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Taguchi-Based Optimization of Drilling Parameters for Minimizing Burr Height and Surface Roughness in Dry Drilling of Al-6063 Aluminum Alloy

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Abstract

Hole quality is a critical factor affecting the dimensional accuracy, structural integrity, and service performance of machined components. This study experimentally investigates the influence of cutting speed and feed rate on surface roughness, entry burr height, and exit burr height during the dry drilling of Al-6063 aluminum alloy using a high-speed steel (HSS) twist drill. A Taguchi L9 orthogonal array was employed to design the experiments, while signal-to-noise (S/N) ratio analysis was used to evaluate the significance of the machining parameters and identify the optimum drilling conditions. Drilling experiments were conducted at three cutting speeds (700, 880, and 1400 rpm) and three feed rates (0.10, 0.20, and 0.30 mm/rev) under dry machining conditions. The experimental results revealed that both cutting speed and feed rate significantly influence hole quality. Surface roughness increased with increasing cutting speed and feed rate, with cutting speed identified as the most influential parameter. Feed rate was found to be the dominant factor affecting both entry and exit burr heights. The poorest drilling performance occurred at the highest cutting speed (1400 rpm) and feed rate (0.30 mm/rev), producing the maximum surface roughness (2.818 µm), entry burr height (2.446 mm), and exit burr height (2.425 mm). Conversely, the combination of a low cutting speed (700 rpm) and a low feed rate (0.10 mm/rev) yielded the best overall hole quality with minimum burr formation and superior surface finish. The optimized machining conditions identified in this study can improve product quality, reduce deburring operations, and support environmentally sustainable dry drilling of Al-6063 aluminum alloy.

Keywords: *Dry drilling; Al-6063 aluminium alloy; Surface roughness; Burr height; Taguchi method; (S/N) ratio; Machining parameter optimization.*

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1.INTRODUCTION

Aluminium 6063 (AA6063) alloy is widely acknowledged across the manufacturing sector for its exceptional engineering properties, including a superior surface finish, an outstanding strength-to-weight ratio, and highly corrosion resistance. Due to this unique combination of characteristics, the alloy is extensively utilized in architectural components, structural frameworks, automotive panels, and heat sinks [1-7]. Within the context of industrial fabrication, drilling stands as one of the most fundamental, economical, and frequently deployed hole-making techniques, accounting for approximately 30% of all metal-cutting operations [1,8]. The final quality of a drilled hole assists as a direct precursor for reliable and secure component assembly, directly determining structural integrity, fatigue strength, and the operational service life of engineered structures [1,9]. Poor hole properties generate additional, non-value-added secondary manufacturing steps such as burr removal, reaming, or boring, which significantly increase production costs and lead times [1]. Therefore, systematically optimizing drilling parameters to achieve superior hole geometric and surface qualities remains a critical challenge for industrial efficiency.

Among the various metrics defining hole quality, surface roughness (Ra) and exit burr height are two crucial parameters of concern. Surface roughness dramatically alters the tribological performance and fatigue resistance of components [5]. Meanwhile, burr formation which occurs due to severe plastic deformation at the exit plane when the drill bit penetrates the material leads to stress concentrations, dimensional divergences, and structural hazards during assembly [9]. Research indicates that the mechanical behavior of the material during drilling is heavily dictated by process variables like cutting speed and feed rate, which influence the uncut chip thickness, tool wear, and material removal rates [1,2]. Elevated temperatures and cutting forces generated during machining worsen tool wear, promote built-up edge (BUE) formation, and thermally effect the workpiece, leading to poor surface finishes and severe dimensional deviation [2,3,9].

To ease these adverse effects, standard industry practices historically depended on the extensive application of flooded coolant systems [2]. However, traditional cutting fluids introduce severe ecological, economic, and occupational health concerns [2]. While alternative cooling techniques such as minimal quantity lubrication (MQL), nanofluid MQL, and cryogenic pre-cooling using dry ice or liquid nitrogen have shown promise in reducing cutting temperatures and improving hole accuracy, dry drilling represents the ultimate target for sustainable manufacturing [1,2,4,5]. Dry drilling minimizes fluid consumption costs, eliminates chemical disposal hazards, and avoids environmental pollution [2,8]. However, the total absence of coolants and lubricants places a severe thermal load on both the tool and the workpiece. In dry drilling configurations, achieving acceptable surface finishes and minimizing exit burr formation relies entirely on selecting the absolute optimal combination of cutting parameters [8].

Investigating multi variable machining parameters using conventional full factorial experimental designs demands a massive investment of time, costs, and materials. To overcome this operational constraint, Genichi Taguchi developed a robust design methodology that employs orthogonal arrays to systematically analyze the effects of entire parameter spans using a significantly reduced number of experiments [8]. The Taguchi method optimizes multi-response quality metrics by translating experimental results into Signal-to-Noise (S/N) ratios to isolate the statistical significance and percentage contribution of each control variable [8]. While various researchers have applied modern cutting techniques, novel tool coatings (such as titanium nitride or chromium nitride), and specialized optimization routines to explore the machinability of aluminium alloys [6,7,8], a focused investigation evaluating parameter interactions specifically targeting both burr height and surface roughness concurrently in the dry drilling of AA6063 alloy requires further academic attention.

Accordingly, this study implements a Taguchi-based optimization framework to identify the optimal drilling parameters (cutting speed and feed rate) required to simultaneously minimize entry and exit burr height and surface roughness in the dry drilling of Al-6063 aluminum alloy. Through severe orthogonal matrix experimentation, signal-to-noise ratio analysis, this paper isolates the primary factors driving hole quality degradation. Finally, this work offers specific machining guidelines for manufacturing facilities looking to maximize dimensional integrity and structural reliability without relying on external cooling fluids.

2.MATERIAL, CUTTING CONDITION, AND PLAN OF EXPERIMENTS

Burr height and the surface roughness of the drilled hole surface were determined by cutting condition. The drilling experiments were conducted in dry cutting conditions on a heavy-duty pillar drilling machine type IXION BS 30 AV. In this study, Al-6063 aluminum alloy was chosen as the work materials with the specimen dimensions 15 mm × 15 mm × 10 mm for each test. The chemical composition of the Aluminum alloy Al-6063 is shown in the table 1 and the mechanical properties of the Al-3036 aluminum alloy are presented in Table 2.

Table 1: The chemical composition of the Aluminum alloy 6063 [1].

Al %	**Mg %**	**Si %**	**Fe %**	**Cu %**	**Mn %**	**Zn %**	**Ti %**
98.32-98.80	0.44 - 0.58	0.43 - 0.50	0.28 - 0.35	.0017-0.0650	.0017-.08	.0017-.035	.017-0.35

Table 2: The mechanical properties for the aluminum alloy 6063 [7].

Properties	**Value**	**Unit**
Ultimate Tensile Strength	250	N/mm^2
0.2 % Proof Stress	160	N/mm^2
Hardness (Brinell)	65	BHN
Elongation on 50 mm	8	%
Density	2.7	g/cm2
Melting Range	500-600	C^0
Modulus Of Elasticity	67000	N/mm^2

Conventional, high-speed-steel twist drills with diameters of 6 mm type (HSS drill bit DIN338 – TAC110601) was used for drilling experiment as shown in table 3. A new drill bit was used for each drilling experiment. The burr heights (H) and surface roughness (Ra, the arithmetic average) of each drilled hole were measured by means of an optical microscope type (Mitutoyo Toolmaker's TM – Generation B series), and a Mitutoyo SJ-210 surface roughness tester using a meter cut off of 5 mm and measured speed of 0.25 mm/s.

Table 3: The specifications of drilling tool used.

Code	**Flute diameter**	**Flute length**	**Shank diameter**	**Overall length**	**Point angle**
M2 - DIN338 – TAC110601	6.0 mm	57 mm	6.0 mm	93 mm	135^o

The entry and exit burr height and surface roughness were measured from three different points and then the mean was taken. The drilling experiments were planned using Taguchi's orthogonal array L9. Three levels of each control factor were taken. The considered experimental factors and their levels are listed in Table 4.

Table 4: Cutting parameters and their levels were used in experimental work.

Factor	**Machining Parameter**	**Level 1**	**Level 2**	**Level 3**
N	Cutting Speed (RPM)	700	880	1400
f	Feed Rate (mm/rev)	0.10	0.20	0.30

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3.EXPERIMENTAL RESULTS AND ANALYSIS

The experimental results obtained from the experiments related to burr height and surface roughness are illustrated in Table 5.

Table 5: Experimental results obtained of surface roughness(µm), burr height (mm).

Cutting speed	Feed rate	Surface roughness	Entry burr height	Exit burr height
RPM	**mm/rev**	**µm**	**mm**	**mm**
700	0.1	1.898	1.083	1.386
700	0.2	2.215	1.323	1.812
700	0.3	2.313	2.022	2.358
880	0.1	2.139	1.353	1.604
880	0.2	2.419	1.882	2.104
880	0.3	2.741	1.986	2.391
1400	0.1	2.527	1.568	1.723
1400	0.2	2.453	2.055	2.317
1400	0.3	2.818	2.446	2.425

Figure 1 illustrates the experimental variation of surface roughness (Ra, measured in micrometers, µm) as a function of the two machining parameters: cutting speed (N, evaluated at 700, 880, and 1400 rpm) and feed rate (f, evaluated at 0.1, 0.2, and 0.3 mm/rev). A consistent, direct relationship is observed between the feed rate and the resulting surface roughness across nearly all tested cutting speeds. At a low cutting speed (700 rpm), increasing the feed rate from 0.1 mm/rev to 0.3 mm/rev elevates the surface roughness from approximately 1.898 µm to 2.313 µm. This smooth upward trend is replicated at the intermediate speed (880 rpm), where Ra increases from 2.139 µm to its localized peak of approximately 2.741 µm. At the highest cutting speed (1400 rpm), the highest feed rate of 0.3 mm/rev yields the maximum overall surface roughness recorded in this study, reaching approximately 2.818 µm.

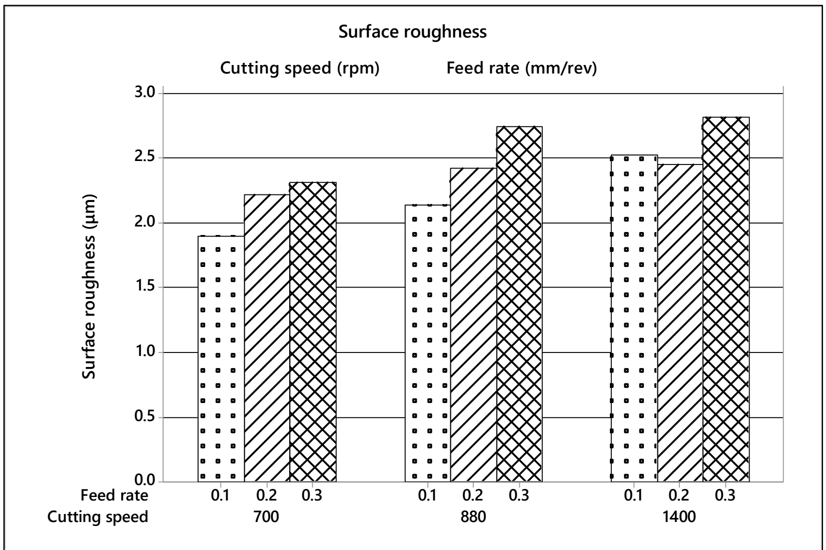

Figure 1: Variation of surface roughness (R_a) with cutting speeds at different feed rates.

The influence of cutting speed reveals a progressive deterioration of surface quality as velocity increases. When fixing the feed rate at 0.1 mm/rev, an increase in cutting speed from 700 rpm to 1400 rpm forces an upward shift in surface roughness from 1.898 µm to 2.527 µm. A subtle anomaly or plateauing behavior occurs at 1400 rpm between the 0.1 mm/rev and 0.2 mm/rev feed rates, where Ra marginally drops from 2.527 µm to roughly 2.453 µm before resuming its upward trajectory at 0.3 mm/rev.

Typically, higher cutting speeds (1400 rpm) induce elevated temperatures within the primary and secondary shear zones. While thermal softening can sometimes facilitate plastic deformation and improve surface finish in highly ductile materials, in this specific situation, the increase of speed to 1400 rpm strictly increases the surface roughness. This is highly indicative of enhanced tool wear mechanisms (such as flank wear or chipping) or high-frequency machine tool vibrations (chatter) operating at elevated rotational speeds. The rapid degradation of the cutting edge profile directly transfers its irregularities onto the workpiece surface, compromising the surface integrity. The slight fluctuation observed at 1400 rpm between 0.1 and 0.2 mm/rev may be attributed to the suppression or shifting of a Built-Up Edge (BUE). At specific critical speed-to-feed ratios, the temperature and pressure are sufficient to prevent workpiece material from welding to the rake face, offering a localized, minor stabilization in surface quality before the dominant geometric feed effect takes over at 0.3 mm/rev.

The Taguchi's technique applies the signal-to-noise ratio (S/N ratio) to calculate the characteristic value deviate from the desired value. A signal to noise (S/N) ratio is used to characterize the control parameter that minimizes the effect of noise on the response. A smaller value reflects a better property type of the S/N ratio, which was used in this analysis.

Table 6 shows the ranks of the parameters resulted by S/N ratio analysis for the different parameter levels for the surface roughness. The most significant parameter affecting the surface roughness was the cutting speed, followed by the feed rate.

Table 6. S/N ratio response table (smaller is better) of surface roughness.

	Control factors	
Level	**Cutting speed (RPM)**	**Feed rate (mm/rev)**
1	-6.586	-6.741
2	-7.678	-7.458
3	-8.282	-8.347
Delta	1.696	1.606
Rank	1	2

Figure 2 shows the experimental variation of entry burr height (measured in millimeters, mm) as a function of two cutting parameters: cutting speed (N, evaluated at 700, 880, and 1400 rpm) and feed rate (f, evaluated at 0.1, 0.2, and 0.3 mm/rev). A highly steady, monotonic upward trend is observed between the feed rate and entry burr height across all tested cutting speed levels. At a cutting speed of 700 rpm, elevating the feed rate from 0.1 mm/rev to 0.3 mm/rev causes the entry burr height to increase from approximately 1.083 mm to 2.022 mm. At the intermediate speed of 880 rpm, a sharp increase is noted when shifting from 0.1 mm/rev (1.353 mm) to 0.2 mm/rev (1.882 mm), followed by a more gradual rise to 1.986 mm at 0.3 mm/rev.

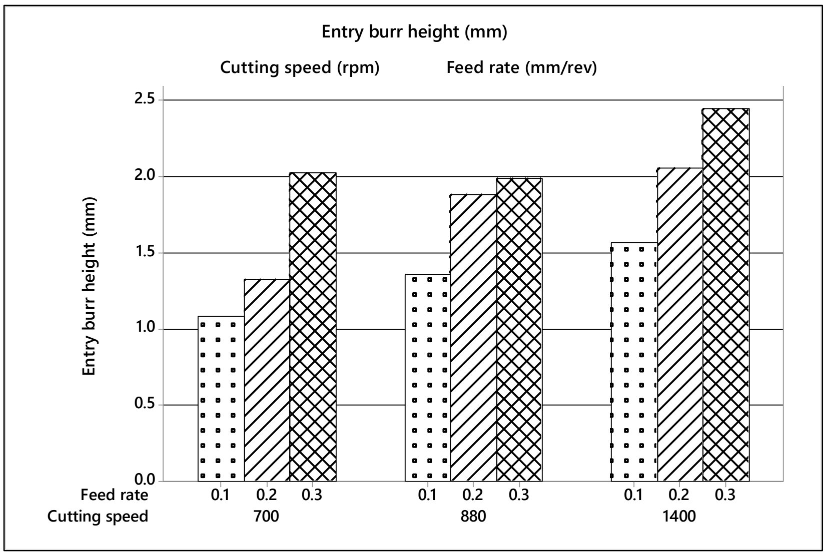

Figure 2: Variation of entry burr height (H) with cutting speeds at different feed rates.

At the maximum tested cutting speed of 1400 rpm, the burr height continuously climbs from 1.568 mm at the lowest feed rate to its overall maximum experimental value of approximately 2.446 mm at the highest feed rate (0.3 mm/rev).

The influence of cutting speed generally acts as an amplifying factor for burr formation, shifting the entire baseline of burr height upward as rotational velocity increases. When keeping the feed rate constant at a low value of 0.1 mm/rev, increasing the cutting speed from 700 to 1400 rpm forces a clear upward shift in burr height from 1.083 mm to 1.568 mm. A minor localized exception to this trend occurs at a feed rate of 0.2 mm/rev, where the burr height slightly drops from 1.882 mm at 880 rpm to 2.055 mm at 1400 rpm, representing a relative plateau compared to the sharper jump observed at 700 rpm (1.323 mm). Ultimately, the interaction of the highest cutting speed (1400 rpm) and the highest feed rate (0.3 mm/rev) produces the most unfavorable condition for burr minimization.

The progressive generation of larger entry burrs under elevated cutting speeds and feed rates can be explained by the following plastic deformation and thermo-mechanical mechanisms: Entry burring (often associated with the initial tool-workpiece engagement or plastic rollover at the edge) is heavily driven by the magnitude of the cutting forces and plastic zone size. As the feed rate increases from 0.1 to 0.3 mm/rev, the uncut chip thickness increases proportionally. This larger chip load scales up the total cutting force components, forcing a larger volume of material at the tool entry edge to undergo severe lateral plastic flow rather than clean shearing, thereby expanding the resultant burr dimension. Raising the cutting speed to 1400 rpm extremely increases the adiabatic shear heating localized within the primary deformation zone. The extreme heat generated induces a thermal softening effect in the workpiece material, lowering its yield strength and increasing its localized plastic ductility. Consequently, as the tool strikes the entry face, the highly ductile material easily flows and rolls over the edge instead of fracturing cleanly into chips, magnifying the final entry burr height.

The rapid increase in burr dimensions at high-speed, high-feed combinations is typically a classic signature of accelerated mechanical tool wear or localized micro-chipping at the tool nose radius. A degraded or dulled tool edge loses its keen shearing efficiency, converting the cutting action into a plowing and rubbing mechanism. This plowing action pushes material outward and upward at the point of entry, creating a more pronounced macroscopic burr.

Table 7 shows the ranks of the parameters resulted by S/N ratio analysis for the different parameter levels for the entry burr height. The most significant parameter affecting the entry burr height was the feed rate, followed by the cutting speed.

Table 7. S/N ratio response table (smaller is better) of entry burr height.

	Control factors	
Level	**Cutting speed (RPM)**	**Feed rate (mm/rev)**
1	-3.080	-2.408
2	-4.693	-4.727
3	-5.977	-6.615
Delta	2.898	4.206
Rank	2	1

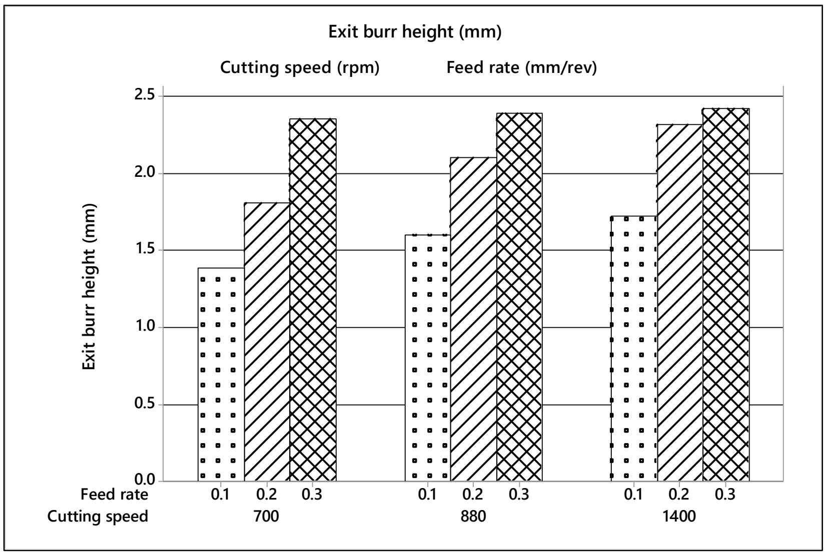

Figure 3: Variation of exit burr height (H) with cutting speeds at different feed rates.

Figure 3 illustrates the experimental variation of exit burr height as a function of cutting speed (N, evaluated at 700, 880, and 1400 rpm) and feed rate (f, evaluated at 0.1, 0.2, and 0.3 mm/rev). A consistent, prominent direct correlation exists between the feed rate and the magnitude of the exit burr height across all investigated cutting speeds. At the lowest cutting speed (700 rpm), increasing the feed rate from 0.1 mm/rev to 0.3 mm/rev expands the exit burr height from approximately 1.386 mm to 2.358 mm. A nearly identical monotonic behavior is replicated at the intermediate speed (880 rpm), where the exit burr height escalates rapidly from 1.604 mm to a localized maximum of 2.391 mm. At the highest velocity parameter (1400 rpm), the exit burr height exhibits a corresponding rise, climbing from 1.723 mm (f = 0.1 mm/rev) to its absolute experimental peak of approximately 2.425 mm at f = 0.3 mm/rev.

The influence of cutting speed functions as an incremental controller of exit burr formation, primarily impacting the low-to-medium feed rate, when evaluating the drilling at a low feed rate (0.1 mm/rev), transitioning the speed from 700 rpm to 1400 rpm elevates the baseline burr height from 1.386 mm to 1.723 mm. Similarly, at an intermediate feed rate (0.2 mm/rev), the burr height exhibits a clear upward shift from 1.812 mm (700 rpm) to 2.104 mm (880 rpm), which then levels off marginally to 2.317 mm at 1400 rpm. Notably, at the highest feed rate (0.3 mm/rev), the system approaches a structural saturation plateau; the exit burr dimensions remain consistently critical across all speeds, converging between 2.358 mm and 2.425 mm.

Unlike entry burrs, exit burrs form as the cutting tool approaches the end of the workpiece cut. As the tool exits the part, the structural support of the remaining material drops rapidly. This induces a pivot action known as the "foot-burr" mechanism. An increase in feed rate (0.1 to 0.3 mm/rev) scales up the uncut chip thickness, increasing the axial thrust force component. This severe mechanical stress overcomes the plastic shear strength of the final edge before a clean chip separation can occur, forcing a larger volume of material to undergo plastic rollover at the exit terminal.

The increase in cutting speed to 1400 rpm heavily accelerates heat generation in the secondary shear zone. The resulting high localized temperatures lower the yield strength of the workpiece material via thermal softening. As the material becomes more ductile, it exhibits prolonged plastic deformation paths rather than brittle fracture. Consequently, when the tool edge sweeps past the exit boundary, the softened material undergoes severe stretching and plastic tearing, yielding taller macroscopic burr profiles.

Table 8 shows the ranks of the parameters resulted by S/N ratio analysis for the different parameter levels for the entry burr height. The most significant parameter affecting the exit burr height was the feed rate, followed by the cutting speed.

Table 8. S/N ratio response table (smaller is better) of exit burr height.

	Control factors	
Level	**Cutting speed (RPM)**	**Feed rate (mm/rev)**
1	-5.150	-3.888
2	-6.046	-6.308
3	-6.573	-7.572
Delta	1.423	3.684
Rank	2	1

The worst-case situation, the interaction of the maximum tested cutting speed (1400 rpm) and maximum feed rate (0.3 mm/rev) consistently marks the peak of structural degradation across all charts, producing the highest surface roughness (2.818 µm), maximum entry burr height (2.446 mm), and maximum exit burr height (2.425 mm). The Exit burr saturation Plateau, Interestingly, while entry burrs and surface roughness show localized fluctuations or continuous scaling at high speeds, the exit burr height reaches a structural saturation point at 0.3 mm/rev. At this severe chip load, the burr height converges between 2.358 mm and 2.425 mm regardless of the cutting speed, indicating that the material's physical limit for plastic deformation before tearing has been fully reached.

For manufacturing optimization, the data presents a clear trade-off: while high-speed, high-feed machining maximizes the material removal rate (MRR) and production efficiency, it significantly penalizes the surface integrity and edge quality of the component. To minimize post-processing deburring stages and maintain stringent surface tolerances, a low feed rate (0.1 mm/rev) paired with a low-to-moderate cutting speed (700 - 880 rpm) represents the optimal window for this specific tool-workpiece combination.

4.CONCLUSIONS

This study investigated the influence of cutting speed and feed rate on surface roughness, entry burr height, and exit burr height during the dry drilling of Al-6063 aluminum alloy using an HSS twist drill. The Taguchi design methodology was successfully employed to evaluate the significance of the machining parameters and to identify the optimal drilling conditions. Based on the experimental results, the following conclusions can be drawn:

1. Both cutting speed and feed rate significantly affected the drilling quality; however, their influence depended on the response considered.
2. Surface roughness increased with increasing cutting speed and feed rate. According to the Taguchi S/N ratio analysis, cutting speed was identified as the most influential parameter affecting surface roughness, while feed rate ranked second.
3. Feed rate was the dominant factor governing both entry and exit burr formation. Increasing the feed rate from 0.10 to 0.30 mm/rev produced a substantial increase in burr height due to the higher chip load and greater plastic deformation during drilling.
4. The lowest values of surface roughness, entry burr height, and exit burr height were obtained at the lowest machining conditions (700 rpm and 0.10 mm/rev), indicating that lower cutting parameters provide superior hole quality under dry drilling conditions.
5. The combination of the highest cutting speed (1400 rpm) and highest feed rate (0.30 mm/rev) produced the poorest machining performance, yielding the maximum surface roughness (2.818 μm), entry burr height (2.446 mm), and exit burr height (2.425 mm). These results indicate that aggressive machining conditions substantially deteriorate hole quality.
6. For dry drilling of Al-6063 aluminum alloy with an uncoated HSS drill, a low feed rate (0.10 mm/rev) combined with a low-to-moderate cutting speed (700–880 rpm) is recommended to achieve improved surface integrity, reduced burr formation, and lower post-processing requirements.

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