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Original Article

Multi-hole simultaneous drilling of aluminium alloy: A preliminary study and evaluation against one-shot drilling process

Muhammad Aamir^a, Shanshan Tu^{b,*}, Khaled Giasin^c, Majid Tolouei-Rad^a

^a School of Engineering, Edith Cowan University, Joondalup, WA 6027, Australia

^b Faculty of Information Technology, Beijing University of Technology, 100124, Beijing, China

^c University of Portsmouth, School of Mechanical and Design Engineering, Portsmouth PO1 3DJ, UK

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ABSTRACT

Poly-drill heads are used in mass production to increase productivity when a large number of holes are required. In this work, drilling experiments on Al5083 aluminium alloy were carried out using a poly-drill head to measure the thrust force and assess hole quality. Analysis of chip formations and post-machining tool condition were evaluated using optical microscopy. Additional drilling tests were conducted using one-shot drilling and results obtained from the two drilling techniques were evaluated against each other. The results showed that the average thrust forces obtained from poly-drill head were slightly lower than those from one-shot drilling. Improvement in hole quality in terms of surface roughness and reduction in chip length were achieved using the poly-drill head. Furthermore, visual inspection of the tools showed that adhesion and built-up edges on drills used in the poly-drill head were lower as compared to drills used in the one-shot drilling. The contribution of input parameters on the measured outputs was determined using an ANOVA statistical tool.

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1. Introduction

The drilling process constitutes a large portion of all machining processes in several manufacturing industries [1]. In the aerospace industry, drilling is one of the most commonly used machining processes during all manufacturing stages of an aircraft, especially prior to the joining process where a large number of rivets are required for assembly of different structures [2–6]. A large commercial aircraft wing is joined together

by almost 750,000 bolts and rivets [7]. According to Felkins et al. [8], large ships contained well over a million rivets before they were replaced entirely by welding after the 1950's. The RMS Titanic which sank back in 1912 contained three million rivets. This shows the significance of drilling in the industry. Accordingly, single hole (one-shot) drilling might not be economically feasible in such large structures that require a large number of holes, where alternatives are needed to increase the productivity of the hole making process using multi-spindle heads also known as poly drill heads.

Poor hole quality reduces strength against fatigue due to stress concentration and can result in hole crack initiation within a material. Indeed, it is estimated that poor hole quality

* Corresponding author.

E-mail: ssutu@bjut.edu.cn (S. Tu).

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is responsible for 60% of all part rejections during final assembly of an aircraft [9]. Furthermore, De Lacalle et al. [10] have noted in their studies that drilling process needs to be monitored and controlled to be used systematically in industrial applications.

Giasin et al. [11] have also reported that drilling concerns arise due to poor hole quality, which subsequently affects dimensional accuracy and surface roughness (R_a). Liu et al. [12] have concluded that the surface quality of a hole deteriorates due to tool-chip friction, which causes fatigue cracks initiation due to the formation of stress concentration zones. According to Uddin et al. [13] burr formation negatively affects the dimensional accuracy, which leads to reworking, additional costs and sometimes damage due to fatigue in assembly. Therefore, deburring is required for the functional reliability of components, where it has been reported by Niknam et al. [14] that deburring accounts for nearly 30% of the total fabrication costs in an aircraft's fuselage assembly. Furthermore, Nouari et al. [15] have stated that the deterioration of tool condition is another problem due to the formation of built-up edges, which weakens tool edges and ultimately results in fracture failure. Accordingly, manufacturing industries are sensitive to their investments, since using improper machine tools can negatively affect productivity. Thus, drilling is the most challenging and necessary process in different industries and requires further research to reduce incidences of the above problems leading to improvement of hole quality [16].

Mass hole production can be achieved by using poly-drill heads. Poly-drill head (PDH) or a multi-spindle system is a drilling system that can be used to increase productivity by drilling multiple holes simultaneously and thus, reducing the overall drilling time [17]. Therefore, PDH is one way to produce a large number of holes with significant time and cost savings, as well as less operator fatigue [18].

Aluminum and its alloys are extensively used in aerospace, automotive and marine applications [19]. Aluminium 5083 (Al5083) alloy is resistance to salt water corrosion making it suitable for marine applications. This alloy is currently used in marine hulls, shipbuilding and drilling rigs due to its excellent corrosion resistance properties and excellent performance in extremely cold environments [1]. Some researchers who have investigated the machining of aluminium Al5XXX alloys are given in Table 1.

An overview of recently cited papers in Table 1 shows that only a handful of studies have been presented on the machining of Al5083. In addition, there are no systematic studies available in open literature that analyze Al5083 using multi-hole drilling techniques. Kechagias et al. [20] have conducted end-milling tests using two flute mill cutters to study the surface finish of Al5083. The tested parameters were cutting speed (V_c), depth of cut, flute angle, rake angle, peripheral relief angles, tool feed and core diameter. They concluded that V_c , the peripheral relief angle, and core diameters have more influence on the surface texture of Al5083. Davoodi et al. [21] have worked on orthogonal cutting process using Al5083 to study cutting and feed forces. They found reduction in cutting forces up to 12% when using coolant and when the thickness of the undeformed chips was up to 0.282 mm. Furthermore, High feed (f) also increased cutting forces. Bahçe et al. [22] have concluded in their study that R_a is directly influenced by

f and drill diameter; however, increases in rotation speed led to decreases in R_a . The decrease in point angle resulted in built-up edges on the tool which ultimately increased R_a . They used drilling process; however, the material was Al5005. In another study by Davoodi et al. [23], the influence of cutting parameters on Al5083 was investigated using a turning process. Their findings showed that cutting forces had a direct relation to undeformed chip thickness during both dry and wet machining. Their results also showed that dry machining of Al5083 performs better at high V_c and produces lower cutting forces than in wet cutting. Khorasani et al. [24] have used different machining parameters and coolant pressure to minimize R_a of Al5083 using a high speed milling operation. They concluded that the best surface quality is possible when the cutting fluid ranges between 2.5–3.5 bars and f between 0.41–0.45 m/min.

According to Totten et al. [25] aluminium alloys are ranked into five groups: A, B, C, D, and E in order of increasing length of the chip to decreasing order of surface quality. Al5083 is ranked in group D, which means it has poor machinability. Furthermore, researchers have focused on finding optimized machining processes using one-shot drilling (OSD). None of the previous studies reported the impact of multi-spindle drilling on hole quality in aluminium alloys in general or Al5083 in particular to the authors' knowledge. Therefore, in this work, a PDH with three adjustable spindles in the assessment of the drilling process is used and compared with OSD in terms of generated thrust force (F_z), average R_a , chips analysis and post-machining tool conditions. The study also evaluates the impact of V_c , f on F_z , R_a , chip formation and post-machining tool conditions. Furthermore, ANOVA (Analysis of Variance) is employed to determine the contribution of drilling input parameters on output parameters.

2. Experimental setup and parameters

2.1. Machine setup

The drilling experiments for both the OSD and PDH were performed on a vertical turret milling machine with a maximum spindle speed of 3500 rpm and a feed of 0.04, 0.08 and 0.14 mm/rev. Fig. 1 illustrates the experimental setup of the drilling tests. The pattern of holes using a PDH is given in Fig. 2. The same pattern was used for OSD for consistency of results.

2.2. Measurement of thrust force

The thrust force (F_z) was measured using a 3-component piezoelectric dynamometer (KISTLER 9257BA) with a built-in 3-channel charge amplifier. The charge amplifier was connected to the control unit Type 5233A1; where a type 5697A2 Kistler data acquisition system was used for interfacing and controlling charge amplifiers in force measurement. The system was connected via a USB 2.0 port and controlled by DynoWare software type: 2825A through a computer that was used to process the data in a force-time graph plot. The dynamometer was mounted on the machine bed and a support plate with a size of 20 mm × 200 mm × 150 mm was placed on the top of the dynamometer. The workpiece was fixed and

Table 1 – Summary of previous studies on machining of Al5XXX alloys.

Material information	Process	Areas studied	Concluding remarks	Ref
Al5083	End milling	R_a	The surface texture was affected more by V_c , the peripheral relief angle, and the core diameters.	[20]
Al5083	Orthogonal cutting process	C, F	Cutting forces were decreased up to 12% using coolant when the thickness of the undeformed chips was up to 0.282 mm. High f increased C.	[21]
Al5005	Drilling	R_a , W	R_a is directly influenced by f and drill diameter, however, the increase in rotation speed decreased R_a . The decrease in point angle resulted in built-up edges on the tool which ultimately increased R_a .	[22]
Al5083	Turning	C, F, T	The cutting forces and the tool-tip temperatures increased when the undeformed chip thickness increased in both dry and wet machining. However, at high V_c , the cutting forces in dry machining of Al5038 were lower than wet machining.	[23]
Al5083	High-speed thread milling	R_a	The best surface quality is possible when the cutting fluid pressure ranging 2.5–3.5 bars and f of 0.41–0.45 m/min.	[24]

Symbols: C: cutting forces, F: feed force, W: tool wear, T: drilling temperature, feed rate: f , cutting speed: V_c .

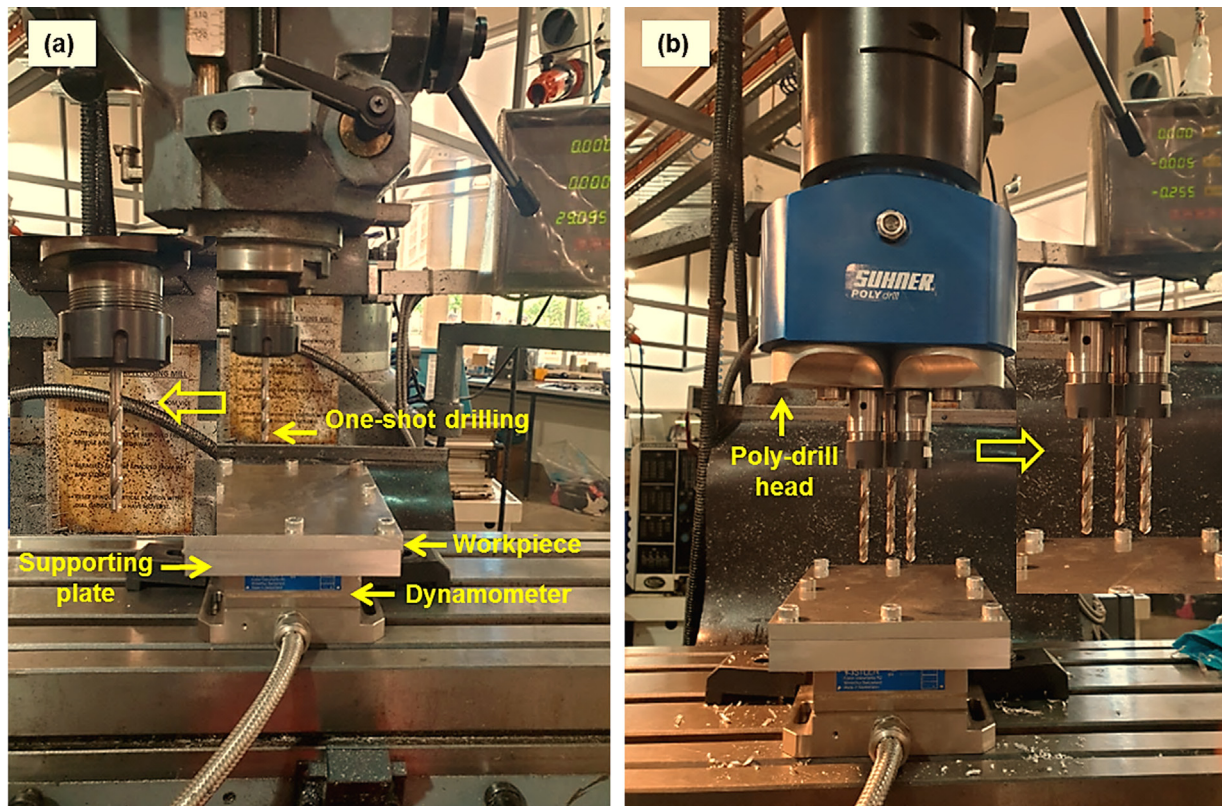


Fig. 1 – Experimental setup (a) one-shot drilling (b) poly-drill head.

bolted on a supporting plate as shown in Fig. 1. A SUNHER PDH type MH 30/13 was used for one-shot multiple drilling.

2.3. Workpiece and cutting tool details

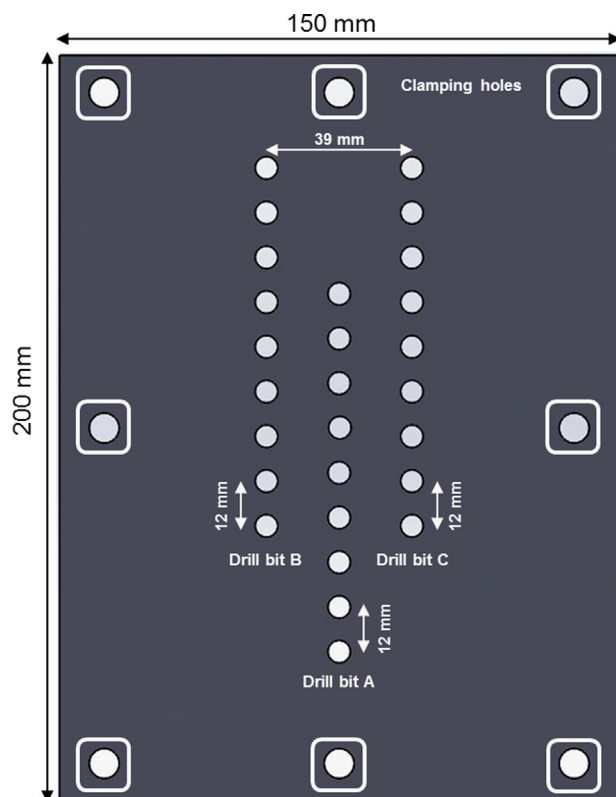
An Al5083 plate with a thickness of 10 mm and a size of $150 \times 200 \text{ mm}^2$ was used in this work. The material was purchased from Robert Cameron & Co Pty Ltd, Burswood, Western Australia. The chemical compositions and some

other properties of the Al5083 alloy are given in Tables 2 and 3, respectively.

The recommended point angles for drilling aluminium alloys are 115° – 140° depending on the silicon content in the aluminium alloy discussed by Geier et al. [7]. Therefore, 6 mm uncoated high-speed steel (HSS) twist drills with a point angle of 118° and a helix angle of 30° were used for both OSD and PDH. Additional details regarding the drills are provided in Table 4.

Table 2 – Chemical compositions of in Al5083 in wt% [26].

Element	Mg	Si	Mn	Ti	Z	Cu	Fe	Cr	Al
Value	4.0–4.9	0.4	0.4–1.0	0.15	0.25	0.1	0.4	0.05–0.25	Balance

**Fig. 2 – Pattern of holes.****Table 3 – Mechanical and physical properties of Al5083 [26].**

Property	Value
Tensile strength	317 MPa
Shear strength	185 MPa
Elongation	17%
Electrical resistivity	$0.058 \times 10^{-6} \Omega \text{ m}$
Thermal conductivity	121 W/m K
Modulus of elasticity	72 (GPa)
Density	2650 kg/m ³
Thermal expansion	$25 \times 10^{-6} \text{ m/K}$
Melting point	570 °C

2.4. Cutting parameters

The cutting parameters used in these experiments are summarized in Table 5. These combinations were considered based on previous studies and limitations of the vertical milling machine that has three fixed feed rates and a maximum spindle speed of 3500 rpm. A new tool was used to confirm the initial conditions of each drilling trial and to minimize any effect arising from tool wear. All the drilling processes were carried out under dry cutting conditions. The reason for choosing dry cutting conditions relate to the environmental risks, reduction in cost and problems related to

Table 4 – Description of the drill bit.

Specification/description	Value(s)	Drill bit
Type	Twist drill	
Material	HSS	
Overall length	93 mm	
Drill diameter	6 mm	
Point angle	118°	
Shank diameter	6 mm	
Helix angle	30°	
Number of flutes	2 mm	
Flute length	57 mm	
Purchase	Sutton Tools, Australia	
Product Barcode	D1040600	

Table 5 – Cutting speed and feed.

Cutting parameters	Level 1	Level 2	Level 3
Cutting speed (m/mm)	19	38	57
Feed (mm/rev)	0.04	0.08	0.14

recycling of chips that also encouraged industries in favour of dry machining [27]. Furthermore, in aircraft industries cutting fluids are eliminated or reduced in order to avoid the need for cleaning the structures before placing the rivets to achieve high-quality holes, especially ones free from burrs or to eliminate the need to deburr before riveting [28].

2.5. Surface roughness

The surface roughness (R_a) of the holes was measured using a portable surface roughness tester TR200 equipped with a natural diamond stylus having a 90° cone angle and a 5 μm tip radius. R_a was measured at 0°, 90°, 180°, and 270° around the hole wall by rotating the sample along its edges, where average values were taken as similar to previous studies [29].

2.6. Inspecting hole quality and tool wear

A digital optical microscope was utilized to check the hole quality. All images were taken on a scale of 1 mm. In addition, the analyses of tool wear were done using an optical microscope.

2.7. Analysis of variance (ANOVA)

ANOVA is a statistical technique that is used to determine the highest influence that each design parameter presents [30]. ANOVA gives the percent contribution which is used to show how much effect each process parameter has on output responses. In ANOVA, the P-value shows that values less than 0.05 have no effect [31] and F-value is used to check the design parameters with a significant impact on the quality characteristic [32]. The confidence interval chosen in this study is 95% ($\alpha = 0.05$). Therefore, ANOVA has been applied in this study to

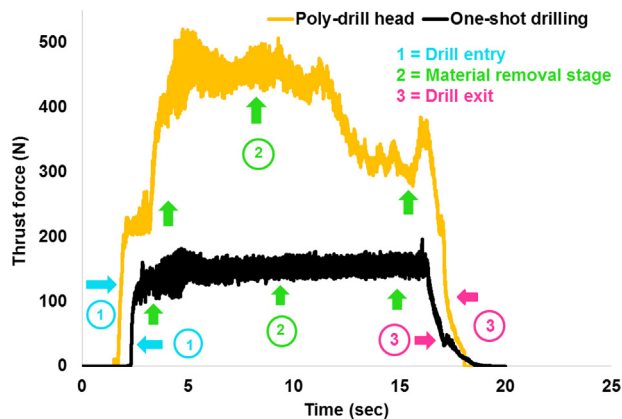


Fig. 3 – Profiles of thrust force.

measure the importance of each of the process parameters on F_z and R_a in both the drilling process including OSD and PDH.

3. Results and discussion

3.1. Cutting force analyses

In a drilling operation, F_z is one of the main force components which represents the interaction of the tool-chip and tool-machined surface as described by Xu et al. [33]. Liu et al. [34] have suggested that F_z depends on input parameters such as V_c , f , tool geometry, tool materials and coatings, number of holes, tool wear and drilling operation. The impact of different cutting parameters on drilling force using OSD has been widely researched [11,29,32,35–41]. Therefore, in this study, simultaneous drilling using a PDH with three adjustable drills is used. Fig. 3 shows the signals of the F_z of OSD and PDH for one of the drilled-holes. The signals for F_z were obtained from the dynamometer under the time domain by monitoring the feed motion of the tool from the time it entered the workpiece until it exited. It is evident from Fig. 3 that as the drilling process started, there was no force recorded because the tool was not in contact with the workpiece. Soon the tool came in contact with the workpiece, F_z started processing and a sharp increase was recorded. As the tool continued to advance into the workpiece, F_z gradually increased until it reached a steady-state maximum value. When the tool approached the bottom of the workpiece, F_z began to decrease due to lower resistance of the workpiece and ultimately reached to zero value with the completion of the hole drilling.

Fig. 4 shows the average F_z at different cutting parameters. The results indicate that F_z increased with increasing f while no significant impact of V_c on the F_z was noted and only a slight decrease was observed when V_c has increased. Beranoagirre et al. [42] have developed predictive cutting forces mechanistic models in which it was also noticed in both experimental and predictive model that F_z can be increased as f increases. Therefore, the impact of f on F_z was more dominant than V_c which is in agreement with Faraz et al. [43]. This is because the chip thickness which is cut per unit time increases and thus, the material showed resistance against rupturing leading to a higher F_z [44]. Therefore, an increase in f resulted in

higher thickness of chips which not only increased F_z but also increased R_a and hence, affected the hole quality [45]. Another reason that has been given by Melentiev et al. [46] for higher F_z could be the impact of the tool wear. When the number of holes increases, the tool wear increased continuously which ultimately increases F_z due to the higher compressive load exerted by the workpiece on the tool. Therefore, tool wear also contributed to enhancing F_z [47].

Furthermore, within plastic deformation, the strength of the material is affected due to rises in cutting temperature and strain rate; therefore, there are possibilities for cutting force to decrease at higher V_c [48]. The drop in forces is caused partially due to a decrease in the contact area and partially due to decrease in the shear strength in the flow-zone because of increases in temperature with increases in speed [49]. However, at some stages during drilling at the high V_c of 57 m/min in spite of a decrease in F_z at f of 0.14 mm/rev, F_z has slightly increased. This slight increase might be due to the tool wear because as Ramulu et al. [50] have mentioned that the tool faces excessive wear when the number of holes increases and ultimately, experiences high tool-workpiece friction that results in high energy consumption and generation of high forces.

In comparison with the OSD, the PDH showed a higher F_z as it was expected that there might be an increase in the torque due to an increase in friction and vibration of the three tools with the workpiece. However, it should be noted that the increase in F_z using a PDH is the combination of the simultaneous drilling of the three tools. However, Fig. 4 also shows that the average F_z of the three tools of the PDH is slightly less than those of OSD. To justify these conclusions, examinations of R_a , analyses of chips and post-machining tool condition were investigated.

Tables 6 and 7 show the ANOVA results for the average F_z of OSD and PDH, respectively. The results indicate that in both drilling types, f has the highest contribution to F_z . For OSD, f has a contribution of 99.57% while the PDH has 99.66%. The interaction of the cutting speeds is not considered for the F_z as the contribution of V_c is almost insignificant in comparison to f .

3.2. Evaluation of the drilled hole quality

3.2.1. Surface roughness

The R_a of any machined workpiece is important as it contributes to functional product quality including contact causing surface friction, wearing, ability to distribute and holding a lubricant, coating, and resisting fatigue as reported by Kurt et al. [32]. In this work, R_a of holes under different cutting parameters using the PDH and OSD are reported and compared. Fig. 5 shows that R_a of holes using the PDH with three adjustable drills working concurrently is lower than those of OSD, which means that PDH provides better R_a than OSD. However, in both cases of drilling process including OSD and PDH, R_a is influenced by the cutting parameters. Both V_c and f contributed to deteriorating the R_a of holes.

The reason for the increase in R_a due to high V_c might be due to the continuous rubbing of the tool on the walls of the hole which heat up the tool and the workpiece. This causes the material to be more ductile and made the hole deformed, giv-

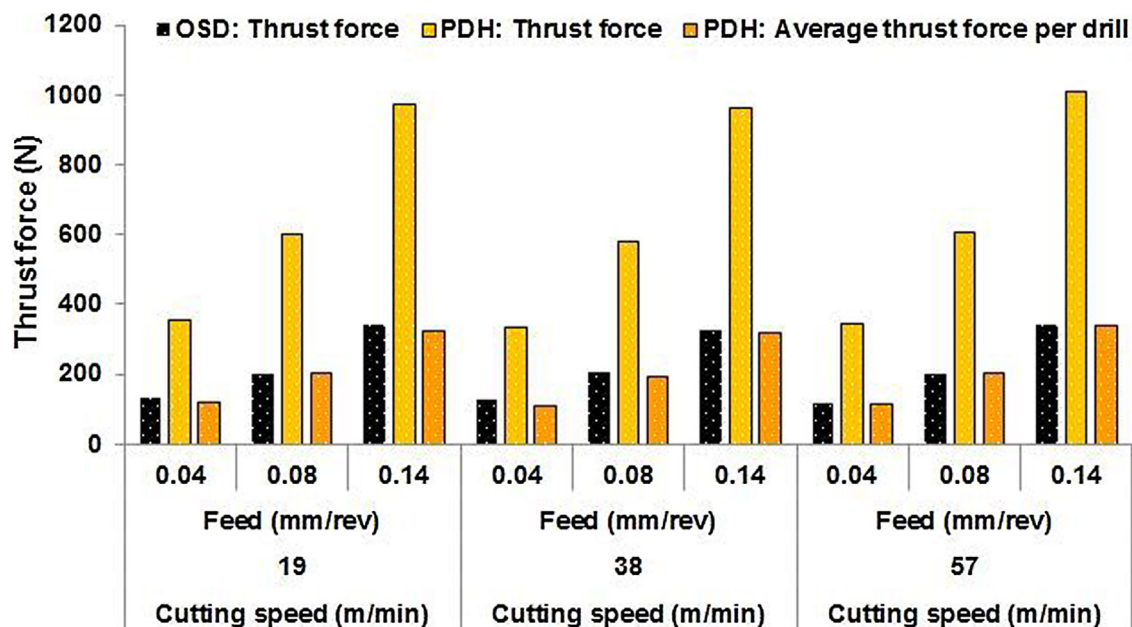


Fig. 4 – Average thrust forces under different cutting parameters.

Table 6 – ANOVA for thrust force generated from one-shot drilling.

Source	DF	Seq SS	Adj SS	Adj MS	F-value	P-value	Contribution
Model	4	69129.3	69129.3	17282.3	327.98	0.000	99.70%
Cutting speed	2	84.1	84.1	42.1	0.80	0.511	0.12%
Feed	2	69045.1	69045.1	34522.6	655.17	0.000	99.57%
Error	4	210.8	210.8	52.7	-	-	0.30%
Total	8	69340.0	-	-	-	-	100.00%

Table 7 – ANOVA for thrust force generated from the poly-drill head.

Source	DF	Seq SS	Adj SS	Adj MS	F-value	P-value	Contribution
Model	4	616131	616131	154033	820.20	0.000	99.88%
Cutting speed	2	1343	1343	672	3.58	0.129	0.22%
Feed	2	614787	614787	307394	1636.82	0.000	99.66%
Error	4	751	751	188	-	-	0.12%
Total	8	616882	-	-	-	-	100.00%

ing higher values of R_a as reported by Giasin et al. [51]. Second, at higher V_c , the tool might face more vibration and chatter, which also contributes to worsening the surface quality of holes. Furthermore, Giasin et al. [39] have mentioned that lower f is acknowledged for minimum hole damage because higher f increased the materials removal rate that caused poor R_a . Moreover, Zhu et al. [45] concluded that higher f also increased the chip thickness which affects the surface quality of holes.

The influence of V_c on R_a is found to be more than f . This is confirmed from our previous work given in Table 8 [6], in which the ANOVA results indicate that the contribution of V_c on R_a is 40.16% where the f has a contribution of 25.02% and no significant contribution with other cutting parameters and their interaction was found. The higher contribution of V_c compared to f has also been found by Kilickap [41].

Table 8 – ANOVA for surface roughness from one-shot drilling and poly-drill head [6].

Source	P-value	Contribution
Cutting speed	0	40.16%
Feed rate	0	25.02%
Drill type	0.004	4.94%
Cutting speed*feed	0.071	5.01%
Cutting speed*drill type	0.837	0.19%
Feed rate*drill type	0.768	0.28%
Cutting speed*feed rate*drill type	0.189	3.44%
Error	-	17.92%
Total	-	100.00%

3.2.2. Analyses of drilled-hole images

Figs. 6 and 7 illustrate the status of the holes at the entry and the exit of OSD and PDH, respectively. It seems that the surface

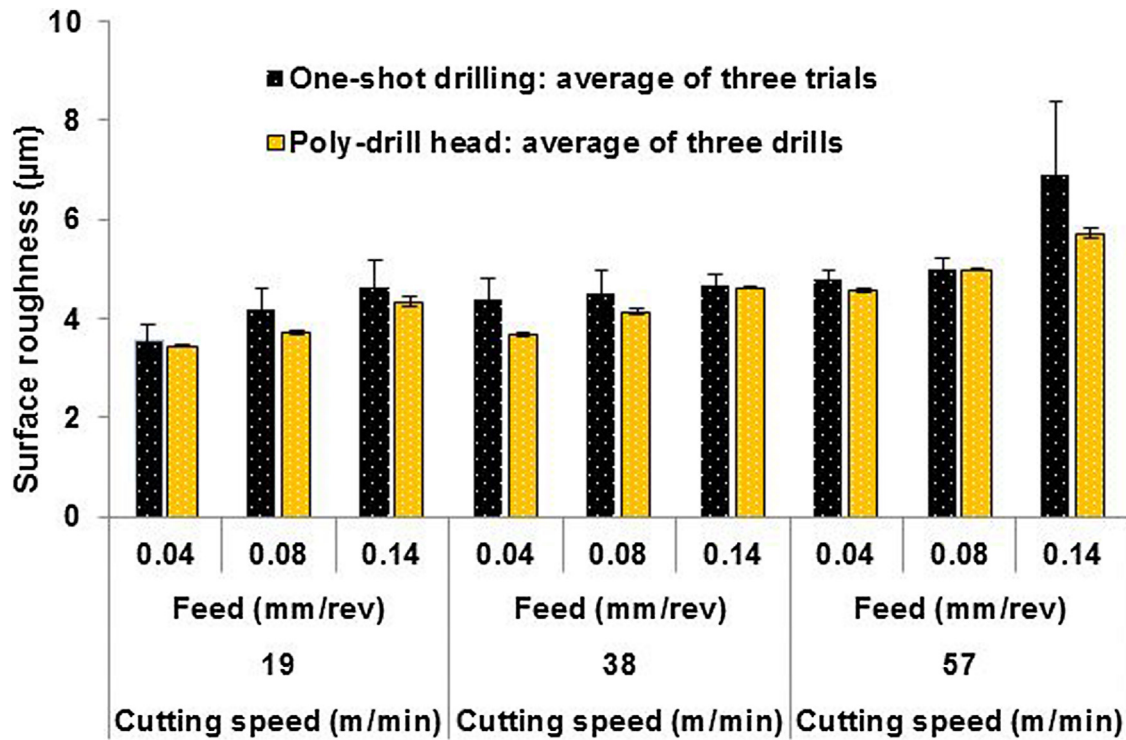


Fig. 5 – Surface roughness at different cutting parameters.

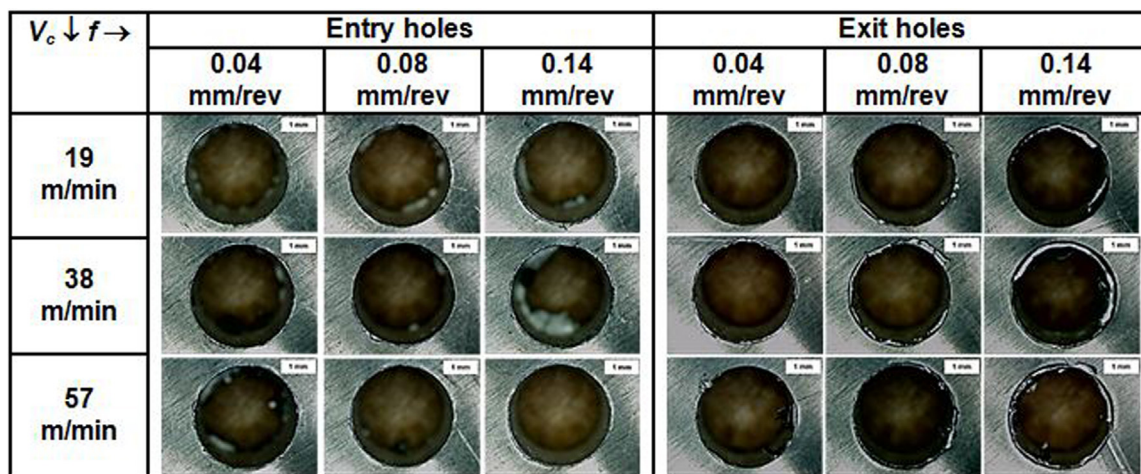


Fig. 6 – Hole images of one-shot drilling.

quality of the exit holes is more affected by cutting parameters. In addition, f had more influence on the quality of holes in comparison with V_c . The hole edge seems more uniform with little burr at lower f and apparently, V_c showed no significant damage to the hole quality. Moreover, it appears that the quality of holes at the start of the tool life was better due to less tool wear.

Zhu et al. [45] have investigated that burrs tend to create problems, especially in components of aircraft assembly. Therefore, in this work, burrs were more visible in OSD as compared with PDH. The main reason for burrs at the entrance side might be due to tearing followed by clean shearing, while

the exit burrs were expected due to thermal effect and plastic deformation of the materials. Another reason might be attributed due to the lower F_z at low f . In general, the presence of burrs around hole edges is not desirable. It is interesting to note that visual and microscopic inspection of the holes produced using PDH showed somewhat less burr as compared with OSD, especially on the entrance side. However, no prominent difference between the burrs at the entry side was observed. The reason for the good hole quality of PDH could be attributed to the lower chip thickness which should be confirmed by chips analyses.

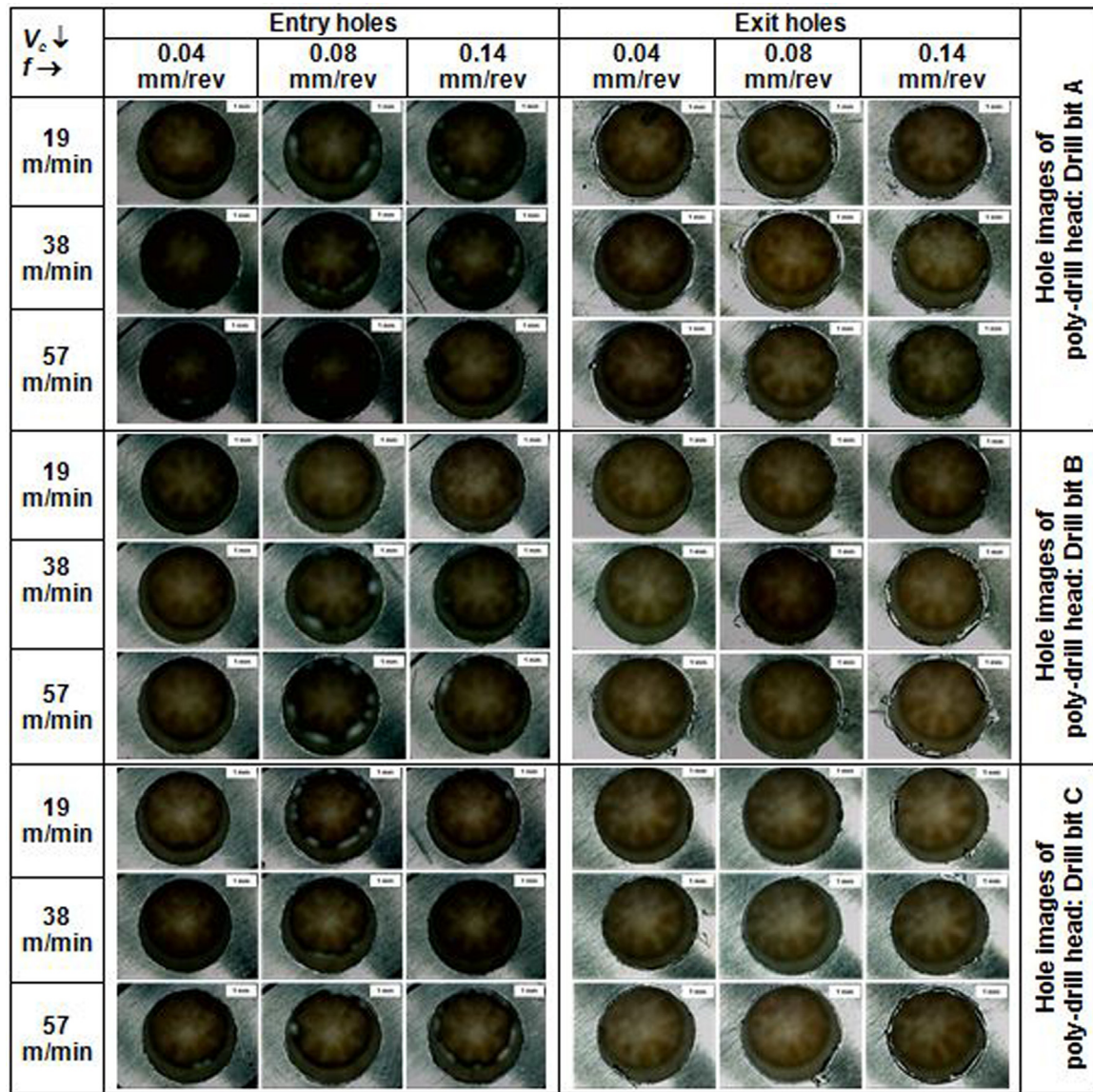


Fig. 7 – Hole images of the poly-drill head.

3.3. Analyses of chips formation

Chip formation and its breaking mechanisms are an important aspect of drilling processes as noted by Liu et al. [52], especially when machining ductile materials like aluminium, a large chip-tool contact area is formed which increases cutting forces, machining power, generates more heat, chips thickness, and affects the surface quality of holes as discussed in Trent et al. [49]. Therefore, Demir et al. [53] have suggested that it is very important to control the formation of chips when drilling aluminium alloys. Furthermore, Zhang et al. [54] have concluded that the size of the chips, mainly the length and thickness, contributed towards forming high-quality holes and less tool wear because drilling would be smooth enough when the chips are shorter in size and well broken because continuous chips in long lengths are usually tangled on the drill, which not only requires manual removal but also affects R_a . It was further noted that the chips can also

lead to blockage of the drill grooves which causes the tools to break and increases machining time. Moreover, Ozcatalbas [55] have discussed that higher cutting parameters can cause higher temperatures, which increases the ductility of the material and thus, produces longer chips. Liu et al. [52] have reported that discontinuous and segmented chips were formed at higher f . As f increased the chips started to break into pieces because higher f increased the cross-sectional area of the chips and thus, their stiffness increased which made the chips easier to break. Therefore, f has been found to be more influential in chip breakability as compared to V_c .

Figs. 8 and 9 show the collection of chips from the OSD and PDH, respectively, under different cutting parameters. Figs. 8 and 9 also illustrate that as V_c increases the thickness of the chips decreases while higher f increases them which is also reported by Giasin et al. [39]. The length of the chips also decreases as the V_c and f increase, and this is in agreement with Sun et al. [56]. However, it was observed that chips

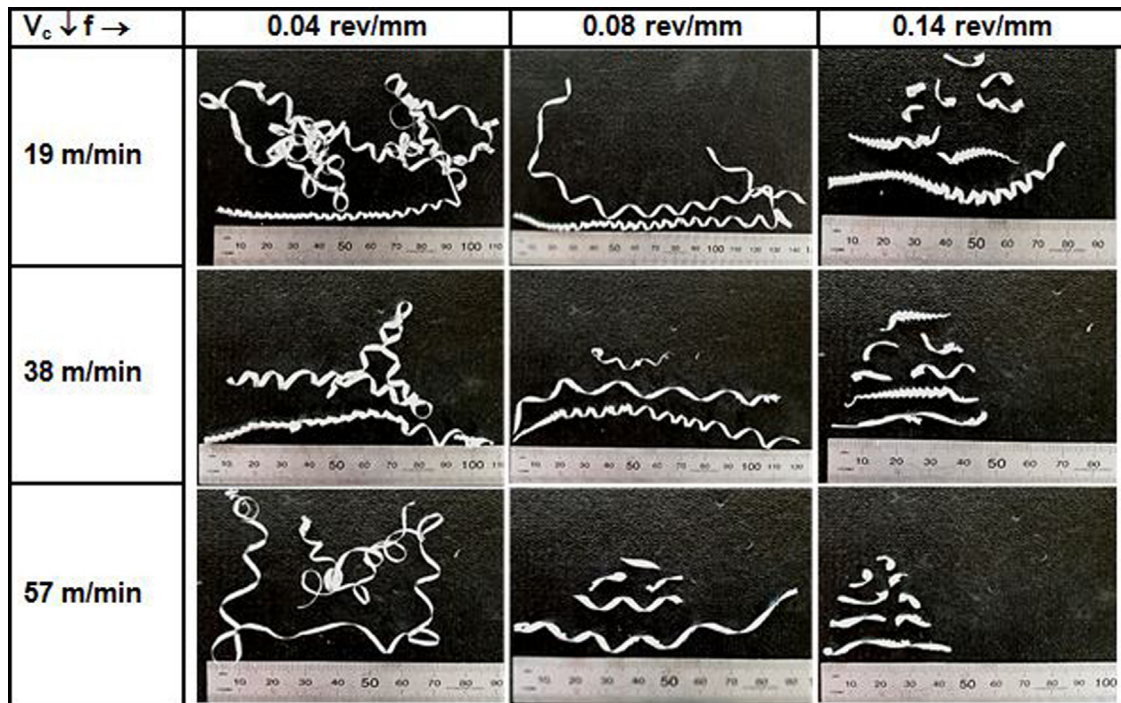


Fig. 8 – Formation chips from one-shot drilling under different cutting parameters.

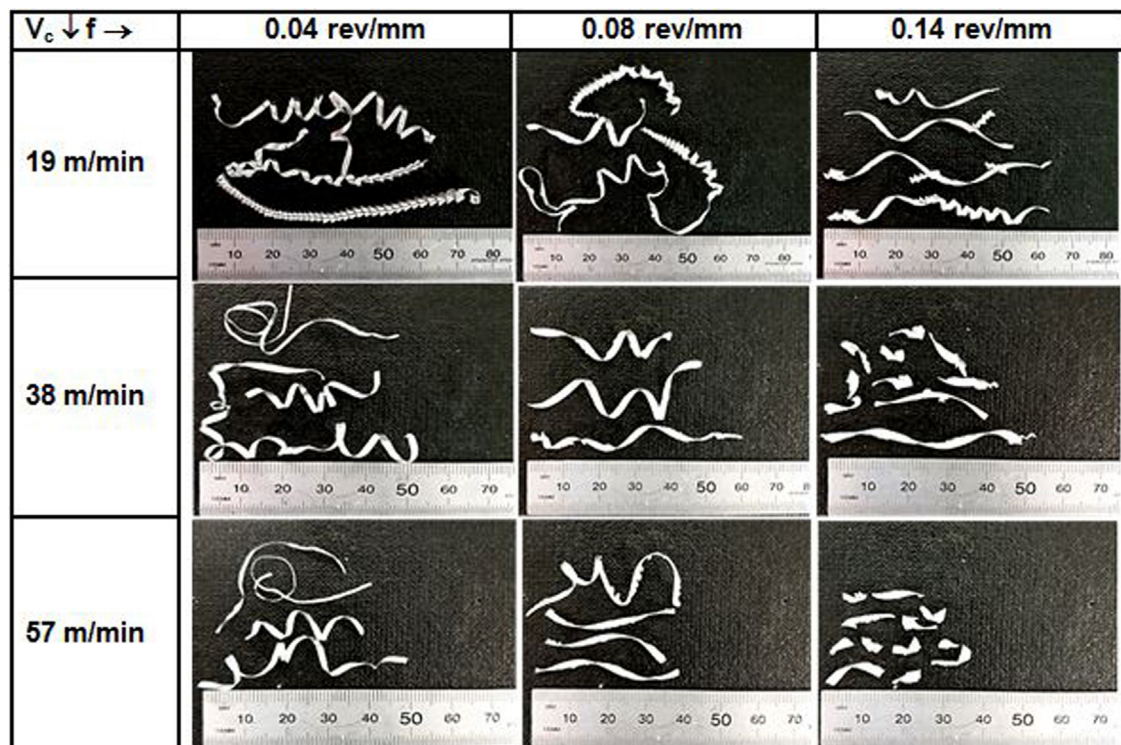


Fig. 9 – Formation chips from poly-drill head under different cutting parameters.

formed from PDH drilling favour the formation of discontinuous chips regardless of cutting parameters. This might be due to the simultaneously drilling of three tools which change the direction of the chips flow during formation and make

the chips physically deformed. Furthermore, the length of the chips was found to be less than OSD which means that these chips were less tangled around the tools of the PDH. The drop in cutting forces would have caused decreases in the contact

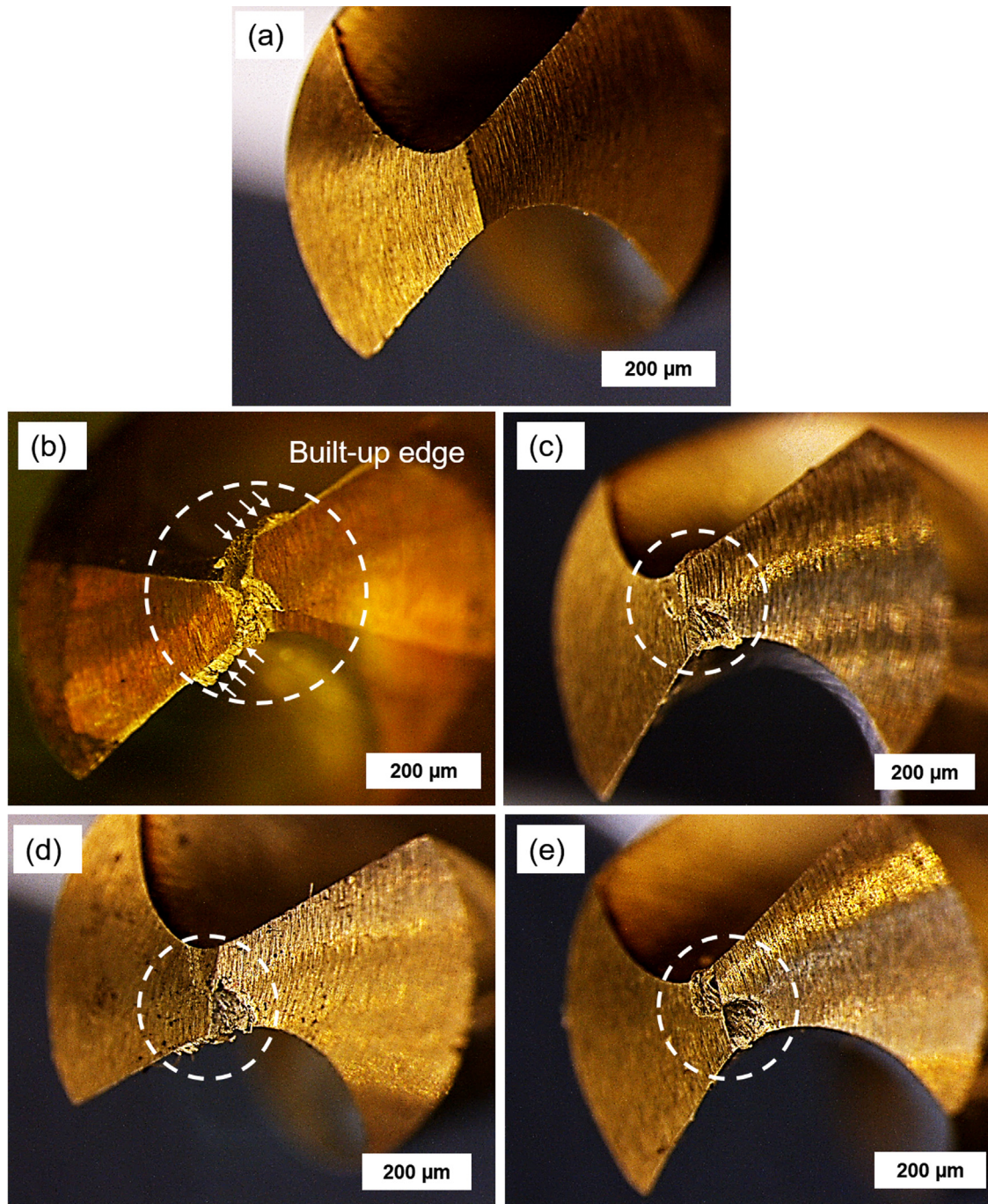


Fig. 10 – Condition of the tool (a) unused; (b) one-shot single drill bit (c) poly-drill head: drill bit A (d) poly-drill head: drill bit B (e) poly-drill head: drill bit C.

area which have possibly produced chips that are thinner and smaller in size than the OSD, that also justify the lower R_a in holes produced using PDH.

3.4. Post-machining tool condition

Tool wear is another important aspect of any machining process, which can cause shorter tool life, poor hole quality, high force generation, excessive power consumption, and high machining cost, etc. as given in Xu et al. [33]. The tools used in

the process of OSD and PDH are shown in Fig. 10, illustrating that the adhesion from the workpiece material was present on all the tools. The adhesion is caused when the materials get accumulated on the cutting edge and form built-up edge (BUE) because the combination of removal process and friction energy causes the material to soften due to high temperature, thus activating the chemical reactivity of materials, where the materials easily adhere to the tool during drilling as discussed by Zhu et al. [45]. Therefore, BUE is formed after gradual increases in the friction of the tool-chip interface,

which causes either complete or partial sticking contact at the tool-chip interface [57]. Another reason for adhesion and built-up edges on tools might be the high cutting parameters. As discussed by Nouari et al. [58], at higher V_c the materials easily move easily towards the tool forming an adhesion layer followed by BUE which might affect the tool life. However, it was noted that relatively less adhesion and BUE was observed on all the three drills of the PDH than those found on the tool of the OSD. This might be due to the smaller chip size formed from PDH compared to chips formed from OSD tests.

4. Conclusions

Proper tool and machining parameters are essential in the drilling process for production of high-quality holes. Therefore, for improving productivity and reducing time, a comparison between one-shot single drilling and multi-hole simultaneous drilling using a poly-drill head was done and the following conclusions are made:

- In both drilling processes, thrust force increases with increases in the feed while it decreases with increases in cutting speed. The influence of feed on thrust force was found to be greater than cutting speed. The poly-drill head shows higher thrust force than one-shot drilling; however, this thrust force is the combination of three drills producing three holes at same the time where the average thrust force of the three tools of the poly-drill head is found to be slightly less than those of one-shot single drilling.
- In both the drilling types including one-shot drilling and multi-hole simultaneous drilling using a poly-drill head, the cutting speed affects the surface roughness more than feed as evident by the ANOVA analysis. However, the holes drilled by the poly-drill head give a relatively lower surface roughness compared to the one-shot drilling. The difference in chip formation between the poly-drill head and one-shot drilling might have an influence on surface roughness.
- Cutting parameters also affect the quality of holes at entry and exit. However, the feed had a greater impact as compared to cutting speed. The burr size at the entrance of holes tends to be smaller than burrs formed at the exit side. In addition, it was observed that burrs were more visible in holes produced using one-shot single drilling as compared to the poly-drill head.
- Chip thickness decreased with the increases of cutting speed while it increased as the feed increases. The length of the chips decreased with the increase of both cutting speed and the feed. Since small and broken chips are desirable in drilling and chips produced using poly-drill head were found discontinuous. Moreover, the length of the chips was less than those produced by one-shot drilling, which means chips are less tangled around the drills of the poly-drill head. The drop in cutting forces would have caused decreases in the contact area which has possibly produced chips that are thinner and smaller in size than the one-shot drilling.
- High cutting parameters has caused adhesion and built-up edge on tools of both drilling types. However, the adhesion and the built-up edges are not significantly influenced by the cutting edges of three tools of the poly-drill head due to

small chips size. Therefore, the poly-drill head performed better by ensuring the demanded of hole quality, reducing the tool wear, giving more desirable chips and most importantly reducing the cycle time which results in higher productivity.

This work should be further extended by analysing the impact of different tool geometries, tool materials and coating, and the optimization of the cutting parameters for the poly-drill head.

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Conflicts of interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.jmrt.2020.02.026>.

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