2020

Machinability of Al2024, Al6061, and Al5083 alloys using multi-hole simultaneous drilling approach

Muhammad Aamir
Edith Cowan University

Majid Tolouei-Rad
Edith Cowan University

Khaled GIasin

Ana Vafadar
Edith Cowan University

10.1016/j.jmrt.2020.07.078
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.
https://doi.org/10.1016/j.jmrt.2020.07.078

J MATER RES TECHNOL. 2020;9(xx):10991–11002

Available online at www.sciencedirect.com

jmr&t
Journal of Materials Research and Technology
https://www.journals.elsevier.com/journal-of-materials-research-and-technology

Original Article

Machinability of Al2024, Al6061, and Al5083 alloys using multi-hole simultaneous drilling approach

Muhammad Aamir[a,*], *Majid Tolouei-Rad*[a], *Khaled Giasin*[b], *Ana Vafadar*[a]

[a] *School of Engineering, Edith Cowan University, Joondalup, WA 6027, Australia*
[b] *School of Mechanical and Design Engineering, University of Portsmouth, Portsmouth PO1 3DJ, UK*

ARTICLE INFO

Article history:
Received 4 May 2020
Accepted 22 July 2020

Keywords:
Aluminium alloys
Multi-hole drilling
Cutting force
Hole quality
Chips formation
Tool condition

ABSTRACT

Aluminium alloys are extensively used in different industries due to their good mechanical properties, machinability, low cost and reliable inspection. Drilling is one of the most important machining processes for assembly operations. The number of holes required in an assembly may vary from several holes to millions depending on the application which increases the manufacturing time and costs. In this study, a multi-spindle drill head also known as the poly-drill head is used to perform multi-hole simultaneous drilling with the aim to increase productivity. Dry drilling tests are performed on Al2024, Al6061, and Al5083 aluminium alloys using uncoated carbide tools. Thrust force, hole quality in terms of surface roughness, burr and chip formation, as well as post-machining tool conditions, were investigated under different drilling parameters. Experimental results showed that Al2024 produced fewer burrs around the hole edges, less built-up edge on tools and formed short and broken chips. Holes machined in Al6061 alloy had a good surface roughness while lowest thrust force was recorded in holes drilled in Al5083 alloy.

1. Introduction

Aluminium and its alloys are favourable choices for various applications in aerospace, automotive and marine industries [1]. Aluminium is still considered one of the most important structural materials in the aerospace industry despite the growing use of composites [2]. Aluminium is also attractive within the automotive industry due to its lightweight. It has been projected that the average content of aluminium in a car will reach 250 kgs by 2025, compared to 35 kgs in the 1970s [3]. Al2024 is one of the most commonly used aluminium alloys in primary aircraft structures. It is commonly installed in areas such as the fuselage skin due to its good resistance to fatigue crack growth, excellent damage tolerance, high fracture toughness and ease of fabrication [4]. Al6061 alloy is mainly used in the automotive industry such as in car steering knuckles, truck bodies and frames due to its good weldability and corrosion resistance [5]. Al5083 alloy is extensively used in the marine industries due to its good corrosion resistance and weldability [6].

In manufacturing industries, drilling is the primary machining process for riveting and hole making applications [7–10]. Conventional drilling remains an important machining

* *Corresponding author.*
E-mail: m.aamir@ecu.edu.au (M. Aamir).

https://doi.org/10.1016/j.jmrt.2020.07.078

operation, despite the development of the modern cutting process in manufacturing industries [11]. In drilling of aluminium alloys, poor surface finish and burrs around the hole edges are the most common problems [12]. Furthermore, dry drilling of aluminium alloys causes increased built up edge formation and rapid tool wear. Therefore, proper selection of cutting tools, machine setup and drilling parameters are important to achieve the desirable hole quality [13].

In the past literature, the majority of the drilling studies have used a single drill to create holes in the workpiece material which is also known as one-shot drilling process. For instance, Giasin et al. [14] investigated the drilling of Al2024 using a TiAlN coated drill to study the cutting forces and several hole quality metrics such as: surface roughness, burr formation, hole size, and circularity. They concluded in their study that drilling parameters significantly affected cutting forces and characteristics of hole quality. Gonçalves and Silva [15] investigated the impact of copper contents on drilling of Al6351 alloy using HSS-Co drills. The selected copper contents in the alloy were 0.07, 0.23, 0.94, 1.43 and 1.93 % where it was found that alloys with a high composition of copper had a greater hardness and ultimate tensile strength. In addition, higher cutting forces were observed with the highest copper content in the alloy. Uddin et al. [16] have used TiN-coated 8 mm HSS drills to perform one-shot drilling experiments on Al6061 alloy. They found that the tool wear increased with the number of holes due to built-up edge. In a study by Sadiq et al. [17], Al6061, Al5083, and LM6 aluminium alloys were considered for optimum drilling parameters. It was concluded that the cutting tools used for drilling Al5083 alloy had minimum built-up edge compared to the tools used for drilling the other two alloys. Moreover, Xu et al. [18] have used high strength T800/X850 CRFP to examine the different aspects of the drilling process such as workpiece damage, dimensional accuracy, morphology of holes as well as analysis of tool. They concluded that several forms of hole surface damage were formed such as matrix smearing, delamination, cracking and cavities. Apart from the abrasive wear and edge rounding of drills, the tool failure modes also extended to edge chipping. Xu et al. [19] also compared the multilayer carbon/epoxy composite-Ti6Al4V and their individual layers by performing drilling experiments using the uncoated WC/Co twist drills. Their study found that tool wear was significantly greater when drilling the stack as compared to the drilling of individual CFRP and Ti6Al4V plates. In the stack form, the hole diameter of CFRP tended to increase due to the scratching caused by the evacuated metallic chips. On the contrary, in Ti6Al4V, the deviation of hole diameter from nominal size initially decreased as a result of tool wear and then increased due to cutting vibration. Zitoune et al. [20,21] studied the drilling of CFRP/Al2024 stacks where tool wear tests have shown that stable cutting forces were observed when drilling up to 60 holes, which was considered as an ideal number of holes for drilling of CFRP/Al stack using a single tool. The study also found that the feed rate and the drill diameter had an influence on chip breakability. In another study by Xu et al. [22], minimum quality lubrication (MQL) was used in drilling of multilayer composite/titanium stacks. The results from MQL drilling were then compared against dry drilling and found that they yielded better result in terms of surface morphologies of cut composites and gave less tool wear; however, the use of MQL failed to minimize the cylindricity errors, the delamination and the thrust force when compared with dry drilling conditions. In addition, experimental studies on CFRP/Ti6Al4V were extended to compare the low frequency vibration assisted drilling (LFVAD) and conventional drilling multilayer CFRP/Ti6Al4V. It was found that the delamination in the composite, the exit burr heights and the surface quality of holes of titanium considerably decreased using the LFVAD [23].

The above literature showed that these studies are limited to focus only on one-shot drilling. It is worth noting that in industries like aerospace where a large number of holes is required, there is need to improve the productivity by reducing the machining time and to maintain hole quality. Therefore, using multi-spindle simultaneous drilling can be an excellent choice to achieve these requirements. Simultaneous hole drilling is performed using a multi-spindle head or poly-drill head that carries multiple tools. Multi-spindle heads are specialized tool holders that mount on machine tools and are used for mass production to improve productivity by producing several holes simultaneously and thus, reducing the machining time [24,25]. In our previous study [26], a comparison between multi-spindle simultaneous drilling and one-shot drilling was conducted, showing that multi-spindle drilling performed better in terms of hole quality by giving a lower surface roughness and burrs. Furthermore, the chips produced by multi-spindle drilling were short and well broken as compared to those of one-shot drilling. Moreover, the condition of the tool after the process of the multi-spindle drilling was better and most importantly the cycle time was reduced, which would result in higher productivity. Furthermore, in our other study [27], it was shown that multi-spindle drilling led to less deviation from the nominal size of the hole as compared to one-shot drilling. The low cutting speed and feed were suggested for the optimized drilling parameters. Therefore, simultaneous drilling using a multi-spindle was found to give better holes compared to the holes produced in one shot drilling process.

In this work, drilling studies using multi spindle drilling head were carried out on three grades of aluminium alloys i.e. Al2024, Al6064, and Al5083. The aim of this work is to evaluate and compare the effect of the cutting parameters on the generated thrust force, hole surface roughness and chip formation for the studied alloys. In addition, Analysis of variance was employed to statistically evaluate the cutting parameters and measured outputs. The studies also aim to show that multi-spindle simultaneous drilling experiments tend to increase productivity and reduce cycle time without compromising hole quality.

2. Materials and methods

In this work, a SUNHER poly-drill head type MH30/13 was used for multi-hole simultaneous drilling. This type has three adjustable spindles that can be easily changed and adjusted as required. The poly-drill head was mounted on the vertical turret milling machine. Fig. 1 illustrates the multi-spindle drill head set up on the vertical milling machine. The milling

Table 1 – Chemical compositions in wt% [32].

Element	Composition in wt%								
	Mg	Si	Mn	Ti	Z	Cu	Fe	Cr	Al
Al2024	1.2–1.8	0.5	0.3–0.9	0.15	0.25	3.8–4.9	0.5	0.1	Balance
Al6061	0.8 - 1.2	0.4–0.8	0.15	0.15	0.25	0.15–0.4	0.7	0.04–0.35	Balance
Al5083	4.0–4.9	0.4	0.4–1.0	0.15	0.25	0.1	0.4	0.05–0.25	Balance

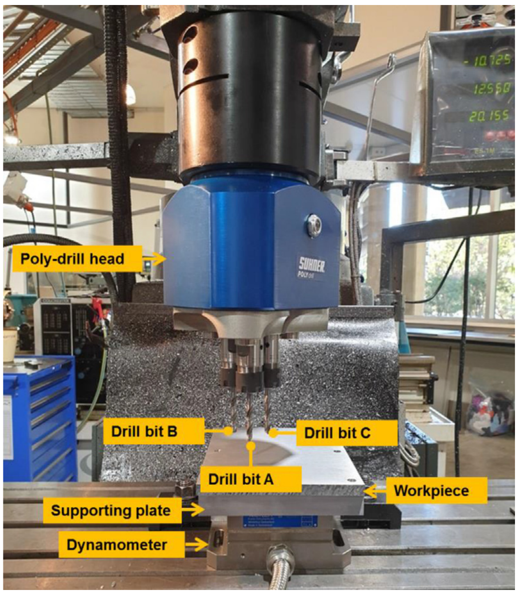


Fig. 1 – Multi-spindle drill head.

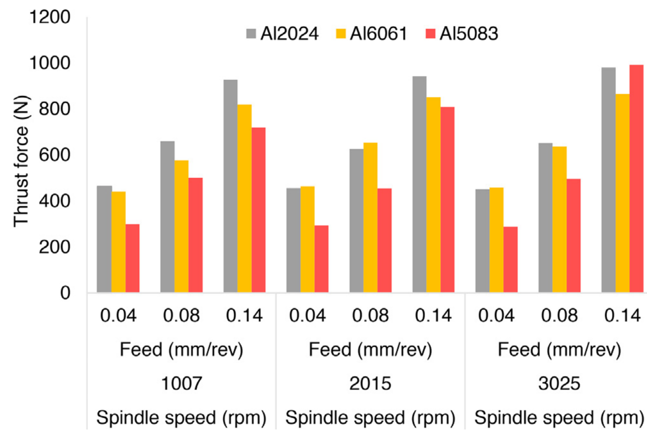


Fig. 2 – Average thrust force.

machine has a maximum spindle of 3500 rpm. Therefore, the combination of drilling parameters used in this study was selected based on previous studies and the available spindle speeds and feeds on the milling machine.

All experiments were performed under dry drilling conditions. Dry drilling conditions help in reducing the cost and problems involved with recycling chips [28]. The tools used in this study include carbide twist drills with a point angle of 140° and helix angle of 30°. Carbide drills are recommended for dry drilling of aluminium alloys [29] where high point and helix angles are recommended to reduce surface roughness and burr height [30,31].

The materials used in this work include Al2024, Al6061, and Al5083 plates. The chemical composition and some properties of the materials are given in Tables 1 and 2, respectively.

The thrust force was measured using the Kistler force dynamometer type 9257BA [26]. To prevent any damage to the dynamometer, a support plate was used at its top where the workpiece was fixed and bolted. The surface roughness of holes was measured using the surface roughness tester type TR200 by rotating the workpiece along its edges at 0°, 90°, 180°, and 270° and then the average of the values was taken for evaluation, similar to previous studies [14]. The quality of the holes was inspected at the entry and exit sides of holes using a digital microscope. The condition of tools after the drilling process was inspected under optical microscopy. Finally, Analysis of variance (ANOVA) was used with a confidence interval of 95% to determine the percentage contribution of the speed and feed on studied hole parameters. The details of the equipment and other experimental conditions are given in Table 3.

3. Results and discussion

3.1. *Thrust force*

The thrust force is considered as one of the important parameters in drilling process [33] which often defines the tool wear and quality of holes [34]. Fig. 2 shows the average values of thrust force using the multi-spindle head under different spindle speeds and feeds. Results showed that the impact of feed on thrust force was higher than that of the spindle speed. The high thrust fore due to increase in feed might be due to increase in uncut chip and the energy required for cutting [36]. This is because the chip thickness increases and thus, the material showed resistance against rupturing leading to a higher thrust force [35]. Furthermore, with the increase in the spindle speed, there was a decrease in the thrust force since at high spindle speeds the material ductility increases because of the rise in drilling temperatures [37]. Fig. 2 also illustrates that at some stages, especially at high feeds, there was an increase in the thrust force as the spindle speed increased which might be due to the tool wear with an increase in the number of holes [38]. The ANOVA results in Table 4 also show that feed has the highest percentage contribution on thrust force. The percentage contribution of feed on thrust force was 99.42%, 97.98%, and 92.04% for Al2024, Al6061, and Al5083, respectively.

Moreover, according to Kaplan et al. [38], mechanical properties, especially the hardness of the material might also affect the thrust force. This is because materials with higher hardness can cause greater wear to the tool and thus drilling generates more thrust force. Therefore, Fig. 2 also illustrates

Table 2 – Properties of aluminium alloys [32].

Properties	Aluminium alloy		
	Al2024	Al6061	Al5083
Machinability	70%	50%	30%
Shear strength (MPa)	283	207	190
Ultimate tensile strength (MPa)	483	310	317
Hardness, Vickers	137	107	96
Elongation at break	18%	12%	16%
Modulus of elasticity (GPa)	73.1	68.9	71
Hardness, Brinell	120	95	85
Thermal conductivity (W/m-K)	121	167	117
The average coefficient of thermal expansion (Coefficient from 20 to 100 °C) (μm/m-°C)	23.2	23.6	23.75

Table 3 – Equipment details and experimental conditions.

Experimental details	
Machine tool	Vertical turret milling machine
Multi-spindle drill	SUNHER adjustable poly-drill head type MH30/13
Spindle speed (rpm)	1007, 2015, and 3025
Feed (mm/rev)	0.04, 0.08 and 0.14
Drilling environment	Dry condition
Drill bits	Carbide twist drills, diameter: 6 mm, point angle: 140° and helix angle: 30°
Workpiece material	Al2024, Al6061, and Al5083 plates each having a size of 150 mm x 200 mm and a thickness of 10 mm
Drilling force	3-component piezoelectric Kistler force dynamometer type 9257BA
Surface roughness	Surface roughness tester type TR200
Hole quality in terms of burrs	USB digital microscope
Post-machining tool signatures	Optical microscope type LEICA M80

Table 4 – ANOVA results for thrust force.

Al2024							
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	4	372138	99.57%	372138	93035	233.46	0
Linear	4	372138	99.57%	372138	93035	233.46	0
n	2	586	0.16%	586	293	0.74	0.534
f	2	371552	99.42%	371552	185776	466.19	0
Error	4	1594	0.43%	1594	399	–	–
Total	8	373732	100.00%	–	–	–	–
Al6061							
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Source	4	234639	99.57%	234639	58660	229.63	0
Model	4	234639	99.57%	234639	58660	229.63	0
Linear	2	3744	1.59%	3744	1872	7.33	0.046
n	2	230895	97.98%	230895	115448	451.94	0
f	4	1022	0.43%	1022	255	–	–
Error	8	235661	100.00%	–	–	–	–
Al5083							
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	4	475339	94.64%	475339	118835	17.67	0.008
Linear	4	475339	94.64%	475339	118835	17.67	0.008
n	2	13066	2.60%	13066	6533	0.97	0.453
f	2	462273	92.04%	462273	231137	34.36	0.003
Error	4	26908	5.36%	26908	6727	–	–
Total	8	502247	100.00%	–	–	–	–

Spindle speed (*n*) Feed (*f*).

that the highest thrust force is generated by Al2024, which has hardness values followed by Al6061 and Al5083 (see Table 4). It should be noted that the high hardness value of Al2024 is due to its high contents of copper [15]. However, a slight increase in thrust force generated by Al5083 was noted at the highest spindle speed and feed, either due to high built-up edges of the tools, long and thickened chips, or higher surface roughness which is further justified in the following sections.

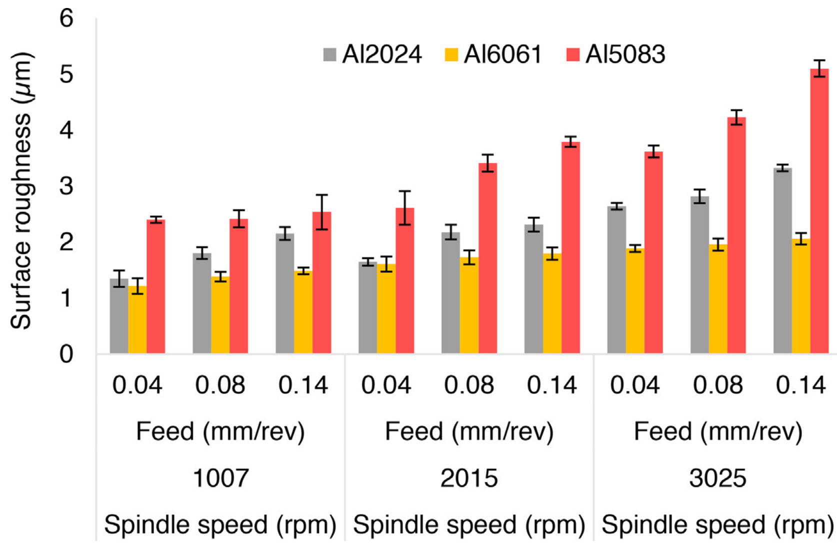


Fig. 3 – Surface roughness.

Table 5 – ANOVA results for surface roughness.

Al2024							
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	10	9.12641	97.20%	9.12641	0.91264	55.46	0
Linear	4	8.92169	95.02%	8.92169	2.23042	135.55	0
n	2	6.59179	70.20%	6.59179	3.2959	200.3	0
f	2	2.32989	24.81%	2.32989	1.16495	70.8	0
2-Way Interactions	4	0.15144	1.61%	0.15144	0.03786	2.3	0.103
n x *f*	4	0.15144	1.61%	0.15144	0.03786	2.3	0.103
Error	16	0.26328	2.80%	0.26328	0.01645	–	–
Total	26	9.38968	100.00%	–	–	–	–
Al6061							
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	10	1.9062	87.20%	1.9062	0.19062	10.9	0
Linear	4	1.87094	85.59%	1.87094	0.467734	26.74	0
n	2	1.671	76.44%	1.671	0.8355	47.77	0
f	2	0.19994	9.15%	0.19994	0.099969	5.72	0.013
2-Way Interactions	4	0.0109	0.50%	0.0109	0.002724	0.16	0.958
n x *f*	4	0.0109	0.50%	0.0109	0.002724	0.16	0.958
Error	16	0.27983	12.80%	0.27983	0.017489	–	–
Total	26	2.18603	100.00%	–	–	–	–
Al5083							
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	10	21.3983	96.53%	21.3983	2.13983	44.51	0
Linear	4	19.6628	88.70%	19.6628	4.91571	102.25	0
n	2	15.7337	70.98%	15.7337	7.86686	163.63	0
f	2	3.9291	17.72%	3.9291	1.96455	40.86	0
2-Way Interactions	4	1.6282	7.34%	1.6282	0.40705	8.47	0.001
n x *f*	4	1.6282	7.34%	1.6282	0.40705	8.47	0.001
Error	16	0.7692	3.47%	0.7692	0.04808	–	–
Total	26	22.1675	100.00%	–	–	–	–

3.2. *Surface roughness*

Fig. 3 shows the surface roughness of holes measured under different drilling parameters. The results showed that the surface roughness was affected by both spindle speed and feed. Previous studies have shown that surface roughness has an inverse relation with the spindle speed where one reason was found to be the contact of the material with the tooltip for a shorter period; another reason could be due to increased surface temperature of the workpiece which softens the materials and ultimately the resistance offered by the material against the tool reduces [39]. However, in this study, the surface roughness is shown to increase with increases in spindle speed which is in agreement with Yaşar et al. [12]. This might be due to the vibration exerted by the three tools of the multi-spindle head during simultaneous drilling at high spindle

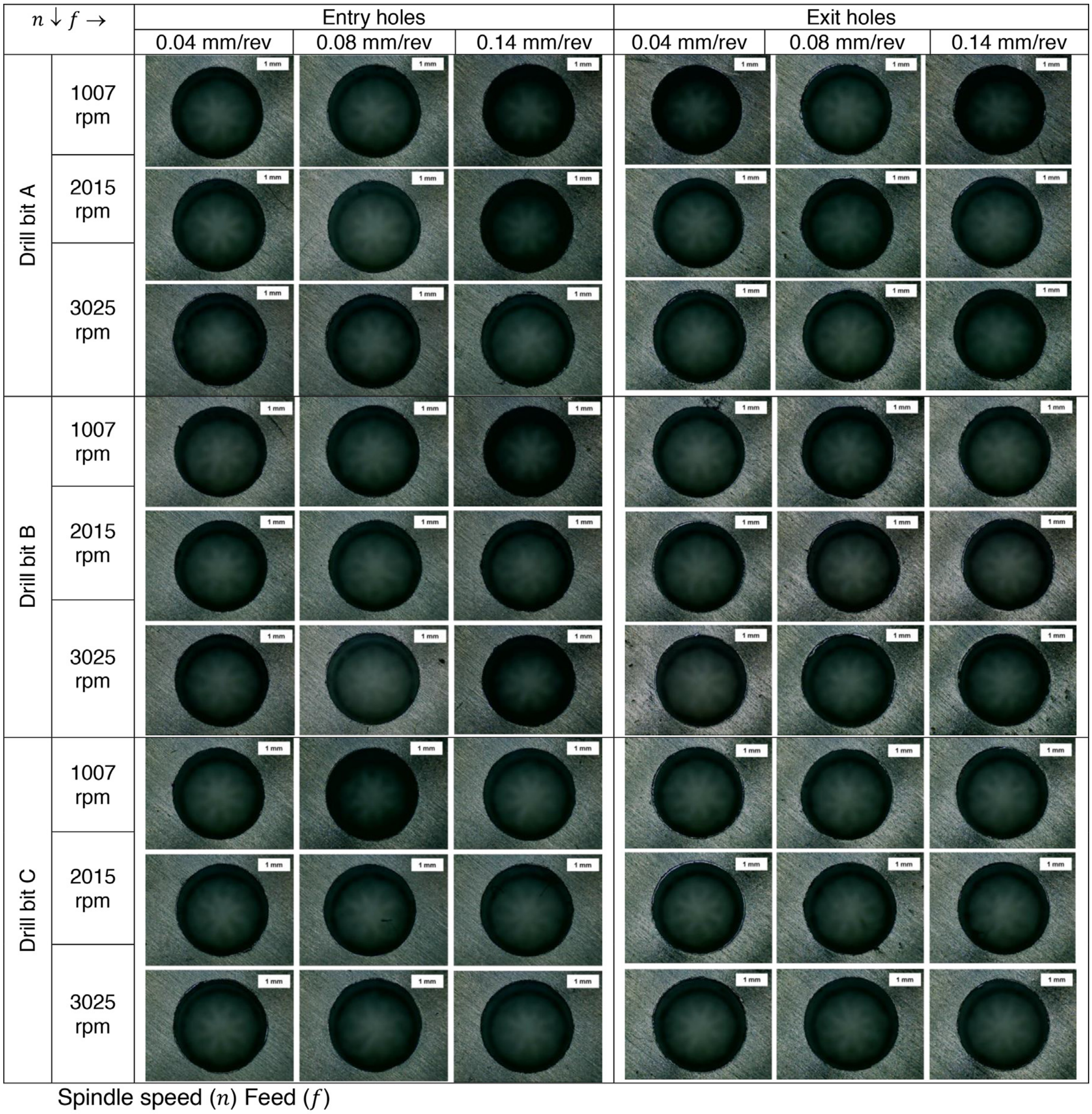


Fig. 4 – Hole images of Al2024.

speed. Furthermore, surface roughness was also affected at higher feeds where the friction between the tool and the workpiece increase due to higher material removal rate, and in return increases the surface roughness [39]. Additionally, the high values of surface roughness at high feed could be due to deformation in the workpiece near the hole wall due to high thrust force and more aggressive vibration of the machine tool structure [40]. These results are also in agreement with our previous investigations [27].

The ANOVA results in Table 5 indicate that the percentage contribution of spindle speed on surface roughness was 70.20%, 76.44%, and 70.98% for Al2024, Al6061, and Al5083, respectively. However, the feed was found to be 24.81% for Al2024, 9.15% for Al6061, and 17.72% for Al5083. Other parameters and their interactions did not show any significant contribution towards the surface roughness.

The results also show that under the same drilling parameters, the surface roughness of Al6061 was the lowest followed by Al2024 and Al5083, respectively. This could be related to the fact that the percentage content of silicon in metallic alloys can influence the surface roughness [41]. Previous studies have indicated that alloys with high silicon content tend to have lower surface roughness irrespective of drilling parameters [42,43]. Therefore, it is speculated that the higher content of silicon in Al6061 alloy resulted in low surface finish compared to that in Al5083 and Al2024 alloys, respectively. The reason for the higher surface roughness in Al2024 than Al6061, despite its higher hardness, might be due to its higher percentage elongation as shown in Table 2. This is in agreement with Köklü [44] who concluded that a higher value of elongation shows the higher ductility of the material which contributes to higher surface roughness. Al5083 possessed the worst surface roughness due to its poor machinability and low silicon con-

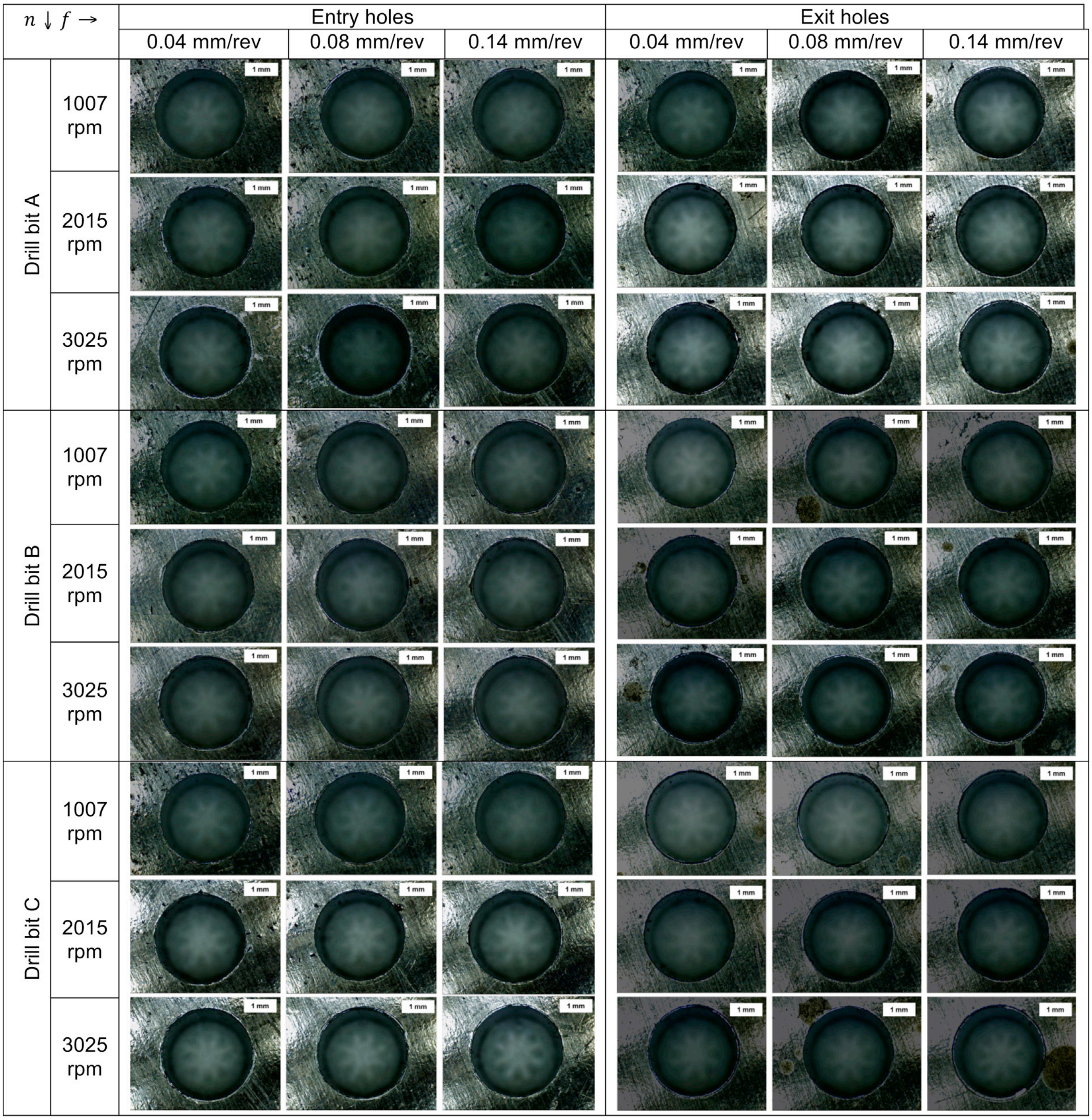


Fig. 5 – Hole images of Al6061.

tents. Another reason for the higher surface roughness values of Al5083 alloy might include the formation of higher built-up edges. Similarly, it could be due to the lower hardness of Al5083 alloy which is an important material characteristic affecting the surface roughness [45].

3.3. *Analyses of hole quality*

Figs. 4–6 show images of the holes at different drilling parameters. According to Yazman et al. [36], there are three types of burrs i.e. uniform, transient and crown burrs. Among all these types, crown burrs are large sizes around the exit hole and irregular in shape where they need more attention. In this study, visual and optical microscopic inspection reveals that the majority of formed burrs are uniform, which reflects that the multi-spindle simultaneous drilling gives better hole quality in terms of burrs. Figs. 4–6 also show that the influence of the feed was found to be more significant as compared to spindle speed because of the formation of more burrs, regardless of the alloy grade. In addition, spindle speed also displayed some influence on burrs, especially at a high feed. This might be due to the dynamic behaviour of the drilling tool as according to Kurt et al. [13], the vibration might be maximum when drill touches the workpiece. Another reason for the formation of burrs at high spindle speed may be due to the increase in temperature at the tool-workpiece interface, subsequently resulting in high plastic deformation around the edges of the hole [46]. Furthermore, burrs at the hole edges were more visible at the exit than those at the entrance side, which is in agreement with Uddin et al. [16]. Figs. 4–6 also illustrate

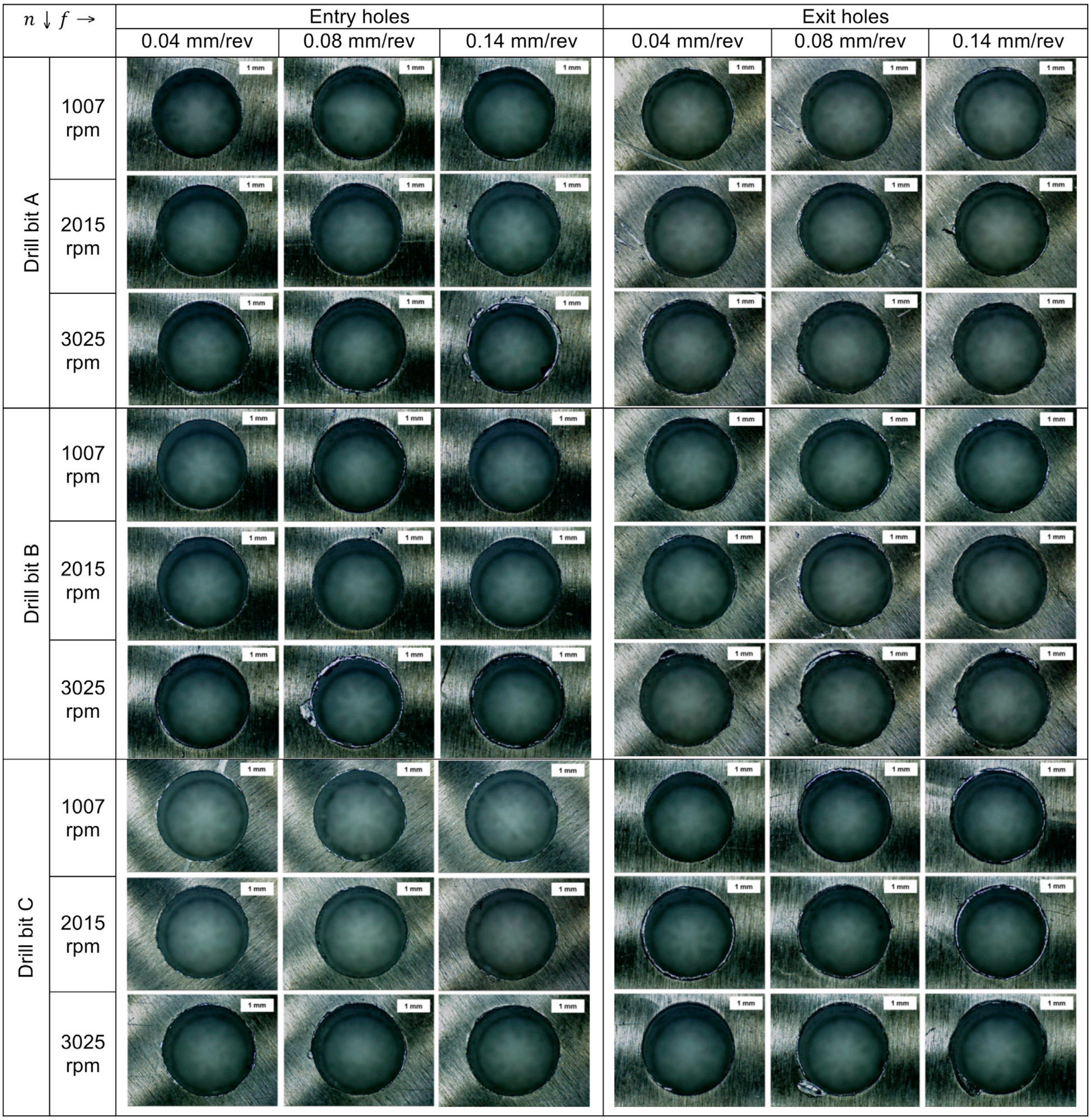
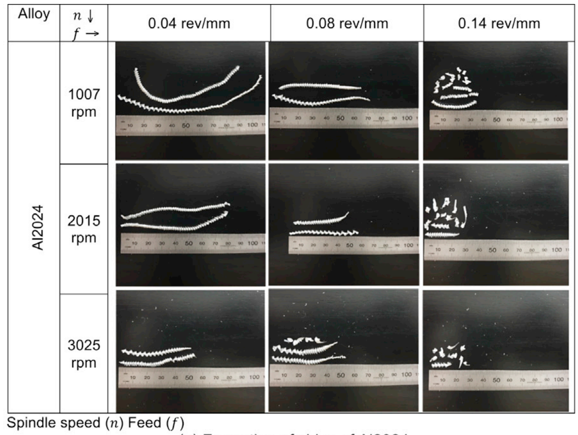


Fig. 6 – Hole images of Al5083.

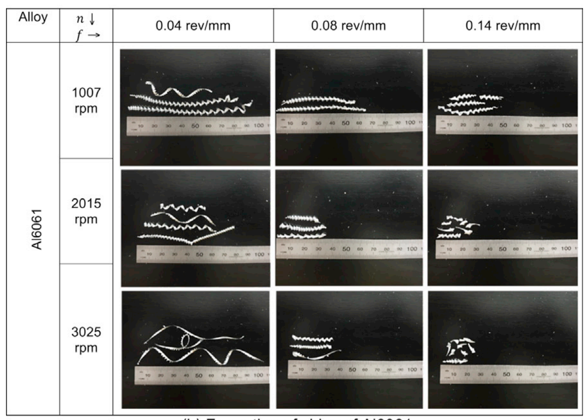
that Al2024 alloy showed hole quality with very little or no burrs around the hole edges, which might be due to its better machinability as compared with Al6061 and Al5083 alloys. Besides, the holes produced from the drilling of Al6061 alloy seem better than Al5083 alloy, which could be explained by its less ductile nature. A likely explanation could be found in a study by Köklü [44], where the ductility was found to be more influential on the amount of burr around the hole edges. It can also be noted that the reason for larger and irregular burrs formed around the edges of Al5083 alloy may be due to its high ductility, poor machinability, and large coefficient of thermal expansion as illustrated in Table 4 [32]. Another reason might be due to longer or greater chip thickness, which is further justified by the analyses of chips in the following section.

3.4. *Chips analyses*

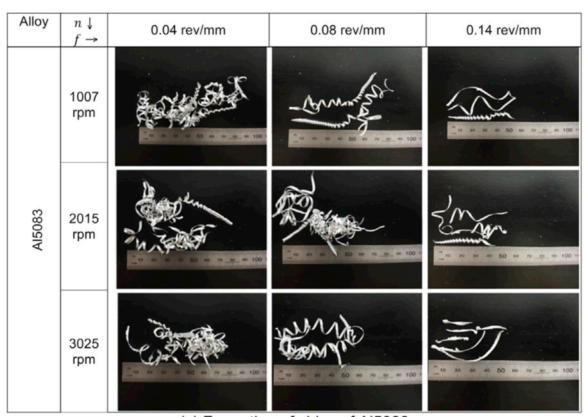
During machining of aluminium alloys, generally, well broken and small size chips are desirable for better hole quality and tool life [47]. Fig. 7(a) to (c) show the collection of chips under different drilling parameters for Al2024, Al6061, and Al5083, respectively. Generally, it was observed that the thickness of the chips decreased with the increase of the spindle speed and increased with increases of feed rate; which is in agreement with [14]. Similarly, the length of the chips decreased with increases in both spindle speed and feed [48]. The length of chips for Al2024, Al6061, and Al5083 ranged between 1.5 to 10.5 cm, 20 to 10 cm and 5.5 to 10 cm, respectively. However, it should be noted that in Al2024 most the chips produced at different drilling parameters are small, thin and well bro-



(a) Formation of chips of Al2024



(b) Formation of chips of Al6061



(c) Formation of chips of Al5083

Fig. 7 – (a) Formation of chips of Al2024 (b) Formation of chips of Al6061 (c) Formation of chips of Al5083.

ken compared with Al6061 and Al5083. In addition, most of the long and curl chips were formed by Al5083 that tangled around the drill as shown in Fig. 8. Zhu et al. [49] have also reported that long chips can easily curl around the tool which required manual removal. These chips are also responsible for the built-up edge and this was the reason that Al5083 showed a high built-up edge on the drills. Furthermore, small and segmented chips prevent the drill from breaking [50]. In this study, it is worth noting that during simultaneous drilling using the multi-spindle head, the length of the chips observed for Al2024 was found to be less than those observed for Al6061 and Al5083 due to its good machinability. This justified the reason for better hole quality as well as the low formation of a built-up edge in Al2024 regardless of drilling parameters. Also, the reason for shorter and thinner chips of Al6061 as compared to Al5083 was due to its high silicon contents which are in agreement with findings reported by Akyüz [42], concluding that alloys of aluminium containing high silicon contents and high hardness could form chips of shorter length.

3.5. *Post machining tool condition*

In machining of aluminium, some of the cut material from the workpiece is melted during the drilling process and adhere to

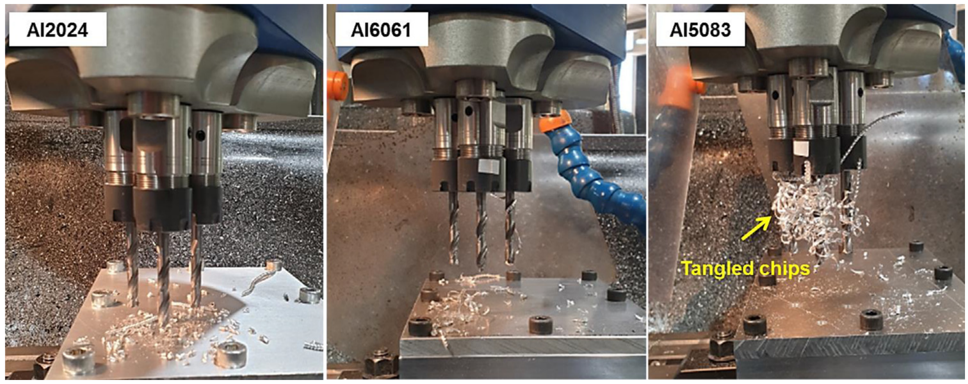


Fig. 8 – Chips tangled around the drills.

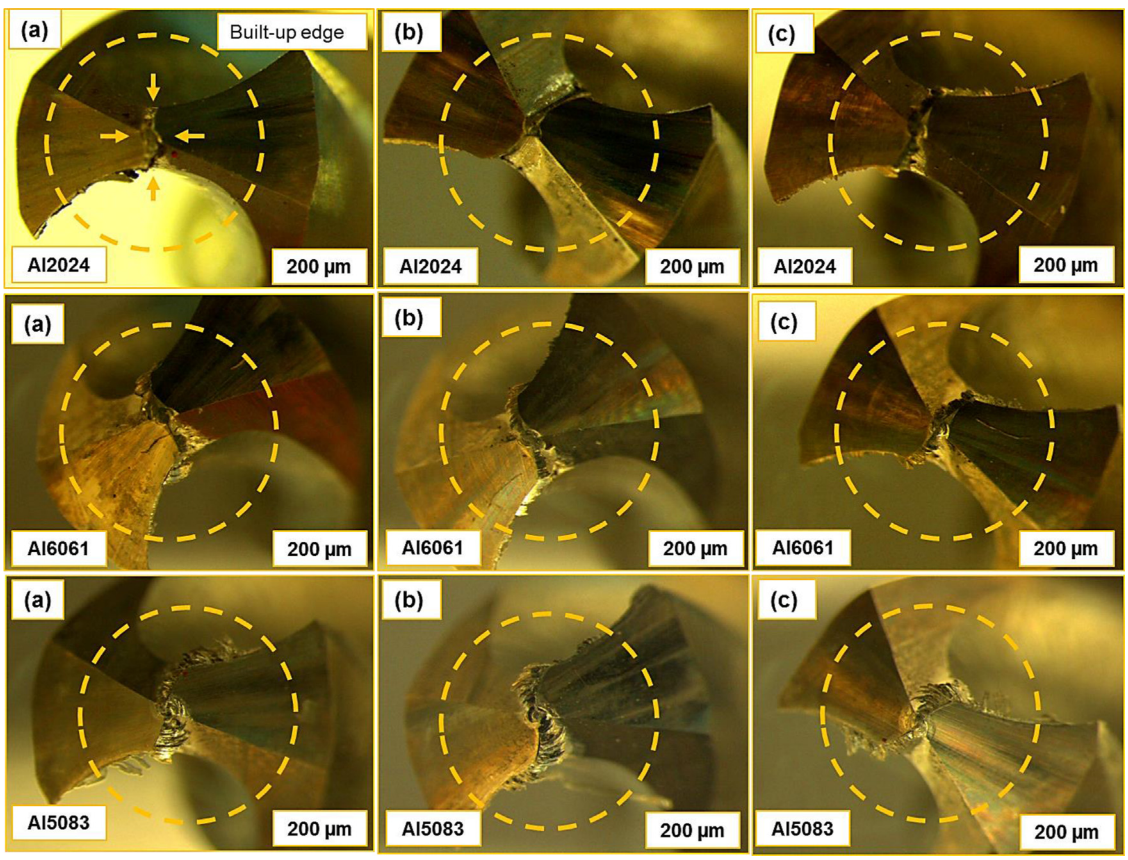


Fig. 9 – Drills condition.

the surface of the cutting tool creating built-up edge. Fig. 9 shows the post-machining conditions of the drills where built-up edge can be seen on all the drills used in the drilling trials of Al2024, Al6061, and Al5083. Fig. 9 also illustrates that cutting tools used for drilling Al5083 alloy showed the highest built-up edge due to large adhesion compared with the cutting tools used for drilling of the other two alloys. This could be due to the large number of chips tangled around the drills during multi-spindle simultaneous drilling, as shown in Fig. 8. Another reason for the higher built-up edge could be the low contents of silicon because as Akyüz [42] has reported, the built-up edge is found more in alloys with the low silicon content. In addition, the low hardness value of Al5083 alloy also contributed in forming the highest built-up edges on the tools because alloys with low hardness values have more tendency to form built-up edges [45]. Furthermore, drilling parameters also participated in adhesion and the formation of built-up edges, regardless of the different alloys.

4. Conclusions

In this work, a multi-spindle drill head was used to perform multi-hole simultaneous drilling for improving productiv-

ity and reducing time. Different aluminium alloys including Al2024, Al6061, and Al5083 were used, representing applications of aerospace, automotive, and marine industries respectively.

Regardless of drilling parameters, the highest thrust force was generated by Al2024 due to its high hardness value followed by Al6061, and Al5083, respectively. Feed was found to be more effective in increasing the thrust force as compared to the spindle speed. Holes drilled in Al6061 alloy showed least surface roughness due to its high silicon content, while the highest surface roughness was found in holes drilled in Al5083 alloy. Both spindle speed and feed affected the surface roughness, regardless of type of the alloy; however, the spindle speed was found to be more influential than the feed. Holes drilling in Al2024 alloy showed less burr formation around the hole edges than that found in Al6061 and Al5083 alloys. Furthermore, the chips produced by Al2024 were formed as short and fragmented, which is an important factor in reducing cutting tool built-up edge. The post-machining tool conditions indicated that least built-up edge was formed on Al2024 followed by Al6061, while Al5083 showed the highest built-up edge due to long and thick chips tangled around the tools.

Conflict of interest

The authors declare no conflicts of interest.

Acknowledgements

The authors would like to thank the technical staff, especially Adrian Davis for his help and support in experiments at the Manufacturing Engineering Lab, School of Engineering, Edith Cowan University, Australia. The first author would also like to thank Edith Cowan University for the awarded (ECU-HDR) higher degree research scholarship and the open access funding support.

REFERENCES

[1] Santos MC, Machado AR, Sales WF, Barrozo MA, Ezugwu EO. Machining of aluminum alloys: a review. Int J Adv Manuf Technol 2016;86(9-12):3067–80.
[2] Mouritz AP. Introduction to aerospace materials. Sawston, Cambridge, UK: Elsevier Science; 2012.
[3] Bach R. https://www.aluminiumleader.com/application/transport/, 2020 (Accessed 26 April 2020).
[4] Dursun T, Soutis C. Recent developments in advanced aircraft aluminium alloys. Materials & Design (1980-2015) 2014;56:862–71.
[5] Demir H, Gündüz S. The effects of aging on machinability of 6061 aluminium alloy. Mater Des 2009;30(5):1480–3.
[6] Sunny JJKora T, Mangalathu Georgekutty S, Mathew Jeeno. A review on mechanical & microstructural property evaluation of aluminium 5083 alloy weldment. Int J Mech Prod Eng Res Dev 2013;3(4):119–28.
[7] Aamir M, Tolouei-Rad M, Giasin K, Nosrati A. Recent advances in drilling of carbon fiber–reinforced polymers for aerospace applications: a review. Int J Adv Manuf Technol 2019;105(5-6):2289–308.
[8] Giasin K, Hawxwell J, Sinke J, Dhakal H, Köklü U, Brousseau E. The effect of cutting tool coating on the form and dimensional errors of machined holes in GLARE® fibre metal laminates. Int J Adv Manuf Technol 2020;107(5):2817–32.
[9] Giasin K, Ayvar-Soberanis S. An investigation of burrs, chip formation, hole size, circularity and delamination during drilling operation of GLARE using ANOVA. Compos Struct 2017;159:745–60.
[10] Giasin K, Ayvar-Soberanis S. Microstructural investigation of drilling induced damage in fibre metal laminates constituents. Compos Part A Appl Sci Manuf 2017;97:166–78.
[11] Kurt M, Bagci E, Kaynak Y. Application of Taguchi methods in the optimization of cutting parameters for surface finish and hole diameter accuracy in dry drilling processes. Int J Adv Manuf Technol 2009;40(5-6):458–69.
[12] Yaşar N, Boy M, Günay M. The effect of drilling parameters for surface roughness in drilling of AA7075 alloy, MATEC Web of Conferences. EDP Sciences 2017:01018.
[13] Kurt M, Kaynak Y, Bagci E. Evaluation of drilled hole quality in Al 2024 alloy. Int J Adv Manuf Technol 2008;37(11-12):1051–60.
[14] Giasin K, Hodzic A, Phadnis V, Ayvar-Soberanis S. Assessment of cutting forces and hole quality in drilling Al2024 aluminium alloy: experimental and finite element study. Int J Adv Manuf Technol 2016;87(5-8):2041–61.
[15] Gonçalves RA, Silva MBd. Influence of copper content on 6351 aluminum alloy machinability. Procedia Manuf 2015;1:683–95.
[16] Uddin M, Basak A, Pramanik A, Singh S, Krolczyk GM, Prakash C. Evaluating hole quality in drilling of Al 6061 alloys. Materials 2018;11(12):2443.
[17] Sadiq TO, Hameed BA, Idris J, Olaoye O, Nursyaza S, Samsudin ZH, et al. Effect of different machining parameters on surface roughness of aluminium alloys based on Si and Mg content. J Braz Soc Mech Sci Eng 2019;41(10):451.
[18] Xu J, Li C, Chen M, El Mansori M, Ren F. An investigation of drilling high-strength CFRP composites using specialized drills. Int J Adv Manuf Technol 2019;103(9-12):3425–42.
[19] Xu J, Zhou L, Chen M, Ren F. Experimental study on mechanical drilling of carbon/epoxy composite-Ti6Al4V stacks. Mater Manuf Process 2019;34(7):715–25.
[20] Zitoune R, Krishnaraj V, Collombet F. Study of drilling of composite material and aluminium stack. Compos Struct 2010;92(5):1246–55.
[21] Zitoune R, Krishnaraj V, Collombet F, Le Roux SJCS. Experimental and numerical analysis on drilling of carbon fibre reinforced plastic and aluminium stacks 2016;146:148–58.
[22] Xu J, Ji M, Chen M, Ren F. Investigation of minimum quantity lubrication effects in drilling CFRP/Ti6Al4V stacks. Mater Manuf Process 2019;34(12):1401–10.
[23] Xu J, Li C, Chen M, Ren F. A comparison between vibration assisted and conventional drilling of CFRP/Ti6Al4V stacks. Mater Manuf Process 2019;34(10):1182–93.
[24] Tolouei-Rad M, Zolfaghari S. Productivity improvement using Special-Purpose Modular machine tools. Int J Manuf Res 2009;4(2):219–35.
[25] Tolouei-Rad M. An intelligent approach to high quantity automated machining. J Achiev Mater Manuf Eng 2011;47(2):195–204.
[26] Aamir M, Tu S, Giasin K, Tolouei-Rad M. Multi-hole simultaneous drilling of aluminium alloy: a preliminary study and evaluation against one-shot drilling process. Journal of Materials Research and Technology In press 2020.
[27] Aamir M, Tu S, Tolouei-Rad M, Giasin K, Vafadar A. Optimization and modeling of process parameters in multi-hole simultaneous drilling using taguchi method and fuzzy logic approach. Materials 2020;13(3):680.

[28] Rivero A, Aramendi G, Herranz S, de Lacalle LL. An experimental investigation of the effect of coatings and cutting parameters on the dry drilling performance of aluminium alloys. Int J Adv Manuf Technol 2006;28(1-2):1–11.
[29] Nouari M, List G, Girot F, Gehin D. Effect of machining parameters and coating on wear mechanisms in dry drilling of aluminium alloys. Int J Mach Tools Manuf 2005;45(12-13):1436–42.
[30] Nouari M, List G, Girot F, Coupard D. Experimental analysis and optimisation of tool wear in dry machining of aluminium alloys. Wear 2003;255(7-12):1359–68.
[31] Ko S-L, Lee J-K. Analysis of burr formation in drilling with a new-concept drill. J Mater Process Technol 2001;113(1-3):392–8.
[32] Committee AH. Metals Handbook: vol. 2, Properties and selection–nonferrous alloys and pure metals. Metals Park, OH: American Society for Metals; 1978.
[33] Vigneshwaran S, Uthayakumar M, Arumugaprabu V. Review on machinability of fiber reinforced polymers: a drilling approach. Silicon 2018;10(5):2295–305.
[34] Xu J, Mkaddem A, El Mansori M. Recent advances in drilling hybrid FRP/Ti composite: a state-of-the-art review. Compos Struct 2016;135:316–38.
[35] Singh RVS, Latha B, Senthilkumar V. Modeling and analysis of thrust force and torque in drilling GFRP composites by multi-facet drill using fuzzy logic. Int J Recent Trends Eng Res 2009;1(5):66.
[36] Yazman Ş, Köklü U, Urtekin L, Morkavuk S, Gemi L. Experimental study on the effects of cold chamber die casting parameters on high-speed drilling machinability of casted AZ91 alloy. J Manuf Process 2020;57:136–52.
[37] Karabulut S. Study on machining parameters for thrust force and torque in milling aa7039 composites reinforced with al2o3/b4c/sic particles. Int J Eng Technol 2016;2(2):68–75.
[38] Kaplan Y, Okay Ş, Motorcu AR, Nalbant M. Investigation of the effects of machining parameters on the thrust force and cutting torque in the drilling of AISI D2 and AISI D3 cold work tool steels; 2014.
[39] Dwivedi S, Kumar S, Kumar A. Effect of turning parameters on surface roughness of A356/5% SiC composite produced by electromagnetic stir casting. J Mech Sci Technol 2012;26(12):3973–9.
[40] Qu S, Sun F, Zhang L, Li X. Effects of cutting parameters on dry cutting of aluminum bronze alloy. Int J Adv Manuf Technol 2014;70(1-4):669–78.
[41] Balos S, Rajnovic D, Sidjanin L, Savkovic B, Kovac P, Janjatovic PJM. Tensile and fatigue properties, machinability and machined surface roughness of Al-Si-Cu alloys 2019;24(3).
[42] Akyüz B. Effect of silicon content on machinability of AL-SI alloys. Advances in Science and Technology Research Journal 2016;10(31):51–7.
[43] Kamiya M, Yakou T, Sasaki T, Nagatsuma YJMt. Effect of Si content on turning machinability of Al-Si binary alloy castings; 2008, 0801280304-0801280304.
[44] Köklü U. Influence of the process parameters and the mechanical properties of aluminum alloys on the burr height and the surface roughness in dry drilling. Mater Tehnol 2012;46(2):103–8.
[45] Ratnam M. 1.1 factors affecting surface roughness in finish turning. in: comprehensive materials finishing. Elsevier 2017;1(1):1–25.
[46] Shanmughasundaram P, Subramanian R. Study of parametric optimization of burr formation in step drilling of eutectic Al–Si alloy–Gr composites. J Mater Res Technol 2014;3(2):150–7.
[47] Zhang P, Churi N, Pei ZJ, Treadwell C. Mechanical drilling processes for titanium alloys: a literature review. Mach Sci Technol 2008;12(4):417–44.
[48] Sun J, Guo Y. A new multi-view approach to characterize 3D chip morphology and properties in end milling titanium Ti–6Al–4V. Int J Mach Tools Manuf 2008;48(12-13):1486–94.
[49] Zhu Z, Guo K, Sun J, Li J, Liu Y, Zheng Y, et al. Evaluation of novel tool geometries in dry drilling aluminium 2024-T351/titanium Ti6Al4V stack. J Mater Process Technol 2018;259:270–81.
[50] Liu K, Li J, Sun J, Zhu Z, Meng H. Investigation on chip morphology and properties in drilling aluminum and titanium stack with double cone drill. Int J Adv Manuf Technol 2018;94(5-8):1947–56.