SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Applied Mechanics

Journal homepage:
https://semarakilmu.com.my/journals/index.php/appl_mech/index
ISSN: 2289-7895

An Analysis of Chip Formation and Hole Circularity in Drilling Applications: An Aircraft Components Perspective

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ARTICLE INFO

Article history:
Received 15 February 2024
Received in revised form 12 April 2024
Accepted 26 April 2024
Available online 30 May 2024

Keywords:
Aircraft; Drilling; Hole circularity; Chip formation; Industrial revolution 4.0

ABSTRACT

Drilling plays a critical role in the production of precise holes for aircraft components. However, drilling aluminium alloys poses challenges, leading to poor hole quality and potential defects in the airframe structure. This study focused on investigating chip formation, hole circularity, and drilling parameters, specifically feed rate and spindle speed. Dry drilling trials are conducted using high-speed steel drill bits and the Al6061-T6 alloy. The CIMCO MDC-MAX software is employed to monitor machine performance and accumulate comprehensive data. The study investigates the effect of varying feed rates on hole circularity, chip development, and chip thickness. Findings indicate that higher feed rates result in increased circularity error and chip thickness. The circularity graph shows inconsistencies due to workpiece vibration during drilling. Chip thickness rises with the feed rate, particularly with an increased number of drilled holes, attributed to factors such as tool rubbing and improper cutting. Additionally, the study highlights the correlation between machine performance and product quality. The CIMCO MDC-MAX data reveals that a feed rate of 0.260 mm/rev corresponds to high machine performance and low circularity. Conversely, Drill 6, operating at a feed rate of 0.230 mm/rev, exhibits poor machine performance and higher average circularity. The research enhances understanding of chip formation and hole circularity in drilling applications for aircraft components. The results emphasize the importance of optimizing drilling parameters to achieve superior hole quality. Practical implications are provided for enhancing the drilling process in aerospace manufacturing

1. Introduction

Drilling is a manufacturing procedure that is widely utilized in various sectors, including the automotive and aerospace industries, where a large number of holes are required for assembly [1,2]. In addition to being able to be utilized as a cutting operation, drilling is used to create holes of all different sizes and shapes for items like screws or bolts. Drilling is an important part of many

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https://doi.org/10.37934/aram.118.1.2839

industries' machining processes. Two businesses which are automotive and aerospace produce millions of holes and are highly dependent on the production, quality, and accuracy of drilled holes. Holes must fulfil the demanding specifications of the aviation industry sector as well as aircraft manufacturers' regulations to ensure the safety and dependability of aircraft especially in hole quality.

The aviation industry imposes stringent requirements on hole specifications to ensure the safety and reliability of aircraft components. The aviation sector establishes specific standards that manufacturers closely adhere to. Hence, it is critical to employ drilling procedures, tools, and parameters that meet the exacting tolerances and requirements of aviation assembly. According to ISO 286, "hole basis fits (as opposed to shaft basis fits) have four preferred hole tolerances (H11, H9, H8, and H7)." When holes are created with typical machine tools (drills, reamers, or end mills), hole basis fits are employed. The hole tolerances listed above are used to describe the accuracy of drilled holes in aerostructures [3]. The presence of poorly drilled holes creates severe implications, including structural fractures that decrease the aircraft's lifespan and escalate maintenance costs. Therefore, it is essential to prioritize proper maintenance for drills to operate optimally. This involves ensuring correct lubrication, regular cleaning, and timely replacement of components to uphold the drill's performance and efficiency.

The most critical characteristics in drilling operations are tool life, surface quality, cutting forces, and burr formation [4,5]. Feed rate, spindle speed, cutting fluid, tool diameter and chip formation are all process parameters that influence hole quality [2-6]. Chip formation in drilling is the work of two primary blades as well as the crosspiece. Each blade is subjected to cutting forces with three perpendicular components. The cutting force at the primary cutting edge consists of the components P_z tangential to the circle on which the blade's tip is located, P_y passing across the bit axis, and P_x parallel to the bit axis as shown in Figure 1. On the other blade, similar forces are at work. The cutting force in half of the crosspiece may be broken down into three components as well. However, because the other components have such a minor impact on the overall drilling force, only P_x is considered [7]. Achieving optimal chip formation and hole circularity is challenging due to the complex interactions between the cutting tool, workpiece material, and cutting parameters. Therefore, a comprehensive analysis of chip formation and hole circularity is essential to enhance drilling processes in aircraft component manufacturing.

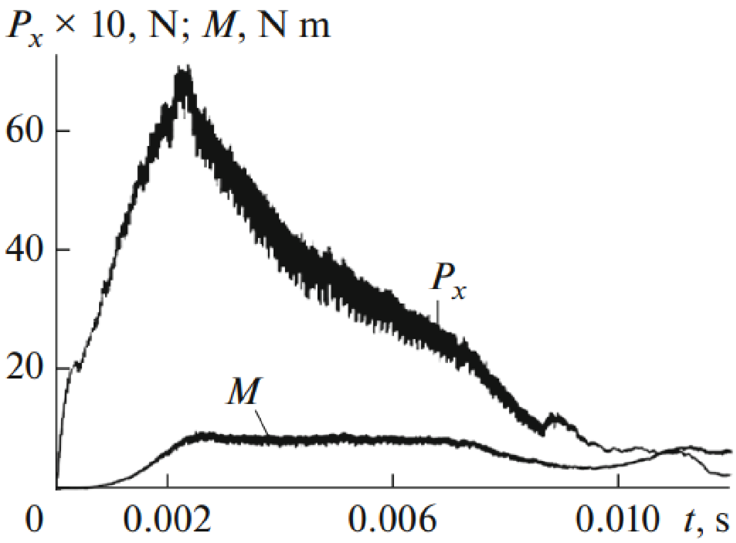

Fig. 1. Axial force P_x and torque M as a function of the time *t* [7]

Chip formation has been extensively researched for turning and milling processes. These cutting investigations have been expanded to include the drilling process. One popular technique for examining the drilling process is to break the cutting edge into multiple tiny pieces and treat each portion as a basic cutting tool. Although this approach gives a straightforward answer, it overlooks several distinct characteristics of drill chip creation [8]. Chip formation affects various aspects of drilling, such as cutting forces, tool wear, surface finish, and heat generation. Producing continuous chips, which are easier to manage and remove, is typically preferred over fragmented chips. In the context of aircraft components, uncontrolled chip formation led to surface defects, compromised structural integrity and even catastrophic failures. Other researcher has been investigating the performance and precision of component hole by using a fuzzy logic method, Taguchi, response surface method in their analysis [9]. Investigating the parameters influencing chip formation and developing ways to optimise chip morphology are crucial for optimising drilling operations.

Hole drilling is extensively used in aircraft production for a variety of purposes. Circularity of a drilled hole at entrance and exit are significant qualities in micro-manufacturing that considerably impact the quality of a drilled hole [10]. Hole circularity directly impacts the functionality and reliability of aircraft components. Inaccurate circularity may result in misalignment of mating parts, reduced load-bearing capacity, and increased stress concentration. Several factors, including the drilling tool geometry, cutting parameters, workpiece material properties, and machine tool dynamics, influence the circularity of drilled holes. Gaining insights into the correlation between these variables and the circularity of holes is crucial for attaining the intended precision in drilling procedures. Additionally, identifying potential sources of error and implementing mitigation strategies can significantly enhance the quality and performance of drilled holes in aircraft components.

This research paper aims to comprehensively analyse chip formation and hole circularity in drilling applications for aircraft component manufacturing. The study will utilize a combination of experimental and analytical techniques to investigate the influence of various parameters on chip formation and hole circularity. The findings of this study will contribute to a deeper understanding of the drilling process, providing valuable insights for optimizing drilling operations in the context of aircraft component manufacturing. Ultimately, these results will facilitate the development of improved machining strategies, leading to enhanced productivity, reliability, and safety in the production of aircraft components.

1.1 Current Drilling Issue

The demand for hole quality measurements in the aerospace industry provides a substantial problem for drilling in aeronautical structures. Numerous endeavours were undertaken to ascertain the crucial process parameters that influence diverse aspects of hole quality, including hole circularity, taper, microhardness, surface roughness, among others. Wang *et al.,* investigated the influence of process factors on hole quality attributes such as circularity and taper [11]. The research conducted by Morar *et al.,* employed the Taguchi technique to analyse the impact of crucial factors on the recast layer [12]. Simultaneously, the investigation is currently focused on examining fracture density. Marimuthu *et al.,* focused on examining the impact of increasing power proportionally and laser drilling speed on hole quality in the context of ms pulsed quasi-continuous wave laser drilling of superalloys [13]. Hole surface finish, also known as hole surface roughness, burr development, and dimensional precision, which includes departure from hole size and circularity error, are some of the most essential characteristics of hole quality. To minimize component rejection during assembly due to fracture initiation within the airframe structure, it is crucial to maintain acceptable hole quality.

Additionally, understanding and documenting the deviation between actual component size and target dimensions is necessary, considering the challenges of achieving consistent sizing. Furthermore, evaluating the shape of chips formed during the drilling process might reveal insights into the drilling operation's efficiency.

The advent of advanced manufacturing techniques in the era of aircraft component manufacturing has brought about a revolution in drilling precision. The creation of high-quality and precisely drilled holes in aeroplane components remains a crucial task as the aerospace industry evolves. The drilling process plays a pivotal role in the creation of these holes, and achieving optimal chip formation and hole circularity is essential for ensuring structural integrity and operational reliability. This study aims to explore the current drilling issues and advancements in chip formation and hole circularity in the context of aircraft component manufacturing.

2. Experimental Methodology

In this experiment, drilling will be executed with a vertical centre machine (Model: MAZAK Nexus 410A-II). Feed rates of 0.100, 0.125, 0.150, 0.175, 0.200, 0.230, 0.260, 0.290, 0.320, and 0.360 (mm/rev) were utilized, while 31.4 was the spindle speed (rpm). The workpiece material was AL6061-T6 alloy with 200 mm × 130 mm and a thickness of 20 mm. Table 1 and Figure 2 show the mechanical properties of Al6061-T6 and the top view of the workpiece after the drilling operation respectively. The twist drills utilized were made of uncoated high-speed steel (HSS) and had a 135 ° point angle. Due to environmental considerations, all drilling tests were carried out in a dry environment. Dry drilling lessens the need to clean the aeronautical structures before attaching rivets in order to obtain high-quality holes [14]. The production of the chip at holes 1, 15, and 30 will be collected to analyse the data.

The circularity error was measured by utilizing a coordinate measuring machine (Mitutoyo CRYSTA-Apex, CMM). The workpiece is set down on the machine table, and a ruby probe of 2 (mm diameter) was contacted with 20 points circulating around the inside wall of the hole, and the measurement was taken at 6 mm below the entry side of the hole.

Table 1
Mechanical Properties of Al6061-T6

Parameters	Values
Young's modulus (GPa)	68.9
Poisson's ratio	0.33
Tensile strength (MPa)	124-290
Density (g/cm^3)	2.7
Thermal Conductivity (W/m.K)	151-202
Specific heat capacity (J/Kg.K)	897

Figure 2 shows the circularity reading obtained from the Coordinate Measuring Machine. The digital micrometre (Mitutoyo Digital Micrometer IP65) was used to measure the chip thickness. To accurately assess the circularity of each hole, high-pressure air was used to clear away any small material from the hole wall.

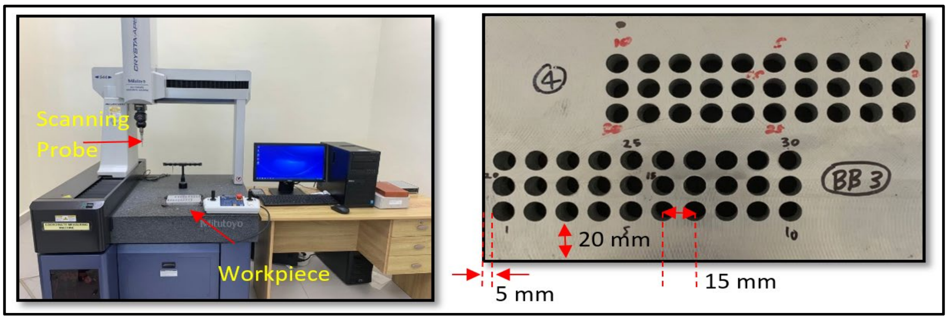

Fig. 2. Measurement setup of Hole Circularity and Top view of the workpiece

Figure 3 shows the UTHM laboratory computer and it was equipped with the CIMCO MDC-Max software, which allows monitoring of the running machine, and gathering data on machine performance during the experiment.

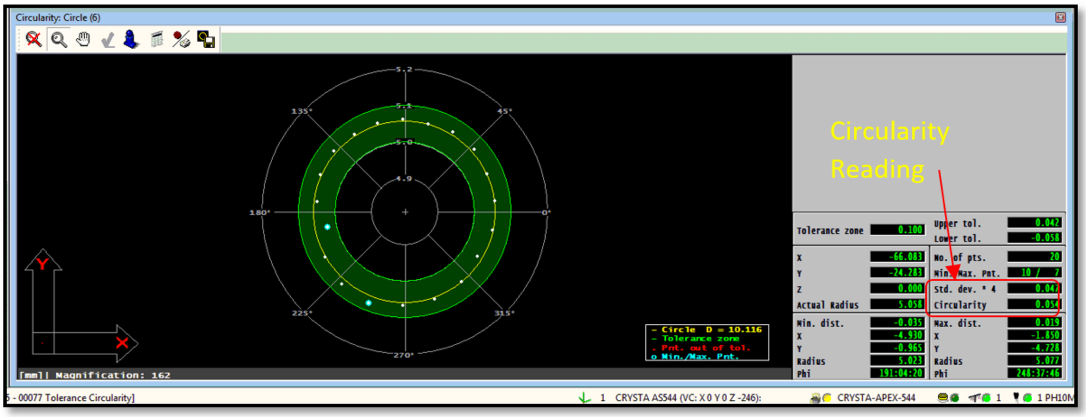

Fig. 3. Circularity reading on screen

The CIMCO-MAX software is capable to obtain data collection on real-time machine performance which comes from the CNC machine tools. The identified data aids in increasing output, making machine maintenance schedules more effective, and automatically calculating machine productivity. MDC-MAX collects machine data without requiring a computer to be placed near the machine tools. Both machine and operator data are pooled across numerous jobs by utilizing an existing network. Each machine linked to the network sends production data to MDC-MAX, and once configured, machine data is gathered in real-time with timeline throughout the day. Using a mobile device, tablets, PCs, or a barcode scanner, the operator machine reports machine downtime such as waiting for service and scrapped parts. Figure 4 shows the real-time with timeline information gathered during the operation.

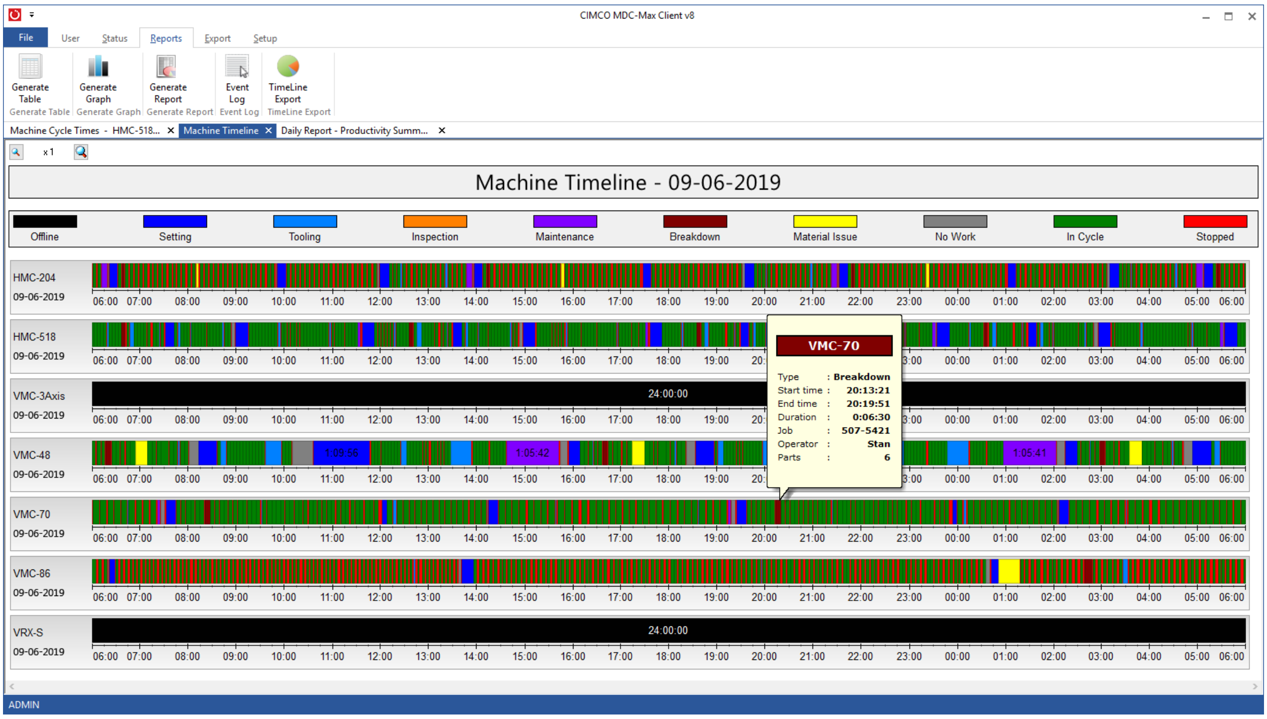

Fig. 4. Real-Time with timeline information

3. Results and Discussion

3.1 Hole Circularity

The highest circularity error at a low feed rate (*fr*= 0.100 mm/rev) is 0.066 mm. Figure 5 shows the hole circularity result. Meanwhile, the highest circularity achieved at high feed (fr=0.360 mm/rev) is 0.085 mm. This indicates that the circularity of the hole increased as the feed rate increased which is in agreement with [15]. This might be due to the increase in cutting forces. As feed rate is increased, the workpiece's deflections and vibrations also increase, accelerating penetration into the workpiece and enlarging circularity defects.

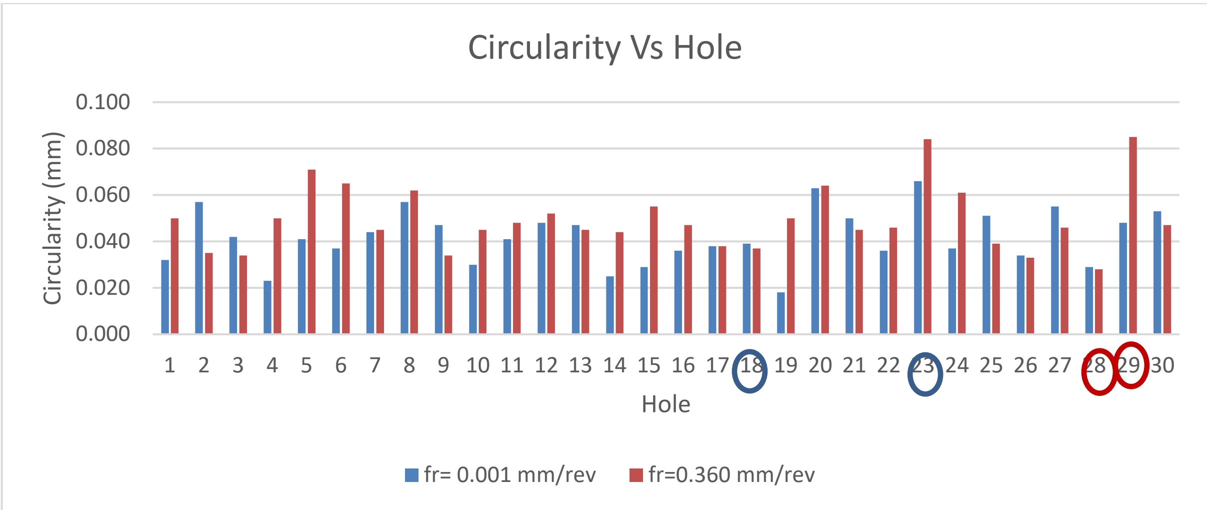

Fig. 5. Hole Circularity Result

The trend for hole circularity data obtained for each hole is unstable and inconsistent as shown in Figure 5. Based on Figure 5, the highest value was on hole 29 as the tool wear increase, the hole become inconsistent. The lowest feed rate was on hole 28. In terms of feed rate, hole 23 had the greatest value while hole 18 had the lowest value. Circularity and feed rate both have their differences. The highest feed rate was (Fr = 0.360 mm/rev).

This might be due to the clamping issue. The experimental setup involved an improper clamping of the workpiece. The workpiece's unsteady position results in vibration, which has an impact on the drilling's overall quality. The amount of the imbalance force produced during drilling is determined by the gap between the clamping points. The setup of the workpiece is shown in Figure 6.

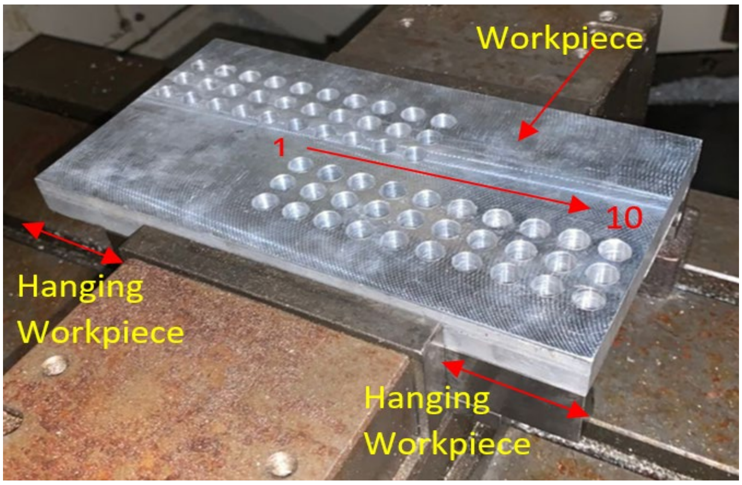

Fig. 6. Hole Circularity Result

3.2 Chip Formation

Properly broken and small size chips are preferred generally during machining of Aluminium alloy. Figure 7 shows the chips produced at the lowest and highest feed rate. The chip formation on the first hole of all drills created a conical helical shape. However, the radius of curvature of the conical helical chip shape decreases from hole 1 to hole 30. It can be seen as the helical chips as they changed to string chips when the hole drilled increases. It is due to the rubbing of the tool during the drilling operation caused by the entangled of the aluminium chip along with the helical flute of the drill. The first formed aluminium chip from the first hole was pushed upward to the end of the helical flute, causing it to curl. The advancement is causing the tool to be improperly cut for the following hole. The generation of the next chip is tended to change to the string chips [16]. Conical helical shapes were discovered to break when the friction torque between the hole wall and the chip was greater than the chip's breaking torque. It also can be observed that the short, segmented, and discontinuous chips were produced at a high feed rate [17].

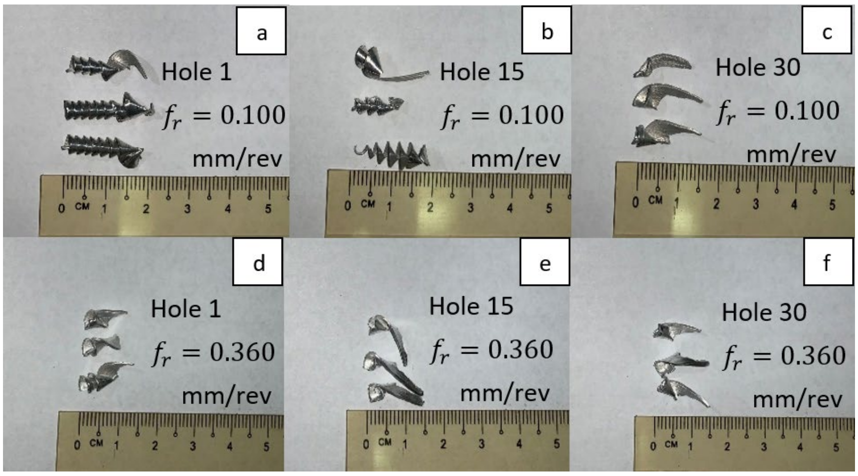

Fig. 7. Image of chips

Referring to Figure 8, from the observation, once the feed rate increase, thickness will increase, which is in agreement with Amir [18]. The feed rate was more influential because the cross-sectional area increased at a high feed rate, increasing the chip's thickness and making the chip prone to breaking easily [18]. Thickness of the chip reflected toward the federate during cutting process and effected by the friction due to the motion of cutting tool will increase the cutting temperature up to entering the melting zone [19]. It will reduce the cutting effectiveness. The thickness for the lowest feed rate is 0.22, 0.239, and 0.246 mm. Meanwhile, for the highest feed rate, the thickness reading was 0.663, 0.684, and 0.702 mm. The thickness of the chip also rises from hole 1 to hole 30. When more holes are drilled, the cutting tool is not adequately cut to the workpiece due to the wear progress which results in rubbing. Rubbing generates additional heat, resulting in rom wear. For assessing any cutting process's production capability, chip thickness is thought to be fundamentally significant [20].

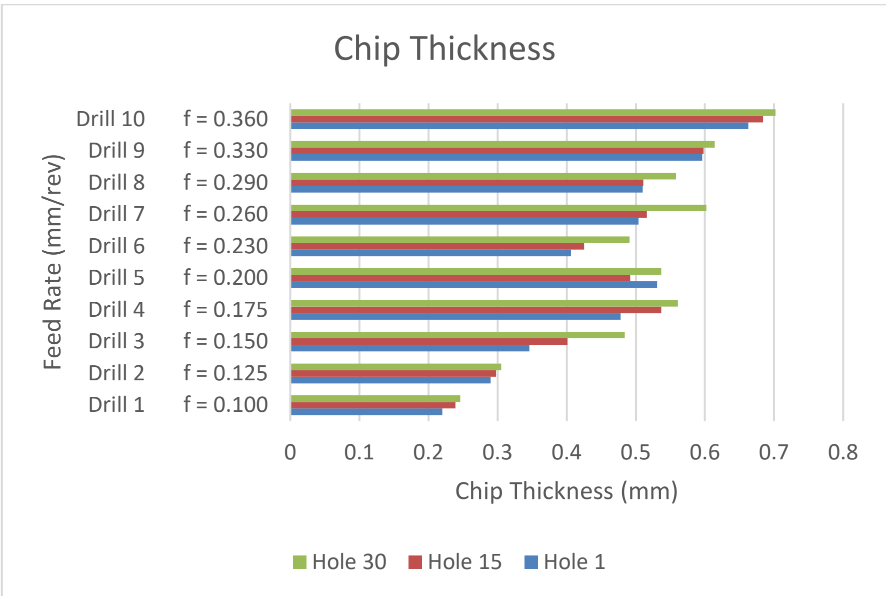

Fig. 8. Image of Chip

It has been observed that the chip thickness greatly rises along with the feed rate. It is noted that with faster cutting rates, the chip thickness drops, indicating that this connection is non-linear. The interplay between feed rate, cutting speed, and chip thickness is complicated, as this phenomenon makes clear, and further research is required to completely grasp it. The analysis's findings have an impact on how best to optimise the cutting parameters used in metalworking and machining processes. Analysing the chip thickness, with the increase in the feed rate, the chip thickness considerably increases. It is also observed that at higher speed the chip thickness decreases.

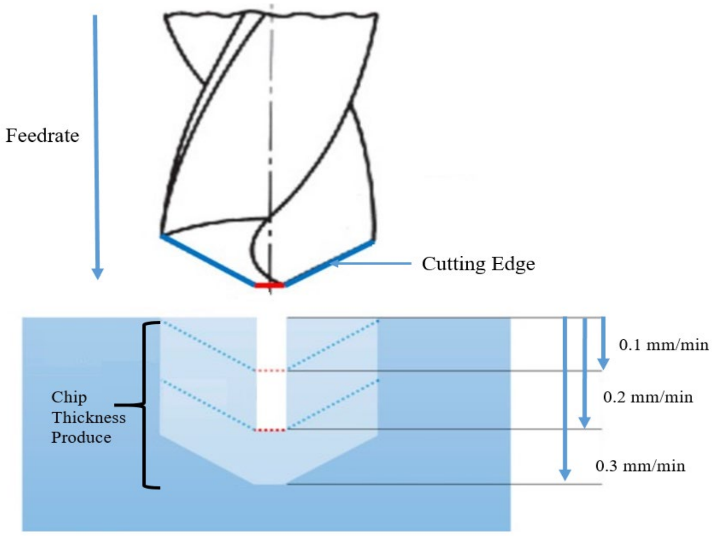

Fig. 9. The Influence of Feed rate over Chip Formation

3.3 Relationship Between Hole Circularity and Chip Formation

From Figure 10, hole circularity in Drill 9 with a feed rate of 0.320 mm/rev experimental is the lowest compared to other Drill. It can be observed that small and segmented chips are produced in Drill 9. It shows that with the small chips produced, the circularity error is excellent. Small chips can prevent tool from worn and prolong tool life. Segmented chips are conical helical chip breaks before becoming a long-pitch form due to restraint from the drill hole's wall brought on by a lack of ductility. It is a top-notch chip discharge and disposal method. However, the highest average circularity is on Drill 5 and Drill 10 which both produced a corkscrew and tangled shape of the chip. Consequently, that the tangled and corkscrew chip is really uneven towards the quality of the hole. Uneven chip shape really affects the hole quality.

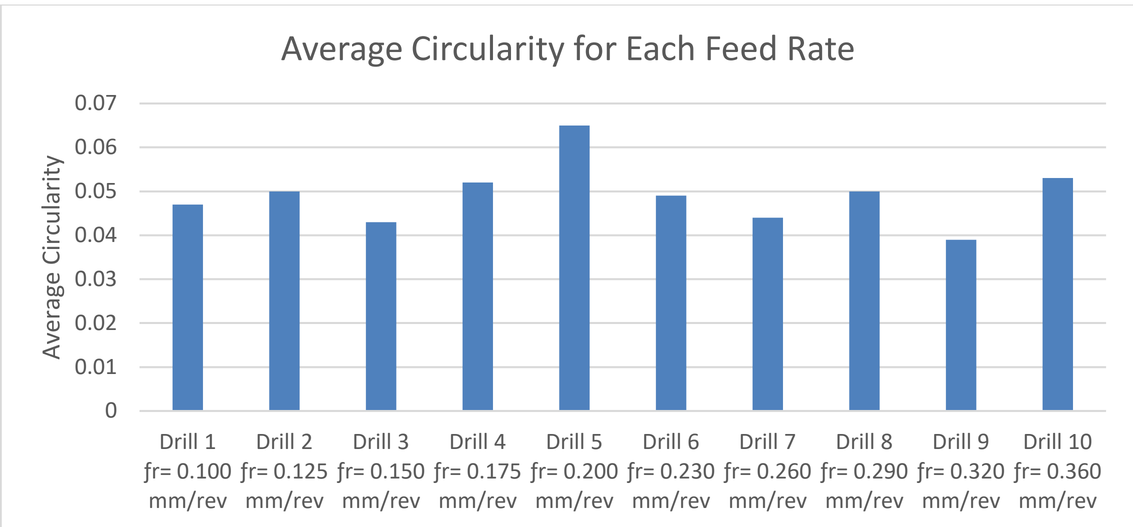

Fig. 10. The Influence of Feed rate over Chip Formation

Figure 11 (a) shows the chip in Drill 9. Figure 11 (b) shows the chip in Drill 5. Figure 11 (c) shows the chip in Drill 10.

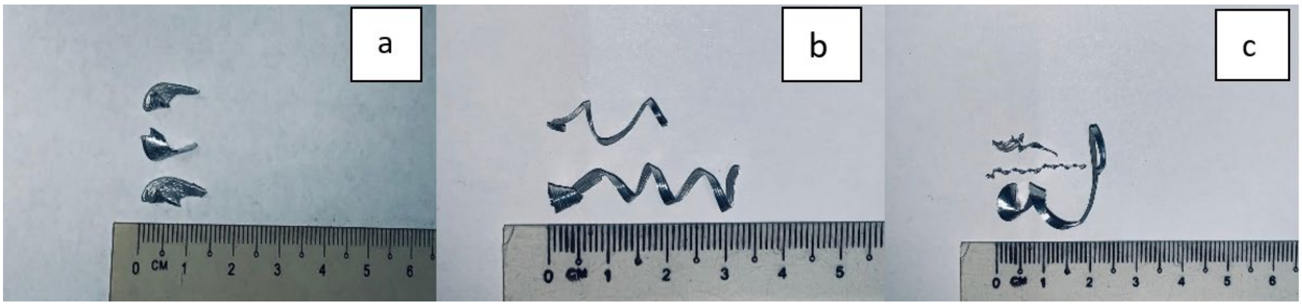

Fig. 11. The Influence of Feed rate over Chip Formation

3.4 CIMCO Analysis

The link between OEE Performance and hole circularity on an aluminium plate is depicted graphically in Figure 12 below. (The consequences at drill 6 was investigate and there has been a shift changes during the process which impacted the performance. The formula of OEE is

OEE = (Good Count × Ideal Cycle Time) / Planned Production Time)

The issue come from the ground floor planned production time whereas, at the tool no. 6, the changes of shift time in the production occurred effected on the OEE. It may also not operate precisely owing to slight misalignments and require minor modifications, or it may choose to work at a slower speed. Its efficiency has to be kept at its peak.

The average circularity data for each feed rate was taken for analysis. From the data collected, the best performance was achieved at Drill 7 with a feed rate of 0.260 mm/rev. The machine performance is excellent while the average circularity error was low on Drill 7. This indicates that at that the machine is operating efficiently and may affect the result of the workpiece. However, the circularity on the drill 9. High percentage of OEE performance means it is also excellent in Availability, Quality and Performance.

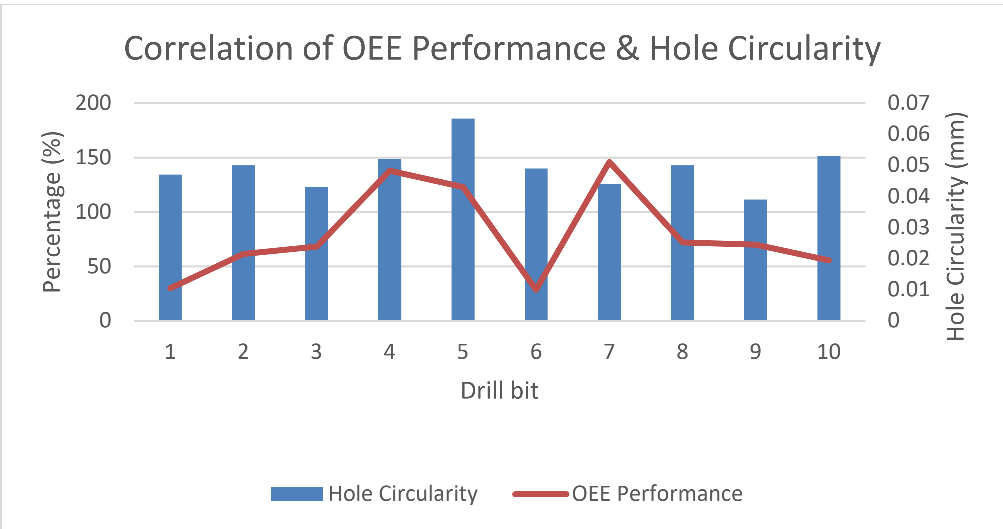

Fig. 12. Correlation of OEE Performance & Hole Circularity

4. Conclusions

The highest circularity at a low feed rate (0.100 mm/rev) is 0.066 mm meanwhile at a high feed (0.360 mm/rev) is 0.085 mm. The hole circularity increases as the feed rate increase due to an increase in cutting force. The hole circularity graph is also inconsistent due to the hanging workpiece during the drilling operation. During machining, improperly positioned workpieces might generate vibration and degrade the hole's quality.

The feed rate significantly influenced the variation of thickness. The thickness of the chip increases as the feed rate increase. The highest thickness recorded is for a feed rate of 0.360 mm/rev which is 0.702 mm meanwhile the lowest thickness is 0.22 mm for experiment Drill 1. The thickness of the chip also rises from hole 1 to hole 30 due to tool rubbing and improperly cutting when the number of holes drilled increases. Besides the feed rate and chip formation that affects the circularity, the performance of the machine might be affecting the quality of the product 10. The CIMCO MDC-Max records all the machine's quality, performance, and availability. The high machine performance and low circularity were achieved at a feed rate of (0.260 mm/rev). The poorest performance of the machine is at Drill 6 with a feed rate of (0.230 mm/rev) which also recorded a high average circularity of 0.049 mm.

In conclusion, the gathering and analysis of data pertaining to the drill's behaviour, encompassing variables like speed, power consumption, and performance fluctuations, has provided a comprehensive understanding of its performance. This research endeavour demonstrates considerable promise in optimizing the manufacturing process of aircraft components. By closely monitoring the performance of each drill, manufacturers able to effectively identify areas for enhancement, ensure the maintenance of consistent and high-quality production standards, and ultimately augment the overall efficiency and reliability of the manufacturing process. Implementing these findings in practice has the potential to significantly contribute to the advancement of aircraft component manufacturing, ultimately leading to improved productivity and product quality.

Acknowledgement
The researchers express their gratitude to the Registrar Office of the University Tun Hussein Onn Malaysia for the financial support provided for this research paper, and extend the appreciation to the Faculty of Mechanical and Manufacturing Engineering for their valuable assistance. Special acknowledgement is given to HPMT Industries Sdn. Bhd. Shah Alam for generously providing the necessary tools for the main instrument utilized in this study.

References

[1] Aamir, Muhammad, Majid Tolouei-Rad, Khaled Giasin, and Ataollah Nosrati. "Recent advances in drilling of carbon fiber–reinforced polymers for aerospace applications: A review." *The International Journal of Advanced Manufacturing Technology* 105 (2019): 2289-2308. https://doi.org/10.1007/s00170-019-04348-z

[2] Aamir, Muhammad, Khaled Giasin, Majid Tolouei-Rad, Israr Ud Din, Muhammad Imran Hanif, Ugur Kuklu, Danil Yurievich Pimenov, and Muhammad Ikhlaq. "Effect of cutting parameters and tool geometry on the performance analysis of one-shot drilling process of AA2024-T3." *Metals* 11, no. 6 (2021): 854. https://doi.org/10.3390/met11060854

[3] " Gardiner, Ginger. "Hole Quality Define" CompositeWorld. 2014. https://www.compositesworld.com/articles/hole-quality-defined

[4] El-Sonbaty, I., U. A. Khashaba, and T. Machaly. "Factors affecting the machinability of GFR/epoxy composites." *Composite structures* 63, no. 3-4 (2004): 329-338. https://doi.org/10.1016/S0263-8223(03)00181-8

[5] Geier, Norbert, and Tibor Szalay. "Optimisation of process parameters for the orbital and conventional drilling of uni-directional carbon fibre-reinforced polymers (UD-CFRP)." *Measurement* 110 (2017): 319-334. https://doi.org/10.1016/j.measurement.2017.07.007

[6] Aamir, Muhammad, Khaled Giasin, Majid Tolouei-Rad, and Ana Vafadar. "A review: Drilling performance and hole quality of aluminium alloys for aerospace applications." *Journal of Materials Research and Technology* 9, no. 6 (2020): 12484-12500. https://doi.org/10.1016/j.jmrt.2020.09.003
[7] Boldyrev, I. S., S. D. Smetanin, and D. Yu Topolov. "Chip Formation in Drilling." *Russian Engineering Research* 41 (2021): 1091-1093. https://doi.org/10.3103/S1068798X2111006X
[8] Ke, Feng, Jun Ni, and D. A. Stephenson. "Continuous chip formation in drilling." *International Journal of Machine Tools and Manufacture* 45, no. 15 (2005): 1652-1658. https://doi.org/10.1016/j.ijmachtools.2005.03.011
[9] Rachmat, Haris, Tatang Mulyana, Sulaiman bin H. Hasan, and Mohd Rasidi bin Ibrahim. "Design selection of In-UVAT using MATLAB fuzzy logic toolbox." In *Recent Advances on Soft Computing and Data Mining: The Second International Conference on Soft Computing and Data Mining (SCDM-2016), Bandung, Indonesia, August 18-20, 2016 Proceedings Second*, pp. 538-545. Springer International Publishing, 2017. https://doi.org/10.1007/978-3-319-51281-5_54
[10] Biswas, R., A. S. Kuar, S. K. Biswas, and S. Mitra. "Characterization of hole circularity in pulsed Nd: YAG laser micro-drilling of TiN–Al 2 O 3 composites." *The International Journal of Advanced Manufacturing Technology* 51 (2010): 983-994. https://doi.org/10.1007/s00170-010-2691-6
[11] Wang, Maolu, Lijun Yang, Shuai Zhang, and Yang Wang. "Experimental investigation on the spiral trepanning of K24 superalloy with femtosecond laser." *Optics & Laser Technology* 101 (2018): 284-290. https://doi.org/10.1016/j.optlastec.2017.10.029
[12] Morar, Nicolau Iralal, Rajkumar Roy, Jörn Mehnen, Sundar Marithumu, Simon Gray, Tracey Roberts, and John Nicholls. "Investigation of recast and crack formation in laser trepanning drilling of CMSX-4 angled holes." *The International Journal of Advanced Manufacturing Technology* 95 (2018): 4059-4070. https://doi.org/10.1007/s00170-017-1481-9
[13] Marimuthu, S., M. Antar, and D. Chantzis. "High speed quasi-CW fibre laser drilling of aerospace alloys." *Proceedings of Lasers in Manufacturing* (2015): 1111-1121.
[14] Habib, Numan, Aamer Sharif, Aqib Hussain, Muhammad Aamir, Khaled Giasin, Danil Yurievich Pimenov, and Umair Ali. "Analysis of hole quality and chips formation in the dry drilling process of Al7075-T6." *Metals* 11, no. 6 (2021): 891. https://doi.org/10.3390/met11060891
[15] Giasin, Khaled, Alma Hodzic, Vaibhav Phadnis, and Sabino Ayvar-Soberanis. "Assessment of cutting forces and hole quality in drilling Al2024 aluminium alloy: experimental and finite element study." *The International Journal of Advanced Manufacturing Technology* 87 (2016): 2041-2061. https://doi.org/10.1007/s00170-016-8563-y
[16] Ke, Feng, Jun Ni, and D. A. Stephenson. "Continuous chip formation in drilling." *International Journal of Machine Tools and Manufacture* 45, no. 15 (2005): 1652-1658. https://doi.org/10.1016/j.ijmachtools.2005.03.011
[17] Zheng, Lijuan, Chengyong Wang, Lipeng Yang, Yuexian Song, and Lianyu Fu. "Characteristics of chip formation in the micro-drilling of multi-material sheets." *International Journal of Machine Tools and Manufacture* 52, no. 1 (2012): 40-49. https://doi.org/10.1016/j.ijmachtools.2011.08.017
[18] Wang, Chengyong, Yingxing Xie, Lijuan Zheng, Zhe Qin, Dewen Tang, and Yuexian Song. "Research on the chip formation mechanism during the high-speed milling of hardened steel." *International Journal of Machine Tools and Manufacture* 79 (2014): 31-48. https://doi.org/10.1016/j.ijmachtools.2014.01.002
[19] Ibrahim, Mohd Rasidi, E. A. Rahim, A. A. Ibrahim, N. A. Maskam, and S. C. Ghani. "The effect on the application of coolant and Ultrasonic Vibration Assisted Micro Milling on machining performance." *Applied Mechanics and Materials* 660 (2014): 65-69. https://doi.org/10.4028/www.scientific.net/AMM.660.65
[20] Rezaei, Hamed, Mohammad Hossein Sadeghi, and Erhan Budak. "Determination of minimum uncut chip thickness under various machining conditions during micro-milling of Ti-6Al-4V." *The International Journal of Advanced Manufacturing Technology* 95 (2018): 1617-1634. https://doi.org/10.1007/s00170-017-1329-3