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Research Paper

An experimental study on conventional drilling of Al6061-T6 aluminum alloy

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ABSTRACT: Aluminum alloy is considered as a difficult-to-cut material, especially for deep drilling where the aspect ratio of the hole depth and diameter is larger than 5. This paper presents experimental study on effects of spindle speed and feed rate on thrust force and torque using typical twist drill bits for Al6061-T6 aluminum alloy with aspect ratio of hole depth and diameter is 8. Under dry cutting condition, the drilling process was able to continuously complete the deep holes. The effects major parameters, including spindle speed and feed rate with three levels are evaluated using Taguchi design of experiment and ANOVA analysis. The results showed that, feed rate is the most factor has significant effect on thrust force and drilling torque. Under the same spindle speed, lower feed rate constitutes smaller of thrust force, drilling torque than those of higher spindle speed.
KEYWORDS: Drilling, Thrust force, Torque, aluminum alloy, Taguchi design.

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I. INTRODUCTION

Nowadays, drilling difficult-to-cut materials, such as aluminum alloys, SUS 304 stainless steel, is still a challenge because of their ductility. Different from other conventional machining processes such as turning and milling, where chips are free of external forces after leaving the cutting area, drills are subjected to severe machining conditions such as higher thrust force, poor chip evacuation and chip jamming as a result of the depth of the cutting zone within the workpiece [1]. Almost 99% of the energy fed to the machine tool is converted into heat [2]. Especially, the drilling process becomes more difficult and complex in deep hole, where the hole depth, L is above five times the drill bit diameter, D [1]. Thus, it is considered the most complex and challenging metal cutting operations [3],[4],[5],[6]. However, drilling is still the most commonly used process. About 40%-60% of the total material removed in the aircraft frame industry is carried out by drilling [3]. In drilling process, the application of cooling is needed to reduce the generated drilling temperature at the machining area, and decrease the wear of cutting edge. However, in drilling, the coolant maybe does not sufficiently reach to the drill tip at the cutting zone because the counter flow of the chips limits further penetration, especially in deep-hole drilling. To solve such problems, different drilling methods were used, such as peck drilling [3],[7]… or ultrasonic assisted directly drilling [8],[9],[10]…

Aluminum alloys have been widely used in various applications, where materials require high strength-to-weight ratio, such as in the automobile and aerospace industries. Generally, aluminum alloys were considered as one of the easiest machining materials. However, these materials have been considered as the most critical materials for dry drilling [11],[12]. In addition, dry drilling, an environmental-friendly machining method, has also given a real challenge in drilling aluminum alloys [13]. During the dry drilling of aluminum alloys, long and ductile chips, especially in deep holes, is bended and coiled and thus caused packing of the drill flutes, interfering with chip ejection [13]. High tendency of aluminum to adhere to cutting tools, causing persistent elongated contact with cutting edges and flutes, produces a high risk of tool breakage.

This paper presents an experimental study on ultrasonic assisted drilling (UAD) and conventional drilling an aluminum alloy, Al6061-T6, in terms of thrust force F, drilling torque T. Experiments were designed using Taguchi method and performed with three levels of the two cutting parameters, including spindle speed and feed rate.

II. EXPERIMENTAL SET UP

The workpieces used for these experiments are made from Al6061-T6 aluminum alloy bars. The composition of Al6061-T6 aluminum alloy is depicted in Table 1. The dimensions of the workpieces were 12 mm in diameter and 32 mm in length. The drill bits used in this work were HSS-Co (Nachi Vietnam Co. Ltd.), which was 4 mm in diameter *D*, 54 mm in flute length *l*, 83 mm in overall length *L*, right hand helix 35°, and a point angle of 118°. The dimensions and photo of drill bit were shown on Figure 1. Drilling processes were performed using the universal lathe machine; model V-Turn 410/1500 (Knuth Machine Tool, German). Experiments were conducted using without flood cooling. A series of pilot test found that all the deep drilling processes can be done at a low feed rate of 0.05 mm/rev.

Table 1. Chemical composition of Al6061-T6 aluminum alloy

Al	**Mg**	**Si**	**Fe**	**Cu**	**Cr**	**Zn**	**Ti**	**Mn**	**Remainder**
97.5	1.1	0.51	0.37	0.25	0.12	0.18	0.16	0.17	-

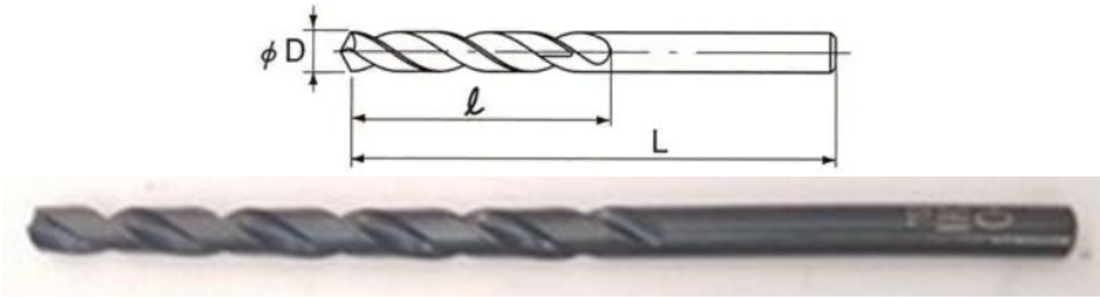

Figure 1: The drill bit

In order to examine the influences of drilling parameters on the thrust force and drilling torque, Minitab 19 Software (Minitab Inc., USA) was used to build experimental procedure. The drilling parameters chosen for studying on drilling process was spindle speed, *n* (*rpm*) and feed rate, f_r (*mm/rev*), both with three levels (see Table 2). In previous studies, drilling torque and thrust force are the two major factors used to examine drilling operation. Thus, in this paper, drilling torque and thrust force were also used to evaluate UAD process and compare between UAD and CD processes. Figure 2 shows the typical plots of thrust force *F* (blue line) and drilling torque *T* (dark line). The maximum values of both thrust force *F_max* and drilling torque *T_max* was collected. The statistical results are shown in Table 3.

Table 2. Input parameters and their levels

Parameters	Units	Levels		
		Low level	Middle level	High level
Spindle speed	rpm	1000	1250	1500
Feed rate	mm/rev	0.050	0.065	0.085

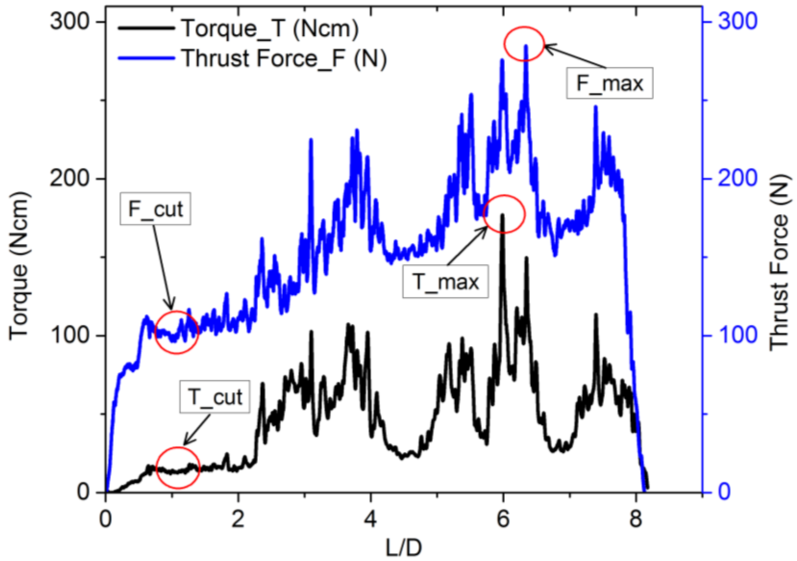

Figure 2: Plots of thrust force F (blue line) and drilling torque (dark line) in during process

Table 3. DOF and experimental results of maximum drilling torque and maximum thrust force

Spindle speed (rpm)	Feed rate (mm/rev)	T_max (Ncm)	F_max (N)	S/N T_max	S/N F_max
1000	0.050	20.513	210.19	-43.8873	-43.2327
1000	0.065	24.761	249.71	-44.1203	-46.8859
1000	0.085	29.936	278.26	-42.8267	-42.3075
1250	0.050	23.071	165.10	-41.4493	-43.6220
1250	0.065	32.588	259.54	-40.7503	-41.0907
1250	0.085	32.278	256.34	-39.0570	-40.5331
1500	0.050	22.954	202.25	-42.4165	-42.3129
1500	0.065	37.657	261.04	-42.1593	-44.9521
1500	0.085	28.484	250.61	-46.5894	-46.6532

III. RESULTS AND DISCUSSION

Effect of drilling parameters on the thrust force

ANOVA analysis for maximum thrust force made with a meaningful level of 0.05 was depicted on the Table 4. The analysis results show that, the feed rate is the most powerful effect on the maximum thrust force, contributing up to 90%. The spindle speed and interaction have a negligible effect regardless of maximum value of thrust force.

Table 4. Analysis of Variance for thrust force

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	6792.5	2264.2	2.97	0.136
Linear	2	6679.9	3340.0	4.38	0.080
Spindle speed (rpm)	1	111.0	111.0	0.15	0.718
Feed rate (mm/rev)	1	6568.9	6568.9	8.61	0.032
2-Way Interactions	1	125.5	125.5	0.16	0.702
Spindle speed (rpm)*Feed rate (mm/rev)	1	125.5	125.5	0.16	0.702
Error	5	3812.6	762.5		
Total	8	7605.1			

Figure 3 shows main effects plot for mean of F_max (on the left) and for S/N ratios (on the right) to three levels of drilling parameters, using smaller is better option. As can be seen, the suitable levels of drilling parameters are spindle speed of 1250 rpm and feed rate of 0.05 mm/rev for minimum value of maximum thrust force. According to data on Table 4, effect of Interaction of spindle speed and feed rate is very small.

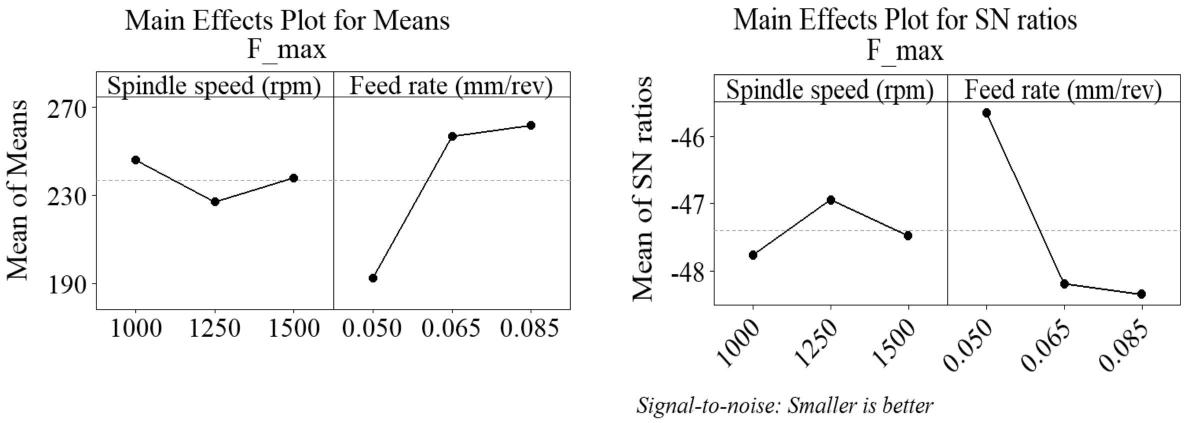

Figure 3: Main effects plot for mean of F_max (left) and for mean of S/N ratios (right)

Effect of drilling parameters on the drilling torque

The same as maximum thrust force, ANOVA analysis for maximum drilling torque made with a meaningful level of 0.05 was shown on the Table 5. The analysis results show that, the feed rate is the most powerful effect on the maximum thrust force, contributing up to 60%. Effect of spindle speed on the drilling torque is about 21% and interaction has a negligible effect regardless of maximum value of torque.

Table 5. Analysis of Variance for drilling torque

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	123.071	41.024	1.58	0.305
Linear	2	114.931	57.465	2.21	0.205
Spindle speed (rpm)	1	30.385	30.385	1.17	0.329
Feed rate (mm/rev)	1	84.546	84.546	3.26	0.131
2-Way Interactions	1	6.393	6.393	0.25	0.641
Spindle speed (rpm)*Feed rate (mm/rev)	1	6.393	6.393	0.25	0.641
Error	5	19.817	25.963		
Total	8	142.888			

Using smaller is better option, figure 4 shows main effects plot for mean of T_max (on the left) and for S/N ratios (on the right) to three levels of drilling parameters,. As can be seen, the suitable levels of drilling parameters are spindle speed of 1000 rpm and feed rate of 0.05 mm/rev for minimum value of drilling torque. According to data on Table 5, effect of interaction of spindle speed and feed rate is very small.

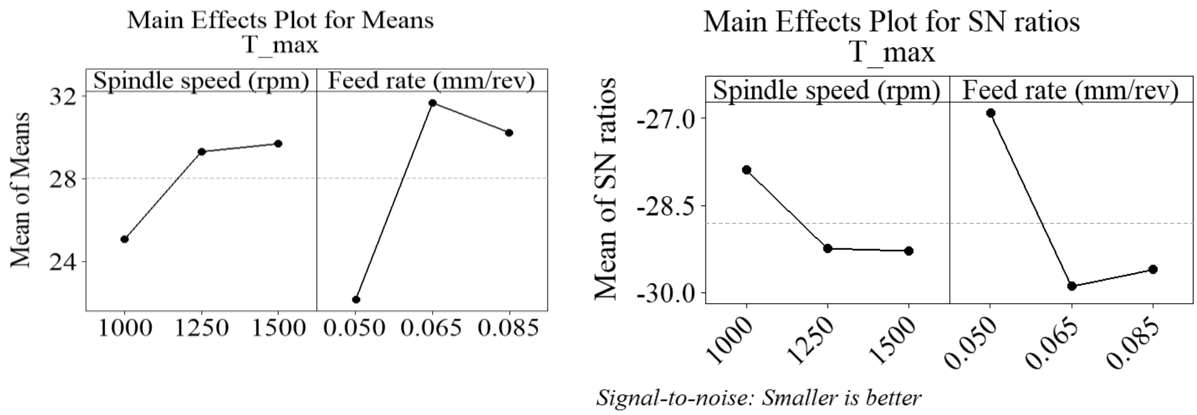

Figure 4: Main effects plot for mean of T_max (left) and for mean of S/N ratios (right)

IV. CONCLUSION

In this study, experiments were performed with three levels of drilling parameters on Al6061-T6 aluminum alloy. The experiments were designed according to Taguchi orthogonal array and experiments were performed with three levels of the cutting parameters, including spindle speed and feed rate. The effects of cutting parameters were analyzed by collecting maximum value of both thrust force and drilling torque during process. Analysis of variance methods were used to identify significant drilling parameters affecting the maximum value of thrust force and drilling torque. The experimental results showed that:

- Thrust force, drilling torque in conventional drilling are more affected by spindle speed, i.e. cutting speed.

- With the same spindle speed, lower feed rate constitutes smaller of thrust force, drilling torque than those of higher spindle speed.

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