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Analysis of Hole Quality and Chips Formation in the Dry Drilling Process of Al7075-T6

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Abstract: Millions of holes are produced in many industries where efficient drilling is considered the key factor in their success. High-quality holes are possible with the proper selection of drilling process parameters, appropriate tools, and machine setup. This paper deals with the effects of drilling parameters such as spindle speed and feed rate on the chips analysis and the hole quality like surface roughness, hole size, circularity, and burr formation. Al7075-T6 alloy, commonly used in the aerospace industry, was used for the drilling process, and the dry drilling experiments were performed using high-speed steel drill bits. Results have shown that surface roughness decreased with the increase in spindle speed and increased with the increase in the feed rate. The hole size increased with the high spindle speed, whereas the impact of spindle speed on circularity error was found insignificant. Furthermore, short and segmented chips were achieved at a high feed rate and low spindle speed. The percentage contribution of each input parameter on the output drilling parameters was evaluated using analysis of variance (ANOVA).

Keywords: drilling; Al7075-T6; surface roughness; hole size; circularity; burrs; chips analysis

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1. Introduction

Drilling is a manufacturing process that is extensively used in many industries such as in the automotive and aerospace industries, where a considerable number of holes are needed for assembly operation [1,2]. The common problems associated with the drilling process include the high surface finish, high circularity error, deviation of the holes from the nominal size, and burr formation around the hole edges [3–5]. Therefore, improper drilling parameters, low hole quality, and rapid tool wear may lead to part rejection, which increases the total manufacturing cost and time [6,7].

Aluminium and its alloys have many applications in different manufacturing industries due to their excellent mechanical properties [8,9]. Al7075-T6 is one of the aluminium alloys used for manufacturing aircraft engines, fuselage, aircraft structure, aircraft skin, and internal supporting parts [10]. Various analytical and experimental approaches were previously applied to improve the drilling process on aluminium alloys. Table 1 shows some of the previous studies on aluminium alloys.

Table 1. Previous studies on drilling of aluminium alloys.

Alloy Type	Cutting Parameters	Cutting Tool	Output Parameters	Ref
Al7075	V_c = 22, 44, 66 (m/min) f = 0.15 (mm/min). Condition = Dry and conventional cutting fluid	HSS D = 6 mm θ = 118°	*Ra*, *C*, *W*	[11]
Al7075	V_c = 25 (m/min) f = 50 (mm/min) Condition = Dry	HSS-Ti HSS-Co HSS-Mo D = 7 mm θ = 123°, 137°, 114° ψ = 65°	*Ra*, F_z	[12]
Al7075	n = 910, 1420, 2000 (rpm) f = 0.06, 0.08, 0.10 (mm/rev) Condition = Dry	HSS D = 5 mm θ = 118°, 126°, 135°	*Ra*, *Z*	[13]
Al7075	f = 0.05, 0.1, 0.15 (mm/rev) V_c = 60, 100, 140 (m/min) Condition = Dry	Tungsten carbide D = 5 mm θ = 120°, 130°, 140°	*Ra*	[14]
Al7075	f = 0.1, 0.2, 0.3 (mm/rev) V_c = 4, 12, 20 (m/min) Condition = Dry	HSS D = 5 mm θ = 90°, 118°, 135°	*Ra*, *H*	[15]
Al6061	n = 1000, 1500, 2000 (rpm) f = 0.04, 0.08 (mm/rev) Condition = Dry	HSS-TIN D = 8 mm θ = 118°	*Ra*, *Z*, *C*, *W*	[16]
Al5050	V_c = 15, 20, 25 (m/min) f = 0.1, 0.2, 0.3 (mm/rev)	HSS D = 6, 8, 10 mm	*Ra*	[17]

Surface roughness: *Ra*, diameter: D, circularity: C, hole size: Z, tool wear: W, feed rate: f, cutting speed: V_c, helix angle: ψ, point angle: θ, high-speed steel: *HSS*, thrust force: F_z, spindle speed: n, burr height: H.

For instance, Abd Halim et al. [11] studied the effects of the cutting condition and cutting parameters during the drilling of Al7075 alloy in terms of hole circularity, surface roughness, and tool wear. The results showed that the hole circularity, surface roughness, and tool wear are influenced mainly by cutting parameters. Ghasemi et al. [12] investigated pre-center holes' drilling strategy and tool material in drilling Al7075 on surface roughness, dimensional accuracy, and thrust force. The results showed that pre-center drill holes on drilling Al7075 improved the hole quality and reduced the thrust force. Kao et al. [13] used the gray-Taguchi method in their study to investigate the machining parameters in the drilling of Al7075. It was concluded that the hole quality was superior in the inverted drilling methods compared to standard drilling. Yasar et al. [14] concluded that the surface roughness decreased with an increase in drill point angle, while the rise in feed rate increased the surface roughness during dry drilling of Al7075. Kilickap et al. [15] discovered that the combination of low feed rate, low cutting speed, and high point angle in drilling Al7075 was essential to minimize surface roughness and burr height in drilling Al7075. Apart from the studies on aluminium alloy Al7075, Uddin et al. [16] studied the drilling of Al6061 and concluded that the burr formation and roundness error were mainly affected by varying the feed rate. Haleel [17] worked on the optimization of process parameters using the Taguchi method for minimum surface roughness in the drilling process of Al5050. The results showed that tool diameter was the most significant factor that affected the surface roughness following the feed rate and cutting speed.

The above studies indicate that most of the previous investigations were made either on other drilling parameters of Al7075-T6 or other alloys of aluminium. Furthermore, there is still a lack of research regarding the hole quality in Al7075-T6 alloy and needs further investigation. A good hole quality with less dimensional deviation improves productivity and decreases manufacturing costs and time. Therefore, this study investigates the drilling of Al7075-T6 to comprehensively analyze the influence of process parameters, i.e., spindle speed and feed rate, on the circularity error, surface roughness, hole diameter, and burr formation, which are the essential characteristics of hole quality. In addition, the generated chips in the drilling process were analyzed. Furthermore, ANOVA (analysis of variance) was used to find the percentage contribution of each input parameter on the analyzed output parameters.

2. Materials and Methods

In the current study, a vertical milling machine (Model: Victoria-Elliott U2, London, UK) was used to conduct the drilling experiments. The spindle speeds used were 141, 308, and 548 (rpm), and the feed rates were 0.53, 1.35, and 1.94 (inch/min). The workpiece material was Al7075-T6 alloy with 110 mm $\times$ 60 mm and a thickness of 10 mm. Uncoated high-speed steel (HSS) twist drills (Dormer Drills, UK) with a helix angle of 30° and a point angle of 130° were used. All the drilling experiments were conducted under dry conditions due to environmental concerns [18]. Dry drilling also reduces the need to clean the aeronautical structures before installing rivets to obtain high-quality holes [19].

The hole size and circularity error were measured using a coordinate measuring machine (CMM, Taichung, Taiwan). The surface roughness tester Mitutoyo (SJ-201, Kawasaki, Japan) was used to measure the surface roughness (*Ra*). Each hole was cleaned with high-pressure air to remove small debris from the hole wall for accurate measurement of *Ra*. Furthermore, the entry and exit burrs of holes were examined using a digital microscope.

3. Results and Discussions

3.1. Surface Roughness, Hole Size, and Circularity

Surface roughness (*Ra*) is critical in assessing workpiece machining performance [20,21]. A high value of *Ra* results in unnecessary fatigue, wear, lower corrosion resistance and reduces the machined product's performance [22]. *Ra* is influenced by various machining conditions such as cutting parameters, tool geometry, vibration induced on the workpiece, etc. [23]. Figure 1 shows the average *Ra* measured under different drilling parameters selected in this study. The *Ra* values varied in the range from 1.6 to 2.628 µm. Results showed that both the n and f affected the *Ra*. The *Ra* value increased with the increase in f and decreased with the increase in n. However, the impact of n was more significant than the f [10], which is evident from ANOVA results given in Table 2, where the n had a contribution of 57%, while the f had a contribution of 42%.

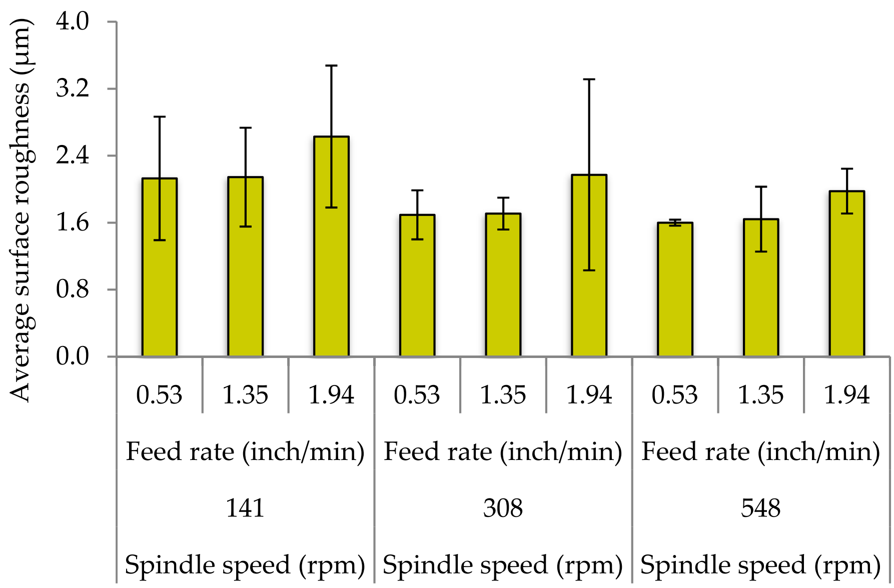

Figure 1. Average surface roughness.

Table 2. ANOVA results.

Source	Surface Roughness		Hole Size		Circularity	
	p-Value	Contribution	*p*-Value	Contribution	*p*-Value	Contribution
Model	0	99.19%	0.001	98.00%	0.022	91.15%
Linear	0	99.19%	0.001	98.00%	0.022	91.15%
Spindle speed	0	57.01%	0.012	15.99%	0.632	2.28%
Feed rate	0	42.18%	0.001	82.02%	0.008	88.87%
Error	-	0.81%	-	2.00%	-	8.85%
Total	-	100.00%	-	100.00%	-	100.00%

The increase in the f increased the uncut chip thickness due to the rise in thrust force [24,25], which deteriorated the hole quality, especially the Ra [26]. Additionally, the decrease in the Ra due to the increase in n might be due to the built-up edge formation (BUE). Materials like aluminium with low ductility form BUE on the cutting tool. Therefore, low n in dry machining contribute to BUE formation [27]. Thus, the high n resulted in a lesser amount of BUE, hence producing a better surface finish [28].

Figure 2 shows the deviation of holes from the nominal size (10 mm in this study). The results indicate that all holes were oversized. The variation in hole size in the current study is only in the range of 0.870–0.198 mm. Both the n and f have an impact on the hole size. However, the contribution of f on hole size was more, i.e., 82.02%, compared to the 15.99% contribution of n. Figure 2 also shows that an increase in n increased the deviation of hole size, while the rise in f reduced the deviation of hole size. According to Kurt et al. [22], the increase in n might result in vibration, chatter, and temperature, which significantly impact the accuracy of drilled holes.

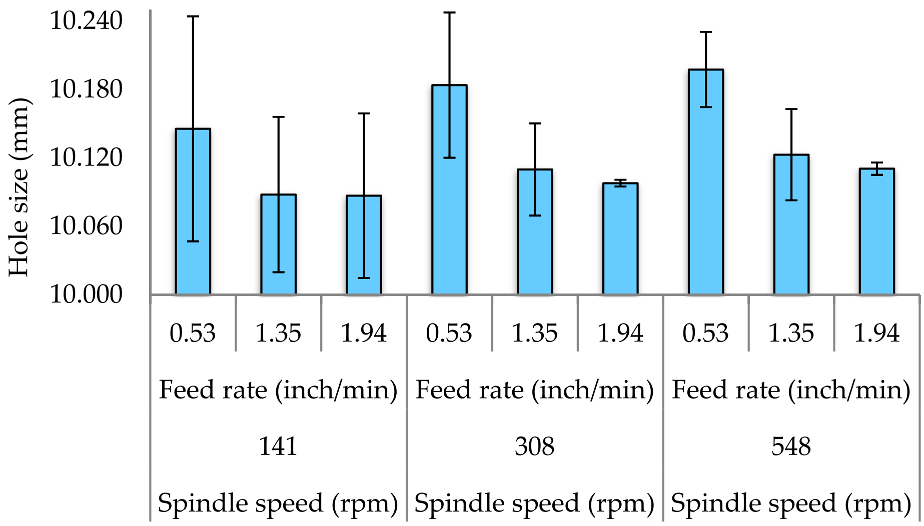

Figure 2. Deviation of hole size.

Figure 3 depicts the circularity error under different drilling parameters selected in this study. In the current study, the circularity was influenced by both n and f. The increase in the f decreased circularity error, while the high n resulted in an increase in the circularity errors. The ANOVA results in Table 2 show that the influence of f on the circularity was more with a percentage contribution of 88.87%. The n indicated a p-value of greater than 0.05, which showed that n had an insignificant impact of only 2.28%. However, at high n, increasing the f from 1.35 to 1.95 inch/min, an increase in the circularity error was found. This rise in circularity error might be due to faster penetration of the cutting tool that increased the hole deflections and vibrations in the cutting tool [29].

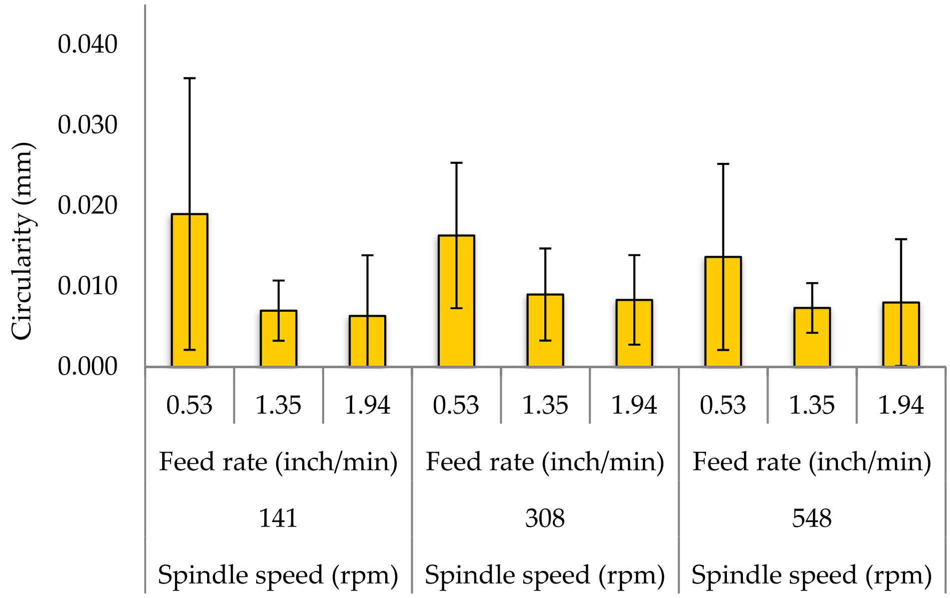

Figure 3. Circularity error.

3.2. Burr Formation Analysis

The burr formation during the drilling process depends on various factors such as the material properties of the workpiece, drilling parameters, and geometry of the drilled tools [30]. Burr formation causes dimensional inaccuracies and the need for de-burring, which consumes about 30% of the total cost of the final product [30]. Additionally, de-burring is carried out manually, which reduces productivity [10]. Yazman et al. [31] explained three types of burr formation during types of burrs during the drilling process under different drilling parameters, i.e., crown, transient, and uniform burrs. Crown burrs at the exit hole are large, irregular in shape, bend outwards, and considered the worst among all the burr types that need more attention.

Figure 4 shows the microscopic and visual inspection of the burrs, which revealed that the f was the most influential parameter in burr formation compared to n. The effect of n on burr formation was also observed; however, only at a high f. According to Costa et al. [30], the high f increased the cutting forces, which result in high burr formation. Additionally, small thickness chips are formed with a low f, allowing jerk-free and stable drilling, which resulted in less deviation from nominal size [16].

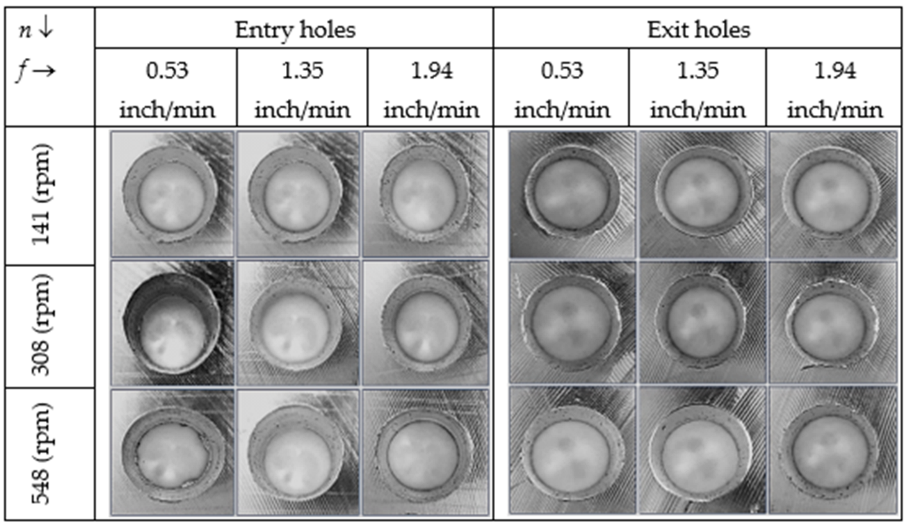

Figure 4. Burr formation.

Figure 4 also shows the burrs at the exit were more prominent than the burrs at the entry side of the hole. This is because as the drill bit approaches the hole exit at higher spindle speed, the temperature rise increases the material's ductility in the cutting area and results in more significant amounts of plastic deformation around the edges of the hole [32].

3.3. Chip Analysis

During the drilling operation of aluminium alloys, usually small and segmented chips are desirable for the high-quality hole and increased tool life [33]. Liu et al. [34] have reported that fragmented and small chips prevent the tool from breaking. Additionally, the smoothness of the drilling process in aluminium alloys can be observed through the chip's size, such as chip thickness and length [35]. Long continuous chips easily tangle around the drilling tool and need manual removal, which might interrupt the production [36]. Figure 5 depicts the chips produced during the drilling process of Al7075-T6 alloy, which shows that the length of chips was affected by both n and f. Sun and Guo [37] investigated that longer chips were produced at high n due to high temperature that causes ductility in the material. Moreover, segmented chips were produced when the f increased, and n was decreased. However, the thickness of chips directly relates to the f and is inversely associated with n. The f was more influential because the cross-sectional area increased at a high f, increasing the chip's stiffness and making the chip prone to breaking easily [34].

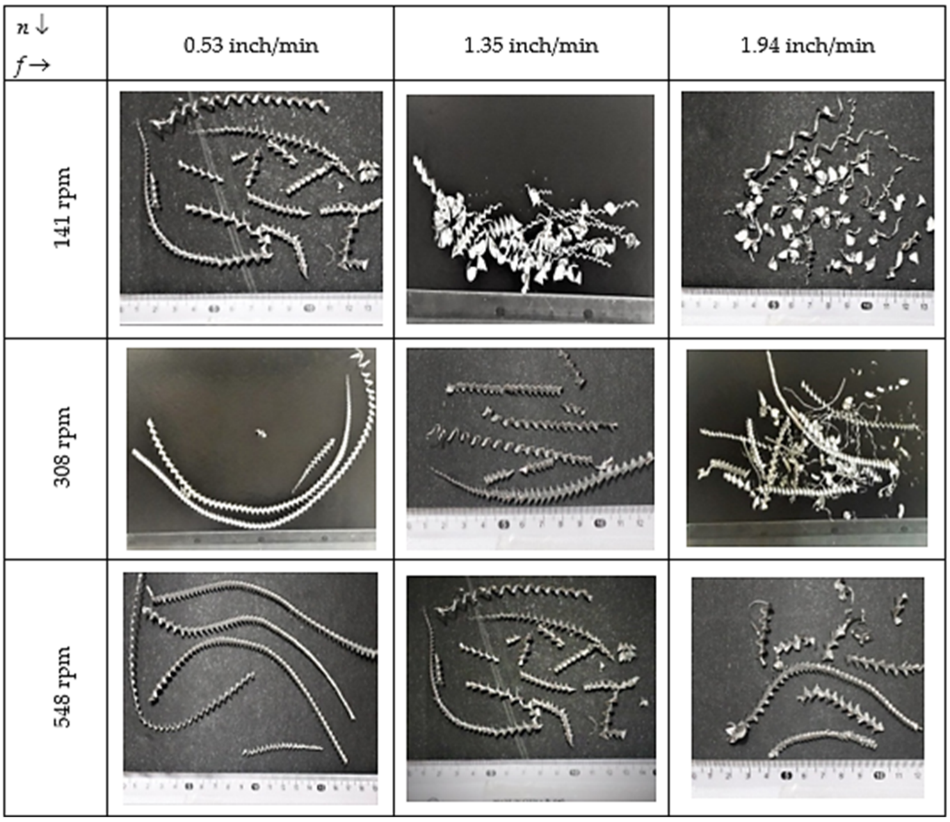

Figure 5. Chip formation at various drilling parameters.

According to the ISO-based chip classification chart, various chips are formed during the machining operation, including ribbon chips, helical chips, tubular chips, spiral chips, corkscrew chips, arc chips, and needle and elemental chips [38]. Some types of chips are further classified as short, long, and snarled chips. In the current study, long-helical chips were achieved at 141 rpm. However, when the f increases from 0.53 inch/min to 1.35 inch/min, the long–helical chips converted into short-helical chips. Further increasing the f to 1.94 inches/min, chips were converted to the combination of short-helical and snarled chips. For 308 and 548 rpm, long-helical chips are formed at 0.53 inches/min. Furthermore, short–helical chips and a combination of short-helical and snarled chips are formed at *f* of 1.35 and 1.94 inch/min at 548 rpm, respectively.

4. Conclusions

In the current study, the evaluation of hole quality in the drilling of Al7075-T6 was investigated. The conclusions drawn from experiments are as follows:

The surface roughness in the drilling of Al7075-T6 decreased with the increase in the spindle speed, while the rise in feed rate resulted in high values of surface roughness. The contributions of spindle speed and feed rate on the surface roughness were 57.01% and 42.18%, respectively. In the case of hole size, the high spindle speed increased the hole size, while the rise in feed rate reduced the deviation of holes from the nominal size, except at high spindle speed, where increasing the feed rate from 1.35 to 1.95 inch/min increased the deviation of hole size. From ANOVA, the percentage contributions of spindle speed and feed rate were 15.99% and 82.92%, respectively. Similarly, the circularity decreased with a rise in feed rate with a percentage contribution of 88.87% compared to the insignificant impact of spindle speed with only 2.28% contribution. The feed rate was also the most influential parameter in burr formation compared to spindle speed. The burrs were mostly observed at a high feed rate. Furthermore, the entry burrs were found to be smaller than those formed at the exit of the hole. The short, segmented, and discontinuous chips were produced with an increase in the feed rate and decreased spindle speed.

Further study could be considered at high cutting parameters using different drill bit materials and finite element modelling to investigate how these factors would affect the quality of the hole.

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