Journal of Materials and Manufacturing (2023) 1: 21-30

Journal of Materials and Manufacturing

Experimental investigation of hole quality and chip analysis during the dry drilling process of Al6061-T6

Aamer Sharif [a]*, Aqib Hussain[a], Numan Habib[b], Waqas Alam[c], Muhammad Imran Hanif[a], Adnan Aslam Noon[d], Muhammad Irfan Khan[a]

[a]*Department of Mechanical Engineering CECOS University of Information Technology and Emerging Sciences, Peshawar, Pakistan*
(ORCID: 0000-0003-1571-8675), aamirsharif120@gmail.com
(ORCID: 0009-0004-9935-0111), iamaqibhussain@gmail.com
(ORCID: 0009-0005-7201-7199), *imranhanif@cecos.edu.pk*
(ORCID: 0000-0003-1245-9065), irfan@cecos.edu.pk
[b]*School of Engineering, Edith Cowan University, Joondalup, WA 6027, Australia*
(ORCID: 0000-0001-8654-0320), numanh@our.ecu.edu.au
[c]*School of Mechanical Engineeing, Purdue University, USA*
(ORCID: 0009-0009-8240-8731), alamw@purdue.edu
[d]*Department of Mechanical Engineering, International Islamic University, Islamabad, Pakistan*
(ORCID: 0000-0002-0986-1312), adnan.aslam@iiu.edu.pk

Abstract

High-quality holes in the drilling process are possible by selecting appropriate cutting parameters, proper machine setup and tools. The current study examines how drilling parameters like spindle speed and feed rate affect the formation of chips as well as hole quality, including hole size, circularity, and surface roughness of Al6061-T6. HSS drill bits were used in dry drilling experiments. The results showed that hole size and circularity are increased with the high spindle speed and feed rate. While the high spindle speed and low feed rate result in low surface roughness. Analysis of variance indicates that the hole size was highly affected by feed rate, having a contribution of 61.58 % compared with spindle speed with a contribution of 36.12 %. Moreover, the contribution of feed rate on circularity is 69.30 % greater than the effect of spindle speed at 28.48 %. In contrast, the spindle speed has a high influence of 56.84 % on surface roughness, than the feed rate with 42.13 %. The outcome also demonstrated that short, segmented chips could be produced at low spindle speeds and high feed rates.

Keywords: Al6061-T6; Drilling; Hole size; Circularity; Surface Roughness; Chip formation.

Nomenclature

C	Circularity	W	Tool wear
D	Diameter	θ	Point angle
H	Burr height	ψ	Helix angle
HSS	High-speed steel	MRR	Material removal rate
F	Feed rate	T	Torque
Fz	Thrust force	Z	Hole size
n	Spindle speed	t	Temperature
Ra	Surface roughness	Af	Axial force
Vc	Cutting speed		

* Corresponding author.
E-mail addresses: aamirsharif120@gmail.com
DOI: 10.5281/zenodo.8020538
Received: 18 April 2023 / Accepted: 29 May 2023
ISSN: 2822-6054

1. Introduction

Aluminum and its alloys are widely used in various manufacturing industries due to their super mechanical properties [1]. For example, Al6061-T6 Alloy is one of the most commonly used in automotive industry [2]. The drilling process, which accounts for a significant amount of overall machining time and costs, is widely used in manufacturing industries. Also, drilling plays an essential economic role in manufacturing many different industrial parts [3]. The success of the automotive and aerospace sectors, which need millions of holes, depends on the productivity, quality, and precision of the drilled holes [4].

HSS drill bits are the main attraction for drilling in aluminium alloy to enhance the quality of the finished hole in a product [5]. Additionally, HSS drill bits are reasonably priced and offer several advantages, including being simple to maintain and having high breaking strength [3]. Irrespective of the material, important process parameters such as spindle speed (n) and feed rate (f) significantly affect the quality of drilled holes [6]. A higher or lesser n and f increase or decrease the dimensional accuracy and surface quality, which directly affects productivity [4]. Different experimental and analytical methods were used in previous studies to enhance the machinability or drilling performance of Aluminum alloys, as given in Table 1.

Table 1. Some of the previous studies on drilling of aluminum alloy

Alloy type	Cutting Parameters	Cutting Tool	Output Parameters	Ref
Al6061	f= 0.04, 0.08 (mm/rev) n= 1000,1500, 2000 rpm Condition= Dry	HSS -TiN D= 8 mm θ= 118º	W, C, Z, Ra	[7]
Al6061	f= 0.05, 0.10, 0.23, 0.35, 0.40 (mm/rev) V_c= 50, 115, 275, 434, 500 Condition= High pressure internal cooling	HSS D= 5 mm θ= 127º	Ra, H	[8]
Al6061	f= 0.3, 0.5,0.6(mm/min) n= 600,800,1000 rpm	HSS D= 8, 10, 12 mm θ=118º, 110º, 100º	H, S, Ra, C,	[9]
Al6061	f= 0.3, 0.5, 0.6 (mm/rev) V_c= 15.08, 25.13, 37.70 m/min Condition= Cnc cutting fluid	HSS D= 8, 10, 12 mm θ= 118º, 110º, 100º	Ra, C	[10]
Al6061/Al_2O_{3p}	f= 0.05, 0.1, 0.2 (mm/rev) n= 2200, 2600, 3000 rpm Condition= Dry	HSS D= 10 mm θ= 90º, 118º, 130º	Ra, Rz, Fz, T, C	[11]
Al 6061-T651	f= 50, 100, 150 (mm/min) n= 1000, 2000, 3000 rpm Condition= Dry	Solid carbide D= 10 mm θ= 30º, 140º	Ra, Rz, Z, C,	[12]

Feed rate: f, thrust force: Fz, cutting speed: Vc, spindle speed: n, diameter: D, Surface roughness: Ra, high-speed steel: HSS, circularity: C, tool wear: W, point angle: θ, helix angle: ψ, burr height: H, hole size: Z, burr thickness: S, Material removal rate: MRR, Torque: T, Temperature: t, Axial force: A_f,

For instance, Uddin et al. [7] investigated the effects of surface finish, dimensional accuracy, and burr formation on hole quality in drilling Al6061, and the findings revealed that the n and tool diameter had a significant impact on the Ra. It was studied that f was the most dominant factor that largely influenced thrust force, torque and hole quality. Popan et al. [8] determined the impact of process parameters on hole quality and absorbed that Ra decreased with increasing n and decreasing f. Furthermore, they reported that f had a higher effect on dimensional deviation. Sreenivasulu [9] carried out experimental data on Al6061 alloy to determine the impact of cutting forces, drill diameter (D) and point angle on Ra, burr size and circularity deviation. The results showed that Ra was significantly affected by the cutting forces despite circularity deviation for which drill geometry and n are more significant. Sreenivasulu and Rao [10] studied the impact of cutting forces and D on circularity and Ra using Al6061 with the help of grey relational analysis for the optimization of drilling parameters. Jadhav et al. [11] carried out experimentations to investigate how drill geometry and cutting forces affect surface finish during drilling of Al 6061/Al2O3p metal matrix composite. The results show that the optimum values for surface finish can be achieved at smaller f, smaller point angles and high n. However, higher values of n and f with smaller value of point angle produces a good hole cylindricity. Al-Tameemi et. al [12] worked on the effect of n and f on the Ra and holes size in Al6061-T651 by using various coated cutting tools. The results showed that the highest Ra was obtained by using TIN-coated tools due to lower coating hardness which results in higher cylindricity and low hole circularity.

The above study indicates how important the drilling parameters are to obtain better hole quality. Numerous studies have evaluated hole quality, cutting forces, and temperature in drilling Al6061. Productivity is increased, manufacturing costs are decreased, and production time is decreased with excellent hole quality and low deviation. When compared to previous research, the current study is based on various cutting parameters, such as n and f, on hole quality, such as hole size, circularity, and surface roughness. Moreover, the current study also described the chip generation during dry drilling of Al 6061-T6.

2. Materials and Methods

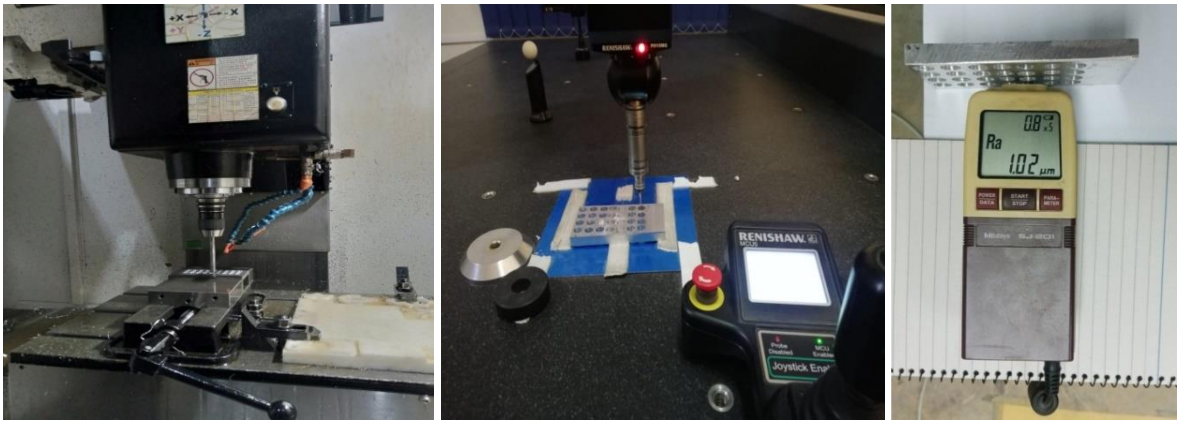
The present work used an aluminium alloy Al 6061-T6 with a 140 mm x 60 mm dimension. The thickness of the plate was 10 mm. The experiments were carried out using CNC vertical milling center as shown in Figure 1. An uncoated High-speed steel (HSS) twist drill was used. The process parameters were selected based on past research and recommendations from the tool manufacturers as shown in Table 2. A circularity error and hole size were measured with the help of a coordinate measuring machine (CMM) as shown in Figure 1. By tracing the hole profile with a probe, CMM measures the coordinates of specified points around the circle of the hole. A probe with a 2 mm diameter encircled the inner wall of the hole while the workpiece was positioned on the machine bed. The probe was moved around the inner circle of a hole at a speed of 1 mm per second, which allowed for the capture of up to 400 points. In the current study, holes were cleaned with highly compressed air to eliminate small debris from the hole wall for precise measurements. In addition, a chip analysis was investigated with the help of a DSLR high-resolution camera 5220. Furthermore, the surface roughness (Ra) was measured with the help of the surface roughness tester as shown in Figure 1. The experimental parameters and equipment details are shown in Table 3.

Table 2. Cutting parameters of drilling

Level	1	2	3
Feed rate (mm/min)	100	200	300
Spindle speed (rpm)	400	800	1200

Table 3. Equipment details and experimental conditions

Machine tool	CNC vertical milling center
Drill bit	High-speed steel (Norseman drill and tool USA) of 11 mm diameter
Drilling condition	Dry
Surface roughness	Surface roughness tester Mitutoyo SJ-201
Hole size and Circularity error	Coordinate measuring machine (CMM, Mitutoyo. Taiwan)
Chip Morphology	DSLR camera 5220.



CNC vertical milling center | Coordinate measuring machine | Surface roughness

Fig. 1. (a) CNC vertical milling center (b) Coordinate measuring machine (c) Surface roughness tester

3. Results and Discussions

3.1. Hole size

The assessment of hole size is the most important output parameter of the drilling operations mostly in dry drilling process, which is related to higher cutting temperature at the tool-chip interface due to higher friction and obstruct of the chips over the flutes of the drill bit [13]. Figure 2 shows the deviation of holes from the nominal size (11 mm) under varying n and f. Results indicated the oversized holes range from 11.087 – 11.198 mm. However, it is noticed that the maximum percentage difference in the hole diameter was less than 2%. A noticeable increase in diameter has been recorded with an increase in f and n. Even though the diameter increase is comparatively small, it shows that smaller f is shown to minimize the dimensional variance. At the same time, the n has minimal effect except for the conditions of f= 100 mm/min and n=400 rev/min, which revealed that low f and n are preferred. The chips are formed with minimum thickness and at low f, allowing jerk-free and constant drilling. Hence, produce holes with less dimension error in diameter [14]. Shear cutting is the main mechanism at low f, resulting in segmented chip formation and low cutting force; hence, the hole size is achieved with minimum deviation. This may be assigned to the high vibratory displacement with the enhancement of the n and the f, which happens during the initial contact between the chisel edge and the workpiece and triggers dynamic instability, resulting in increasing hole size variations [13, 15]. Lower f results in slower penetration rate and the cutting edge eliminates material with minimum chip thickness, permitting a stable and jerk-free drilling, resulting in hole diameter with minimum dimensional error. With low f, shear cutting is the dominant mechanism, which results in a continuous chip formation and minimum force as a result, hole deviation decreases. This reveals that, given a n, slower f can ideally be selected to lower the dimensional error. However, a minimum f compromises productivity, the decision must be taken by setting a fair balance between the productivity and the dimensional accuracy required.

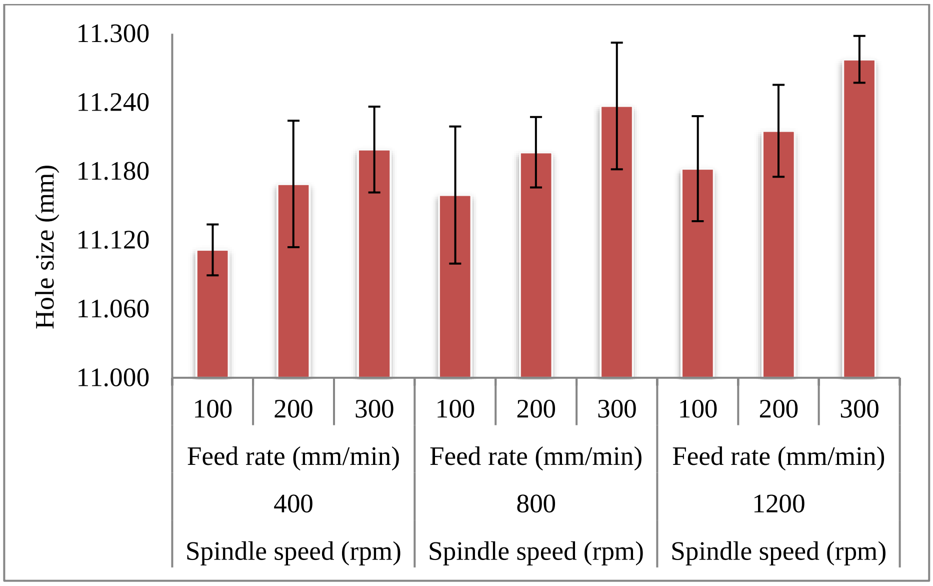


Fig. 2. Hole size

3.2. Circularity

Figure 3 shows the circularity error with respect to n and f. Generally, the circularity increased with increased n due to excessive cutting vibrations [16]. However, in the present study circularity decreased notably with increasing both f and n. Moreover, at a n of 400 rev/min, when the f increases from 100 mm/min to 300 mm/min, the circularity decreased by 71.6%. This is because discontinuous chips are achieved at a high f. Therefore, at low f, continuous chips tangled around the cutting tool, disrupting the dynamic balance and imposed high vibration [15]. The decrease in circularity with the increase in n may be possible due to the minimum contact duration between chip and tool [12].

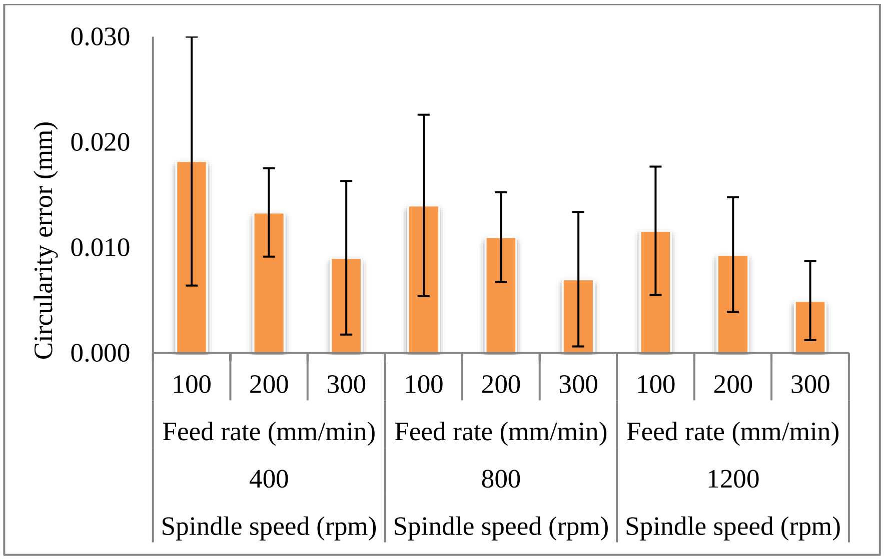


Fig. 3. Circularity error

3.3. Surface roughness

Surface Roughness (Ra) is one of the most significant aspects of metal cutting that is monitored during the machining process. A high Ra caused unneeded fatigue, wear, reduced performance of the machined product and decreased corrosion resistance [1]. Ra is affected by a number of machining factors, including cutting parameters, tool geometry, and vibration applied to the work piece [17]. Ra was measured under different drilling conditions, as shown in Figure 4. Ra has an inverse relation with n and direct relation with f. This is similar to the previous studies, which showed that the high f directly influenced Ra due to the high thrust force required to deform the chip having thick layer that induces more truculent vibration and results in a high surface finish [13]. However, increasing spindle speed decreased the Ra. The decrease in Ra due to the high spindle speed might be due to the rise in surface temperature of the hole wall, which softens the material and reduces the resistance against the tooltip [18]. Therefore, 100 mm/min of feed rate and 1200 rpm of spindle speed are suitable for surface roughness in the current study to produced high quality holes.

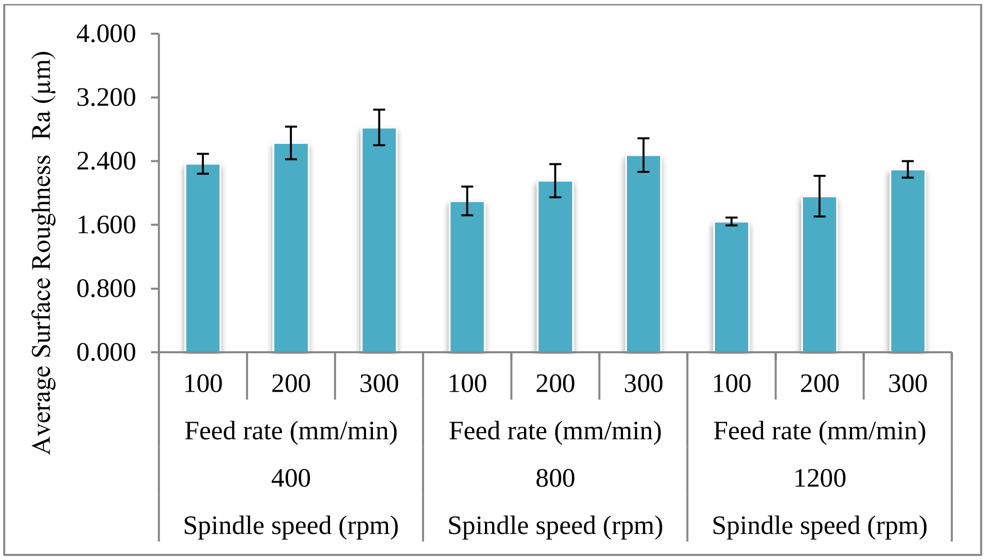


Fig. 4. Average surface roughness

3.4. Analysis of variance

ANOVA is a helpful statistical tool for predicting the impact of process variables and their mutual interaction on the output [19-21]. The current study conducted ANOVA with a 95% confidence level [3, 22]. Therefore, if a P-value is greater than 0.05, the effect of variable on response is treated to be insignificant. P-values are selected as a result to illustrate how process factors affect response. Moreover, the percentage contribution also revealed the amount to which each process parameter affects the response [23]. The ANOVA result from Table 4 shows that n and f significantly affect hole size. However, the contribution of the feed rate was 61.58%, while the percentage contribution of n was 36.12%. For the circularity, the impact of f in influencing circularity was 69.30%, which is higher than that of n with 28.48 %. In the case of Ra, the n was found to be more significant than the f. The n had an impact of 56.84%, and the f contributed 42.13% in affecting the Ra in the current study.

Table 4. ANOVA table

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Hole size							
Model	4	0.015805	97.70%	0.015805	0.003951	42.48	0.002
Linear	4	0.015805	97.70%	0.015805	0.003951	42.48	0.002
Spindle speed	2	0.005844	36.12%	0.005844	0.002922	31.42	0.004
Feed rate	2	0.009961	61.58%	0.009961	0.004981	53.55	0.001
Error	4	0.000372	2.30%	0.000372	0.000093	-	-
Total	8	0.016177	100.00%	-	-	-	-
Circularity							
Model	4	0.000119	97.78%	0.000119	0.00003	44.02	0.001
Linear	4	0.000119	97.78%	0.000119	0.00003	44.02	0.001
Spindle speed	2	0.000035	28.48%	0.000035	0.000017	25.64	0.005
Feed rate	2	0.000084	69.30%	0.000084	0.000042	62.39	0.001
Error	4	0.000003	2.22%	0.000003	0.000001	-	-
Total	8	0.000122	100.00%	-	-	-	-
Surface roughness							
Model	4	1.11091	98.97%	1.11091	0.277728	95.94	0
Linear	4	1.11091	98.97%	1.11091	0.277728	95.94	0
Spindle speed	2	0.63803	56.84%	0.63803	0.319013	110.2	0
Feed rate	2	0.47289	42.13%	0.47289	0.236444	81.68	0.001
Error	4	0.01158	1.03%	0.01158	0.002895	-	-
Total	8	1.12249	100.00%	-	-	-	-

3.5. Chip Formation

A small, segmented and discontinuous chip are preferred for the high-quality hole and longer too life while drilling aluminium alloys [24]. According to Liu et al. [25] small and fragmented chips keep the tool from breaking. On the other hand, continuous and long size chips entangled in the drilling tool and need to be manually removed, which might stop production [26]. Therefore, the unwanted chips increase the generation of built- up edge (BUE), which in results in the reduction of hole quality. This is due to the fact that, generation of BUE is the peak value of the coefficient of friction at the tool tip-chip interface [27]. During machining operation, chips can allow the cutting tool to form BUE, which results in failure of the cutting tool [28]. According to Rodríguez et al. [29], both high friction phenomena and chemical diffusion may occur in dry drilling operations, which results in adhesion and burn marks. Therefore, the maximum generation of BUE in drilling influences the hole quality. Figure 5 illustrates the chips formed during the drilling process of Al6061-T6.

In the present study, long-helical chips are obtained at 400 rev/min at f of 100 mm/min. However, when the f increases from 100 mm/min to 200 mm/min the long-helical chips convert into short-helical chips. Increasing the f to 300 mm/min converts to a mixture of short-helical and snarled chips. Moreover, at 800 and 1200 rev/min long-helical chips are formed at 100 mm/min. However, combinations of short-helical and snarled chips are formed at 800 rev/min at f of 300 mm/min. Furthermore, increasing f from 100 to 300 mm/min at 1200 rev/min long helical chips is transformed into snarled and needle chips. Figure 5 indicates that the length and thickness of chips are influenced by both f and n. Chips thickness is inversely related to n and directly related to f. The f was more prominent because at a high f the cross-sectional area increased, increasing the chip's stiffness and making the chip prone to break easily [25, 30]. A longer chips is formed due to high temperature caused by a high n value which results in material ductility [31]. Additionally, at high n, long continuous chips are produced, increasing the friction area between the chip and the drill bit flute and drastically increasing the temperature, leading to high thermal stresses in the drilled hole periphery [32]. Moreover, as n increases from 400 to 1200 rev/min, long and helical chips are observed and the Ra of the drilled holes are improved. However, increased f from 100 to 300 mm/min thick and discontinuous chips lead to increase in the surface roughness of the drilled hole.

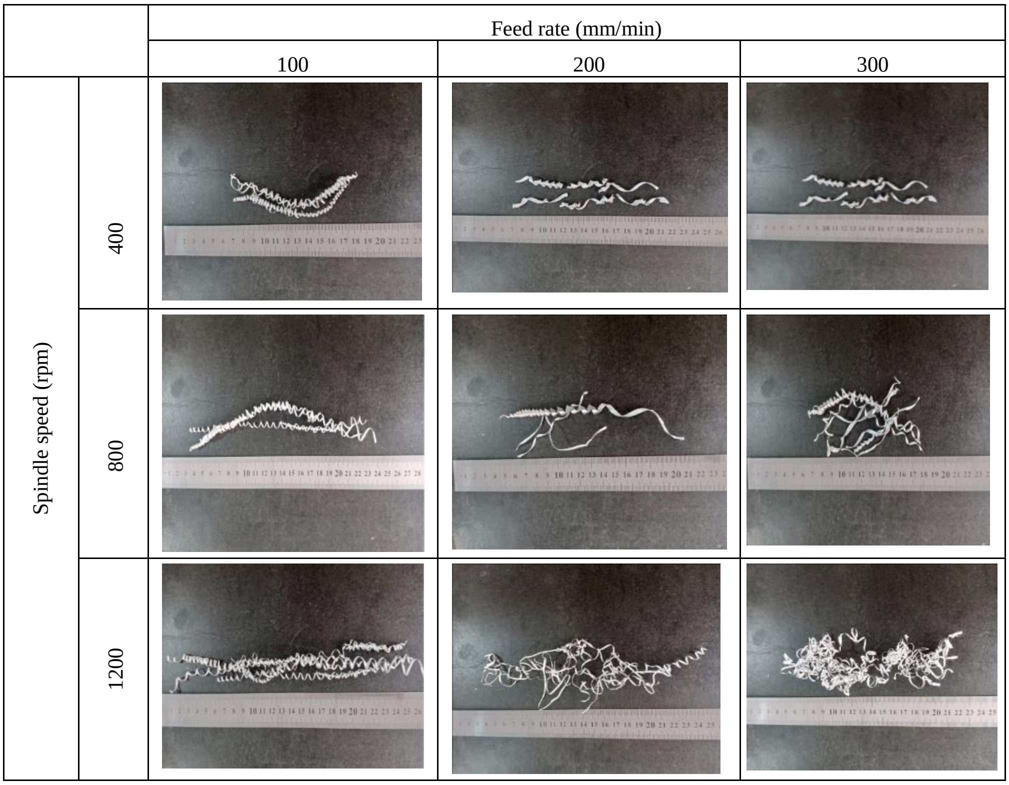


Fig. 5. Chip formation

4. Conclusions

This study concludes that increasing spindle speed (n) and feed rate (f) resulted in large deviation in hole size. However, the f significantly influenced the hole size with percentage contributions were 61.58% than that of n with impact of 36.12%. In the case of circularity, it was concluded that rising n and f resulted in a reduction in the circularity. With a percentage contribution of 69.30%, the f had a more significant impact on the circularity than the n, which had a percentage contribution of 28.48%. It was also found that while drilling Al6061-T6 alloy both n and f have a significant impact on surface roughness (Ra). Ra has an inverse relationship with n and direct relations with f. However, f had less impact on Ra than n i.e., n contributed 56.84 % and while the influence of f was 42.13 %. In chip formation, the f was found to be more influential than n.

References

[1] Aamir, M., Giasin, K., Tolouei-Rad, M., & Vafadar, A. (2020). A review: Drilling performance and hole quality of aluminium alloys for aerospace applications. Journal of Materials Research and Technology, 9(6), 12484-12500.

[2] Aamir, M., Tolouei-Rad, M., Giasin, K., & Vafadar, A. (2020). Machinability of Al2024, Al6061, and Al5083 alloys using multi-hole simultaneous drilling approach. Journal of Materials Research and Technology, 9(5), 10991-11002.

[3] Habib, N., Sharif, A., Hussain, A., Aamir, M., Giasin, K., Pimenov, D. Y., & Ali, U. (2021). Analysis of hole quality and chips formation in the dry drilling process of Al7075-T6. Metals, 11(6), 891.

[4] Aamir, M., Giasin, K., Tolouei-Rad, M., Ud Din, I., Hanif, M. I., Kuklu, U., ... & Ikhlaq, M. (2021). Effect of cutting parameters and tool geometry on the performance analysis of one-shot drilling process of AA2024-T3. Metals, 11(6), 854.

[5] Masooth, P. H. S., & Jayakumar, V. (2020). Experimental investigation on surface finish of drilled hole by TiAlN, TiN, AlCrN coated HSS drill under dry conditions. Materials Today: Proceedings, 22, 315-321.

[6] Koklu, U., Morkavuk, S., Featherston, C., Haddad, M., Sanders, D., Aamir, M., ... & Giasin, K. (2021). The effect of cryogenic machining of S2 glass fibre composite on the hole form and dimensional tolerances. The International Journal of Advanced Manufacturing Technology, 115(1-2), 125-140.

[7] Uddin, M., Basak, A., Pramanik, A., Singh, S., Krolczyk, G. M., & Prakash, C. (2018). Evaluating hole quality in drilling of Al 6061 alloys. Materials, 11(12), 2443.

[8] Popan, I. A., Popan, A. I., Carean, A., Fratila, D., & Trif, A. (2019). Study on chip fragmentation and hole quality in drilling of aluminium 6061 alloy with high pressure internal cooling. In MATEC Web of Conferences (Vol. 299, p. 04014). EDP Sciences

[9] Sreenivasulu, R. (2015). Optimization of burr size, surface roughness and circularity deviation during drilling of Al 6061 using Taguchi design method and artificial neural network. Independent Journal of Management & Production, 6(1), 93-108

[10] R Sreenivasulu, R., & Rao, C. S. (2012). Application of grey relational analysis for surface roughness and roundness error in drilling of Al 6061 alloy. International journal of lean thinking, 3(2), 67-78

[11] Jadhav, S. S., Kakde, A. S., Patil, N. G., & Sankpal, J. B. (2018). Effect of Cutting parameters, Point angle and reinforcement percentage on surface finish, in drilling of AL6061/Al2O3p MMC. Procedia Manufacturing, 20, 2-11

[12] Al-Tameemi, H. A., Al-Dulaimi, T., Awe, M. O., Sharma, S., Pimenov, D. Y., Koklu, U., & Giasin, K. (2021). Evaluation of cutting-tool coating on the surface roughness and hole dimensional tolerances during drilling of Al6061-T651 alloy. Materials, 14(7), 1783

[13] Kurt, M., Kaynak, Y., & Bagci, E. (2008). Evaluation of drilled hole quality in Al 2024 alloy. International Journal of Advanced Manufacturing Technology, 37

[14] Uddin, M., Basak, A., Pramanik, A., Singh, S., Krolczyk, G. M., & Prakash, C. (2018). Evaluating hole quality in drilling of Al 6061 alloys. Materials, 11(12), 2443

[15] Giasin, K., Hodzic, A., Phadnis, V., & Ayvar-Soberanis, S. (2016). Assessment of cutting forces and hole quality in drilling Al2024 aluminium alloy: experimental and finite element study. International Journal of Advanced Manufacturing Technology, 87

[16] Abd Halim, N. F. H., Dahnel, A. N., Ismail, A. A., & Zainudin, N. A. (2020). An Experimental Investigation on Drilling of Aluminum Alloy (Al 7075) using High Speed Steel Cutting Tools. Test Eng. Manag, 83, 1451-1456

[17] Giasin, K., Ayvar-Soberanis, S., & Hodzic, A. (2015). An experimental study on drilling of unidirectional GLARE fibre metal laminates. Composite Structures, 133, 794-808

[18] Dwivedi, S. P., Kumar, S., & Kumar, A. (2012). Effect of turning parameters on surface roughness of A356/5% SiC composite produced by electromagnetic stir casting. Journal of Mechanical Science and Technology, 26, 3973-3979

[19] Aamir, M., Tolouei-Rad, M., Vafadar, A., Raja, M. N. A., & Giasin, K. (2020). Performance analysis of multi-spindle drilling of Al2024 with TiN and TiCN coated drills using experimental and artificial neural networks technique. Applied Sciences, 10(23), 8633

[20] Habib, N., Sharif, A., Hussain, A., Aamir, M., Giasin, K., & Pimenov, D. Y. (2022). Assessment of hole quality, thermal analysis, and chip formation during dry drilling process of gray cast iron ASTM A48. Eng, 3(3), 301-310

[21] Sharif, A. (2022). Study on burr formation, tool wear and surface quality in machining Al6063. Journal of Materials and Manufacturing, 1(2), 1-9

[22] Hussain, A., Sharif, A., Habib, N., Ali, S., Akhtar, K., Ahmad, F., ... & Ishaq, M. (2021). Effect of Drilling Process Parameters on Brass Alloy 272 Through Experimental Techniques. Journal of Mechanical Engineering Research and Developments, 44(11), 222-234

[23] Aamir, M., Tu, S., Giasin, K., & Tolouei-Rad, M. (2020). Multi-hole simultaneous drilling of aluminium alloy: A preliminary study and evaluation against one-shot drilling process. Journal of Materials Research and Technology, 9(3), 3994-4006

[24] Zhang, P. F., Churi, N. J., Pei, Z. J., & Treadwell, C. (2008). Mechanical drilling processes for titanium alloys: a literature review. Machining Science and Technology, 12(4), 417-444

[25] Liu, K., Li, J., Sun, J., Zhu, Z., & Meng, H. (2018). Investigation on chip morphology and properties in drilling aluminum and titanium stack with double cone drill. The International Journal of Advanced Manufacturing Technology, 94, 1947-1956

[26] Ke, F., Ni, J., & Stephenson, D. A. (2005). Continuous chip formation in drilling. International Journal of Machine Tools and Manufacture, 45(15), 1652-1658

[27] Astakhov, V. P. (2006). Tribology of metal cutting.

[28] Pramanik, A., Islam, M. N., Basak, A., & Littlefair, G. (2013). Machining and tool wear mechanisms during machining titanium alloys. In Advanced Materials Research (Vol. 651, pp. 338-343). Trans Tech Publications Ltd

[29] Rodríguez, A., Calleja, A., de Lacalle, L. L., Pereira, O., Rubio-Mateos, A., & Rodríguez, G. (2021). Drilling of CFRP-Ti6Al4V stacks using CO2-cryogenic cooling. Journal of Manufacturing Processes, 64, 58-66

[30] Zhu, Z., Guo, K., Sun, J., Li, J., Liu, Y., Chen, L., & Zheng, Y. (2018). Evolution of 3D chip morphology and phase transformation in dry drilling Ti6Al4V alloys. Journal of Manufacturing Processes, 34, 531-539

[31] Sun, J., & Guo, Y. B. (2008). A new multi-view approach to characterize 3D chip morphology and properties in end milling titanium Ti–6Al–4V. International Journal of Machine Tools and Manufacture, 48(12-13), 1486-1494

[32] Zhu, Z., Guo, K., Sun, J., Li, J., Liu, Y., Zheng, Y., & Chen, L. (2018). Evaluation of novel tool geometries in dry drilling aluminium 2024-T351/titanium Ti6Al4V stack. Journal of Materials Processing Technology, 259, 270-281.