significantly reducing the number of required combinations compared to full factorial tests. This optimized approach not only streamlines the research process but also ensures statistically robust results while maintaining resource efficiency.

Hole No.	Spindle Speed (RPM)	Feed Rate (mm/min)	Depth per pass (mm)
1	1592	3	2
2	1592	3.6	3
3	1592	4.2	4
4	1910	3	3
5	1910	3.6	4
6	1910	4.2	2
7	2229	3	4
8	2229	3.6	2
9	2229	4.2	3

Table 2: Orthogonal array

### III. EXPERIMENTAL WORK

This study employed a CNC mill trainer machine equipped with a PC-based controller for drilling experiments. The workpiece material was an 80mm x 80mm x 25mm block of Al2024 alloy. A 10mm diameter HSS twist drill bit was utilized for the drilling process. To minimize tool wear and improve overall machining performance, coolant was employed instead of dry drilling. Utilizing CNC programming, nine equidistant through-holes with a diameter of 10mm were created in the workpiece.



Fig. 1: CNC machine

Following the drilling operation, the workpiece was subjected to rigorous dimensional analysis using a coordinate measuring machine (CMM). This highly precise instrument enabled the accurate measurement of both cylindricity and mean diameter for each of the drilled holes. Notably, the CMM stylus meticulously probed multiple points within each hole to capture the crucial geometric details and assess cylindricity, which reflects the deviation from a perfect cylindrical form. This comprehensive approach ensured a thorough evaluation of the drilling process outcomes.



Fig. 2: CMM

In high-wear applications, surface roughness plays a vital role in determining component performance and longevity. To evaluate this crucial parameter, a portable Mitutoyo surface roughness tester was utilized. This instrument offers the capability of generating roughness values in various formats, including Ra, Rq, and Rz. For this study, we primarily focused on the Ra value due to its widespread adoption and relevance in industrial manufacturing processes to characterize surface finish.



Fig. 3: Surface roughness tester

### IV. OBSERVATIONS

Following the successful implementation of the workpiece for drilling operations, a comprehensive analysis was conducted encompassing hole geometry evaluation and surface roughness assessment. Observation as follows:

Hole No.	Mean Diameter(mm)	Cylindricity
1	10.3361	0.1571
2	10.2403	0.099
3	10.1929	0.0661
4	10.1352	0.0849
5	10.184	0.0562
6	10.2645	0.1269
7	10.1738	0.1181
8	10.1694	0.0505
9	10.1581	0.0857

Table 3: Dimension of holes

Hole No.	Ra	Rq	Rz
1	6.06	7.616	27.661
4	5.573	6.72	27.221
7	7.133	8.98	36.444
2	3.252	4.32	20.485
5	8.838	10.899	44.383
8	8.088	11.016	45.33
3	9.964	11.342	43.902
6	8.16	10.263	46.709
9	6.481	8.621	38.294

Table 4: Surface roughness value in microns

### V. RESULTS AND DISCUSSION

#### A. Material Removal Rate (MRR)

The Material Removal Rate (MRR) in drilling process is the volume of workpiece material removed by the drill bit per unit time while fabricating hole. In this experimental work actual material is not measured in volume and only calculated

with theoretical formula. So, for a drill diameter D, the cross-sectional area of the drilled hole is  $A = (\pi D^2/4)$  in  $\text{mm}^2$  and f is the feed that has introduced while drilling in  $\text{mm}/\text{min}$ .

The material removal rate is calculated by product of area of hole and feed rate (f). Thus,

$$\text{MRR} = ((\pi D^2)/4) * (f) \text{ (mm}^3/\text{min)}$$

For 10 mm of hole diameter with 3 different feed rates, MRR is calculated as below.

Hole No.	Spindle Speed (RPM)	Feed Rate (mm/min)	Depth per pass (mm)	MRR (mm <sup>3</sup> /min)
1	1592	3	2	236
2	1592	3.6	3	283
3	1592	4.2	4	330
4	1910	3	3	236
5	1910	3.6	4	283
6	1910	4.2	2	330
7	2229	3	4	236
8	2229	3.6	2	283
9	2229	4.2	3	330

Table 5: MRR

Hole No.	Spindle Speed (RPM)	Feed Rate (mm/min)	Cylindricity	Ra (mm)
1	1592	3	0.1571	0.0061
4	1592	3.6	0.099	0.0056
7	1592	4.2	0.0661	0.0071
2	1910	3	0.0849	0.0033
5	1910	3.6	0.0562	0.0088
8	1910	4.2	0.1269	0.0081
3	2229	3	0.1181	0.0100
6	2229	3.6	0.0505	0.0082
9	2229	4.2	0.0857	0.0065

Table 6: Cylindricity and Ra value

For understanding results in constructive format taguchi based used. This approach helps identify factors that contribute most to variation and prioritize their optimization. It uses signal to noise ratios to quantify the desired outcome (signal) against undesirable variations (noise).

Taguchi Analysis for MRR versus Spindle Speed, Feed Rate, Depth per pass:

Level	Spindle Speed	Feed Rate	Depth per pass
1	48.94	47.44	48.94
2	48.94	49.02	48.94
3	48.94	50.36	48.94
Delta	0.00	2.92	0.00
Rank	2.5	1	2.5

Table 7: Response table for signal to noise ratios for MRR  
Aim: Larger is better.

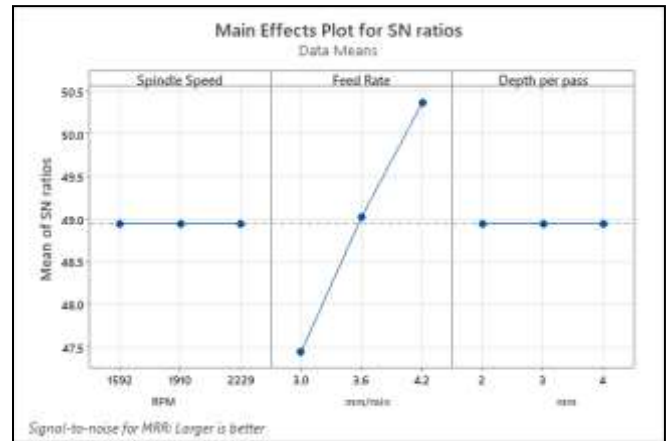


Fig. 4: SNR for MRR

With reference to the main effects plot for the signal-to-noise (SN) ratios, presented in figure 4 and table no. 5 indicates that feed rate exerts a prominent effect on MRR. This aligns with expectations, as higher feed rate directly translate to higher chip removal rates. Spindle speed and depth per pass ranges not induced substantial variations in chip formation and shear mechanics, potentially masking their individual effects on MRR as feed rate is main driving force for extracting material.

Taguchi Analysis for Cylindricity versus Spindle Speed, Feed Rate, Depth per pass:

Level	Spindle Speed	Feed Rate	Depth per pass
1	19.92	18.68	19.98
2	21.45	23.68	20.95
3	21.94	20.96	22.39
Delta	2.02	4.99	2.40
Rank	3	1	2

Table 8: Response table for signal to noise ratios of cylindricity  
Aim: Smaller is better.

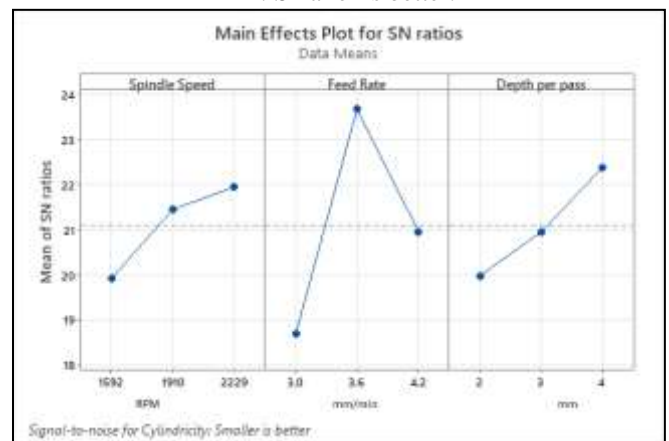


Fig. 5: SNR for Cylindricity

The main effects plot for the signal-to-noise (SN) ratios, presented in figure 5, indicates that lower parameter values of spindle speeds, feed rate and depths per pass are associated with better cylindricity (smaller SN ratio). This aligns with expectations, in which the feed rate is the most influential parameter, as at a lower feed rate, the tool moves slowly towards the workpiece, which gives more stability, and lower depths per pass allow for better tool guidance and ranking second to achieving a lower cylindricity value. Also,

lower spindle speeds generally reduce cutting forces and vibrations, leading to improved hole roundness.

Taguchi Analysis for Surface roughness versus Spindle Speed, Feed Rate, Depth per pass:

Level	Spindle Speed	Feed Rate	Depth per pass
1	44.12	44.71	42.65
2	44.22	42.64	46.20
3	41.85	42.85	41.35
Delta	2.37	2.07	4.85
Rank	2	3	1

Table No: 9 Response table for signal to noise ratios of surface roughness  
Aim: Smaller is better.

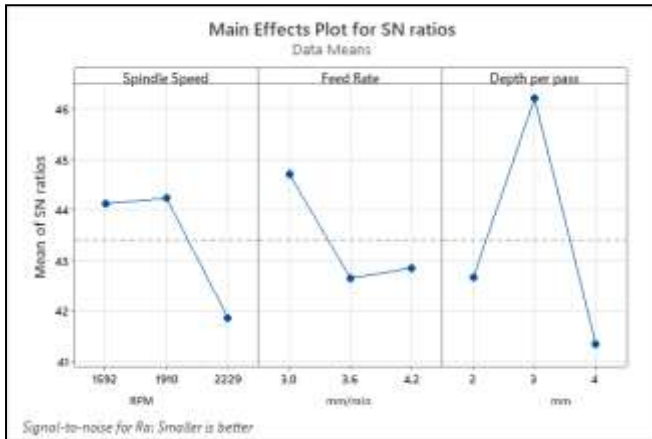


Fig. 6: SNR for Surface Value

The main effects plot for the signal-to-noise (SN) ratios, presented in figure 6, reveals that depth per pass exhibits the most prominent effect to achieve better surface finish. Increased depth per pass enhances tool rigidity and reduces tool deflection, particularly at higher depths. This improved stability minimizes tool chatter and vibrations. At higher speeds, the chip formation process becomes more shearing, generating smaller and less adherent chips. This reduces the tendency for built up edge, which can leave deposits on the hole wall and contribute to roughness. While higher feed rates remove material more quickly, they can also induce ploughing and tearing effects, leading to rougher surfaces. Conversely, excessively low feed rates might result in built-up edge and higher tool wear, also deteriorating surface quality. A moderate feed rate balances these competing factors, promoting shearing action and smoother chip formation and becomes an influential factor to good surface finish.

## VI. CONCLUSION

Feed rate had the most significant impact on MRR, with higher feed rates leading to higher MRR. The study shows spindle speed and depth per pass do not significantly affect MRR within the investigated range, suggesting potential opportunities for process optimization in terms of energy consumption and tool wear.

All three parameters influenced cylindricity, with lower values of spindle speed, feed rate, and depth per pass leading to better cylindricity. Feed rate was the most dominant factor, followed by depth per pass and spindle speed.

Increased depth per pass enhances tool rigidity and reduces deflection, minimizing vibrations and contributing prominently towards a smoother surface. Higher spindle speeds promote shearing chip formation, reducing built-up edge and contributing to smoother surfaces. A moderate feed rate balances chip formation and tool wear, achieving a good surface finish.

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