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Comparative analysis of different machining condition in drilling cobalt chromium molybdenum

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KEYWORDS

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Flank wear
Hole quality

ABSTRACT

Cobalt chromium molybdenum (CoCrMo) is renowned for its challenging machinability due to its unique properties, including exceptional wear resistance, low thermal conductivity, toughness, and high strength. However, machining this hard material often encounters a prominent issue of rapid tool wear, significantly impacting cutting tool performance and surface quality especially in drilling process. Drilling CoCrMo can generate a lot of heat, which can cause thermal damage to the surrounding hole as well as the cutting tool. A series of controlled experiments were conducted to assess the efficacy of different machining conditions—dry machining, minimum quantity lubrication (MQL) using Karanja oil, and chilled air—on tool wear and hole quality of CoCrMo. Due to properties of materials, 20m/min of cutting speed and 0.035 mm/rev of feed were selected to conduct drilling process. Specifically, the MQL using Karanja oil condition demonstrated markedly reduced growth of flank wear compared to dry machining and chilled air. The number of holes increase 360% in MQL using Karanja oil compared to dry condition. Additionally, it exhibited a positively influencing on the overall hole quality such as surface roughness, circularity and burr formation. Surface roughness result using MQL with Karanja oil is 14.8% better than the chilled air.

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1.0 INTRODUCTION

Cobalt chromium is categorized under biocompatibility material as titanium alloy. Both materials are popular choices for medical applications, including orthopedics, dentistry, and cardiovascular implants (Baron et al., 2019; Allergri et al., 2019). However, machining cobalt chromium is more challenging compared to titanium alloy due to its hardness and brittleness properties which is higher than titanium (Devgan et al., 2023). In addition, the studies in machining cobalt chromium molybdenum are still insufficient, especially in the drilling process (Saravanan et al., 2021; Zaman et al., 2017). Drilling cobalt chromium can generate a lot of heat, which can cause thermal damage to the surrounding hole (Zaman et al., 2017). This is due to its low thermal conductivity, which means it does not dissipate heat as effectively as titanium alloy. As result of this, it leads to shorten tool life and also poor surface finish of the machined part. It remains very important to use cooling and lubricating agent in cutting process to improve tool life and surface finish (Gupta et al., 2018). There are different cooling and lubricating agents in machining process such as: flood coolant, chilled air, minimum quantity lubricant (MQL), and cryogenic cooling (Sharma et al., 2009). Using flood coolant shows a better result in term of tool life as it can minimize the heat generated (Sun et al., 2006). Still, this condition has several issues such as flood coolant can create airborne mists that can be hazardous to workers' health and environmentally harmful that require special disposal or recycling procedures.

Dry machining was considered a good choice for replacing flood coolant (Das et al., 2022; Dawood et al. 2015). Dry machining has some benefits such as reduced environmental impact, lower operating costs, and improved workpiece cleanliness. However, it can also present some challenges, particularly when cutting hard-to-cut materials (Sun et al., 2006). The challenge of dry machining is high temperatures at the cutting zone, which can lead to thermal damage to the cutting tool and the workpiece. In addition, poor chip evacuation in dry machining can cause problems such as chip recutting, clogging of the cutting tool, and poor surface finish (Balaji et al., 2016). A comparatively recent cooling condition that has impressed many authors in machining operations is using compressed or chilled air (Kumar & Gandotra, 2020; Zainal et al., 2020; Deshpande & Deshpande, 2019). As air is the cooling medium in this process, it could be defined as the environmentally safe cooling condition in cutting operations. In addition, it is more economical than the cryogenic cooling method, especially for setup costs (Swain et al., 2022). The other option to reduce environmental effects is minimum quantity lubricant (MQL). MQL is the minimum quantity of lubricant mixed with compressed air to form an aerosol. The design of MQL system helps the coolant to reach hard to access tool chip interface more effective. During the machining, MQL will also lower the temperature, reduce friction, produce a better surface finish, and minimize the tool wear. In addition, the utilization of minimal amount of liquid is more economical and faster heat transfer through the evaporation of the oil during machining process is safer for the environment (Salur et al., 2021; Said et al. 2019; Elbah et al., 2019).

In their study, Rahman et al. (2003) investigated the effects of dry, flooded, and chilled air conditions on the machining performance of milling AISI P20 tool steel with uncoated tungsten carbide cutting tools. The results revealed that at low feed rates and cutting speeds, the tool wear was less under chilled air conditions than under dry and flooded conditions. Altan Ozbek et al. (2022) used Taguchi experimental design with ANOVA analysis to study the effect of MQL on cutting performance such as cutting temperature, tool wear, surface roughness, vibration amplitude and tool life in machining high strength steel. From the result, cutting speed was the most significant especially on tool wear.

Furthermore, Mahboob et al. (2018) used TiAlN PVD coated carbide as the cutting tool to study the specific cutting energy of Inconel 718 under chilled air, dry and MQL conditions. In their research, they concluded that the chilled air is able to cool the cutting zone but is unable to enhance the lubrication and friction. Kumar et al. (2020) focused on the effect of cutting condition such as chilled air, MQL, dry and flood cooling condition on tool wear, surface roughness and cutting force in machining AISI 4340. Chilled air condition improves more than 50% compared to dry machining, followed by MQL about 30% improvement. Experiment conducted by Ozbek et al. (2023) investigated the effect of dry, cryo, and cryoMQL on machining high vanadium alloyed powder metallurgy tool steel. CryoMQL outperformed other cutting conditions with more than 50% improvement for surface roughness and tool wear.

Rahim and Sasahara (2011) demonstrated MQL productivity over air blowing and flood cooling. They analyzed the efficiency of MQL using palm oil over MQL with synthetic ester and flood cooling in high-speed drilling of titanium alloy. They also found that the cutting force, torque, and heat generation are reduced for MQL using palm oil than MQL using synthetic ester. Analytical studies have shown that vegetable oil is better than other selected oils in terms of tool life. Due to the composition of triglycerides, vegetable oils have a better lubricant film layer. It also reduces the coefficient of friction and accelerates wear resistance. But some of the significant disadvantages are the thermal instability and higher cost of vegetable oils (Nazma et al., 2019).

Roy et al. (2019) reviewed the performance of different lubrication technique in milling, turning and grinding process. The comparison focuses on flood coolant, MQL with different oils and dry machining. They concluded that better penetration of machining fluid in machining zone of MQL technique helps to reduce machining temperature which benefited the tool life and surface finish.

In contrast, study by Revuru et al. (2020) concluded dry condition gave same performance in machining carbon steel alloy. However, they also recommended the use of MQL to reduce cutting temperature in cutting zone.

From the studies mentioned, MQL has more advantages compared to flood coolant condition and dry machining condition. However, the performance of different cooling condition in drilling cobalt chromium is still questionable due to the unique combination of properties such as high strength, toughness, high wear resistance and poor thermal conductivity. Thus, in this study, performance of MQL with Karanja oil and chilled air on cutting tool and hole quality will be studied. The result also will be compared with dry machining condition.

2.0 EXPERIMENTAL PROCEDURE

2.1 Experimental Setup

The drilling process was conducted using a CNC milling machine; Akira-Seiki Performa SR3. A medical grade cobalt chromium molybdenum was selected as a workpiece material with a dimension of 94 mm × 68 mm × 10 mm. The hardness test of material was performed using HRS-150 Digital Rockwell Hardness Tester. Five readings were taken from the test and the average value is 38 HRC. Figure 1 shows the drilling sequence on the process. The cutting tool used in this experiment was Titanium Aluminum Nitride (TiAlN) coated carbide which has a diameter of 6 mm, 30 mm length of cut, 70 mm of overall length, 30° of helix angle, and 140°point angle. A constant cutting speed of 20 m/min and feed of 0.035 mm/rev were used as established from pilot tests.

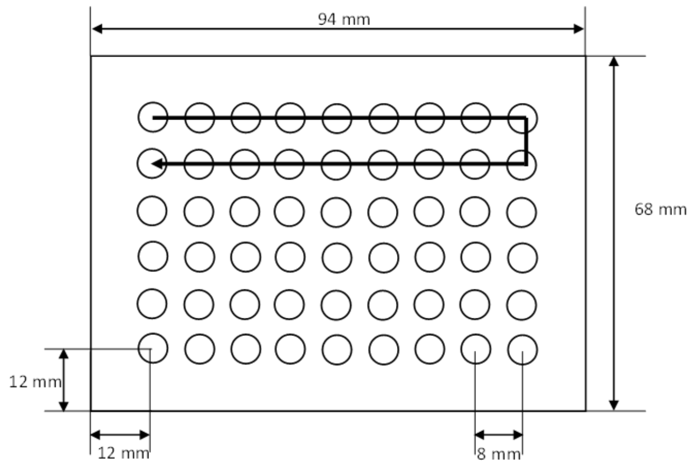


Figure 1: Workpiece dimension and drilling sequence.

2. 2 Machining Condition

The experiment was conducted with three different machining conditions such as dry, chilled air, and MQL using Karanja oil as presented in Table 1. The dry condition is where the cutting zone is not filled by any coolant or lubricant. In MQL using Karanja oil condition, the lubricant is sprayed from the nozzle which is located close to the workpiece and tool. The lubricant is used under continuous supply at constant pressure. The property of high flash point and viscosity index makes Karanja oil an effective and sustainable choice for lubrication in drilling process. The parameters for the MQL system were set at a flow rate of 50 ml/h and 4 bar of air pressure. In chilled air condition, the chilled air was carried as a medium close to the cutting zone through a vortex tube. The chilled air method is different from the MQL using Karanja oil where the chilled air was sprayed directly at the material to control the workpiece temperature. Figure 2 and Figure 3 shows the experimental setup for MQL with Karanja oil condition and chilled air condition, respectively.

Table 1: Machining conditions.

Machining Condition	Cutting Speed m/min	Feed rate mm/rev
Dry	20	0.035
Chilled Air	20	0.035
MQL using Karanja oil	20	0.035

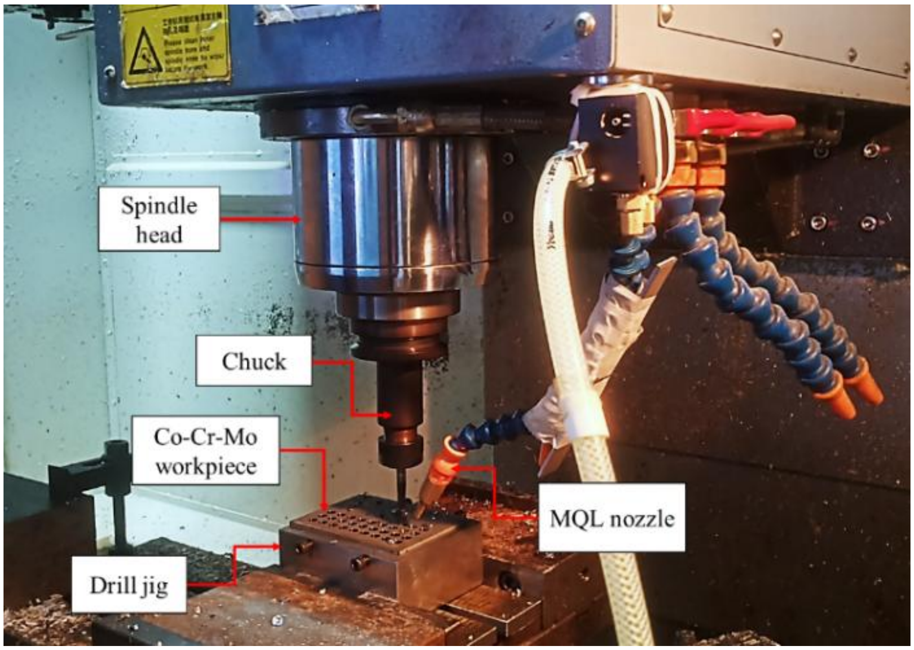


Figure 2: Drilling process in MQL with Karanja oil condition experimental setup.

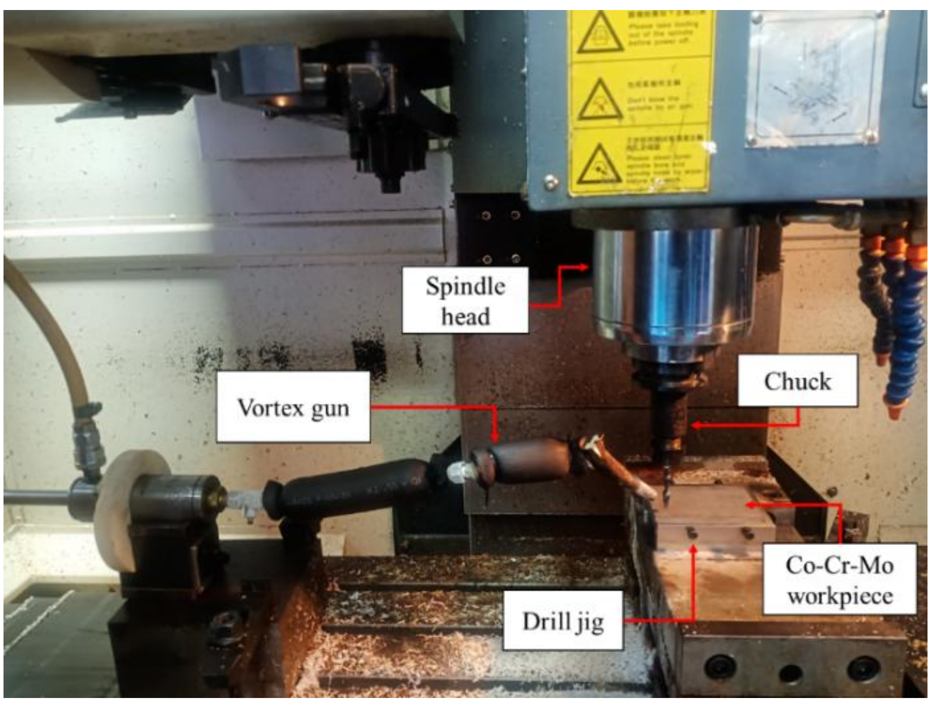
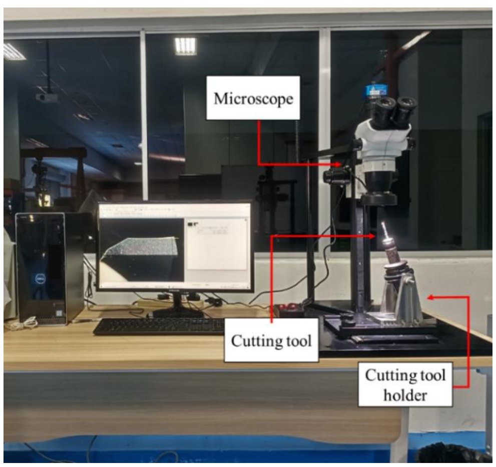


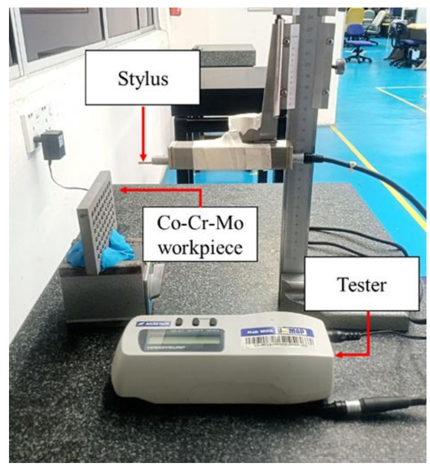
Figure 3: Drilling process in chilled air condition experimental setup.

2. 3 Tool Wear, Burr, Surface Roughness and Hole Diameter

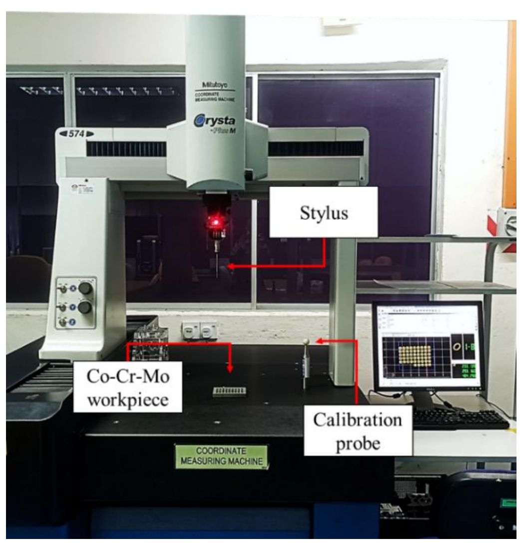
The drill bit was placed on a fabricated jig and tilted angle 60° to obtain the flank wear measurement using Stereo Microscopy Image Analyzer as shown in Figure 4(a). The flank wear was measured with a magnification of 35× to determine the average flank wear on every cutting tool used with the application of image processing software. The maximum flank wear criteria tolerable is (V_{Bmax}) ⩽ 0.3 mm on the cutting tool before stop drilling process. The burr width was observed using a Stereo Microscopy Image Analyzer.



(a)



(b)



(c)

Figure 4: (a) Stereo Microscopy Image Analyze (b) Accretech Handysurf E-35 equipped with portable stylus and (c) CMM-Mitutoyo Crysta-Plus M.

The surface roughness, Ra was measured on the drilled hole along the drilling surface parallel to feed motion using an Accretech Handysurf E-35 equipped with a portable stylus (Figure 4 (b)). The parameters were set at 0.8 mm cut of length and 2.4 mm transverse length for each measurement. The surface roughness, Ra values of the drilling surface were determined in four positions parallel to the drilled axis at 0°, 90°, 180°, and 270° for each hole and measured three times to obtain the average of Ra at four positions measured. Hole diameters were measured using Coordinate Measuring Machine (CMM) for its dimension and accuracy. The CMM model used is Mitutoyo Crysta-Plus M and the probe installed is Renishaw probe as represented in Figure 4(c). 12 points for each hole were measured with various depth at entry, middle and exit part. The measurement points diagram for surface roughness and hole diameter is shown in Figure 5.

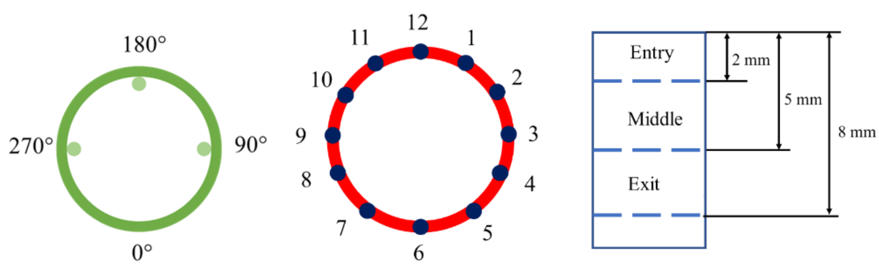


Figure 5: Number of points for surface roughness and hole diameter measurement.

3.0 RESULTS AND DISCUSSION

3.1 Average Flank Wear

The condition of flank wear for the three machining conditions are tabulated in a bar chart as shown in Figure 6. For the first five holes, dry machining condition shows the highest value of 0.25 mm. Dry machining condition may give some advantages when machining certain materials such as carbon steel and by utilizing coated cutting tools (Yugeshwar et al., 2023). Inversely, cobalt chromium is a hard and abrasive material with a high possibility of chip adhesion to the cutting tool. This would further complicate the chip evacuation process especially at high temperature during drilling process. The absence of lubricating medium exposes the cutting tool to direct contact with the workpiece material, resulting in the workpiece to rub against the cutting edge causing gradual tool material removal and flank wear (Zailani et al., 2021). Moreover, cobalt chromium is known for its high temperature resistance. The combinations of high temperature generation in dry condition along with the material own properties could lead to an accelerated wear of the cutting tool. The burn mark on cutting tool represented that cutting tool experienced high temperature during the process in dry machining condition. With the present of cooling agent such as chilled air and MQL, the temperature can be reduced. As represented in the bar chart, chilled air and MQL using Karanja oil machining condition show the reduction of average flank wear by 72% and 76% respectively compared to dry condition at 5th hole.

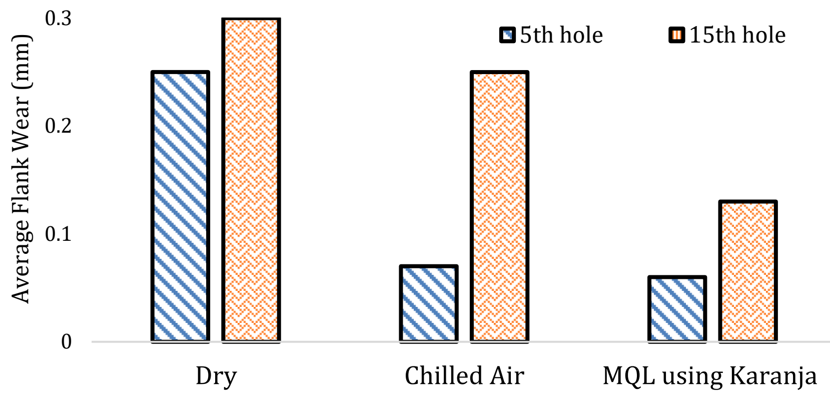


Figure 6: Average flank wear for 5th and 15th hole.

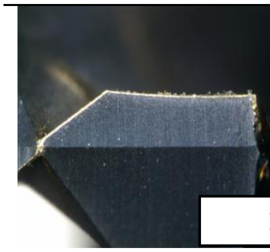
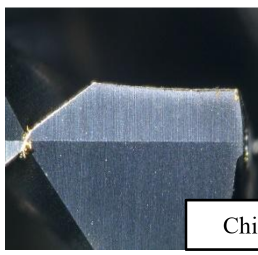
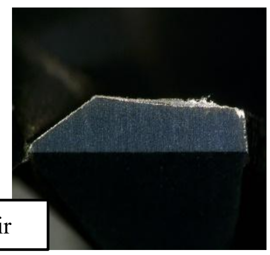
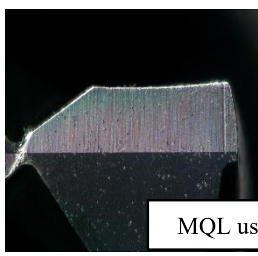
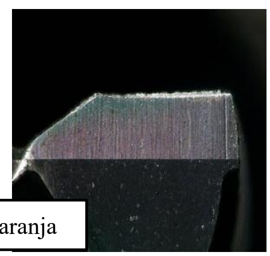
In dry machining condition, cutting tool fails at 6th hole. The average flank wear for 15 holes were measured for chilled air and MQL using Karanja oil machining conditions. Surprisingly, the MQL using Karanja oil performed better compared to chilled air machining condition. Only slight increment of tool wear from 5th hole to 15th hole as shown in the bar chart. The substantial enhancement in the MQL condition is due to the maximum fine spray of oil that penetrates into the tool and workpiece more effectively than chilled air machining conditions. Consequently, there was less heat around the holes during the drilling process. The conditions of the cutting tool at 5th hole and 15th hole for the three conditions are represented in Table 2. The results aligned with the study by Husshini et al. (2021) which MQL performed better compared to chilled air and dry cutting.

3. 2 Number of Holes

According to the graphical result in Figure 7, rapid flank wear occurred in dry machining condition. Only 5 holes attained below 0.3 mm in which initial rapid wear occurred at 4th holes. Obvious rapid wear happened at the 5th hole with a catastrophic failure. Cutting hard-to-cut materials without coolant can generate high temperatures at the cutting zone, which can lead to thermal damage to the cutting tool. In addition, without a coolant to flush chips away from the cutting zone led to clogging of cutting tool that caused the catastrophic failure.

The number of holes increase by 200% in chilled air condition compared to dry condition. The flank wear steadily increases until the 15th hole. The stream of chilled air directed to cutting tool and workpiece helps to cool them down during the drilling process. The pressure of chilled air can help to evacuate chips away from the cutting zone more effectively, preventing chip recutting and clogging of the cutting tool. However, rapid tool wear arises at 16th holes in which the flank wear is more than 0.3 mm. At 16th hole, the tool wear reached catastrophic failure where the deterioration occurred on the drill bit. MQL using Karanja oil machining condition shows the highest number of holes compared to dry and chilled air condition. Catastrophic failure did not occur in this condition. The flank wear gradually increases until 23rd holes. Initial rapid wear occurred at 24th holes until it reached 0.32 mm at 28th holes. The result agreed with Chen et al. (2019) which states that the best tool life achieved in MQL condition compared to dry and cryogenic condition. The lubrication provided by the MQL can proficiently lubricate the friction between tool and workpiece, thus enhancing the tool life (Swain et al., 2022).

Table 2: Flank wear for the three machining conditions.

	5th hole	15th hole
Dry		Fail at 6th hole
Chilled air		
MQL using Karanja		

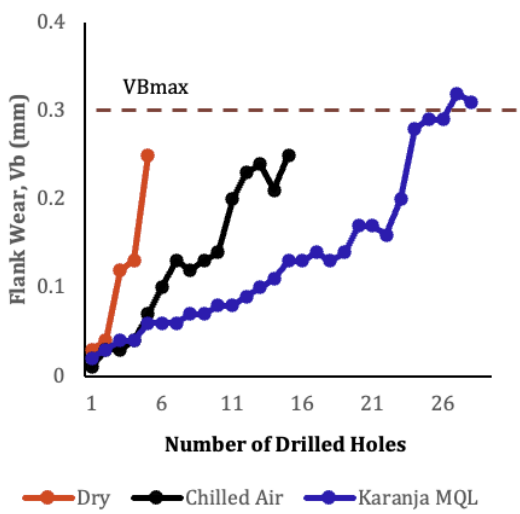


Figure 7: Number of holes before the tool fails.

3. 3 Catastrophic Failure

Mechanical breakage is the most common cause of cutting tool failure due to shocks and excessive forces. Aside from that, catastrophic failure might occur when the cutting tool's rake surface or flank face starts to deteriorate gradually. Catastrophic failure due to gradual flank wear is inevitable. In this study, most of the catastrophic failure occurred in dry machining condition such as burn mark, chipping and outer corner wear as shown in Figure 8. Drilling cobalt chromium without proper cooling or lubrication can generate high temperatures at the cutting zone. Rapid heating and cooling cycles can induce thermal shock in the cutting tool, causing cracks or fractures at the corner of the cutting tool. The outer corner wear occurred when drilling at 6th hole. The tool is considered as failed when the flank wear is higher than VB_{max}. By continuing using the failed cutting tool, the burn mark can be observed at the cutting tool due to thermal shock. Thermal shock is especially prevalent when there is a significant temperature difference between the workpiece and the tool. The high cutting forces involved in drilling cobalt chromium can lead to the chipping or fracturing of the cutting tool. Chipping also occurred due to thermal softening of the cutting tool due to absent of cooling agent. The result agreed with the study conducted by Pradeep et al. (2022). The combination of the material's hardness and the stress concentration at the cutting edge can cause localized failure, resulting in the breakage of the tool. In addition, catastrophic failure in dry machining occurred after development and accumulation of crater wear (Pimenov et al.,2024).

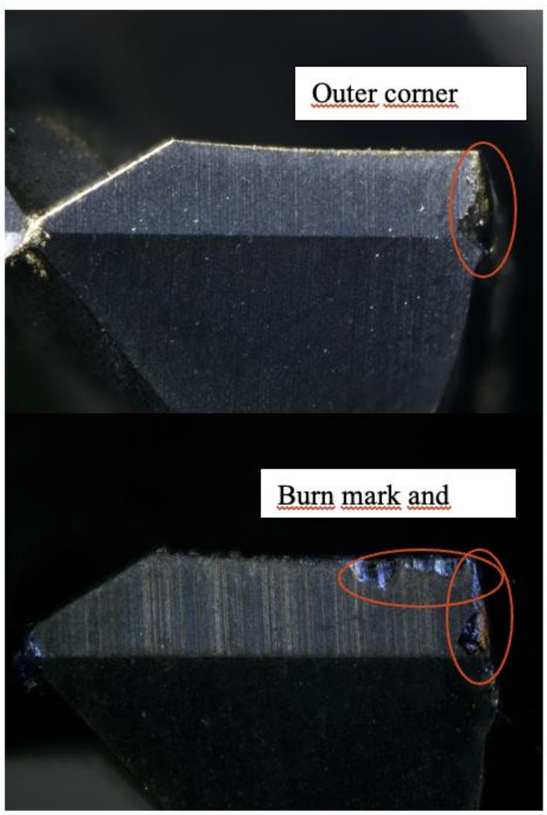


Figure 8: Catastrophic failure in dry machining condition.

In chilled air machining condition, the catastrophic failure occurred at 16th hole. The stair-formed face wear as shown in Figure 9 occurred due to temperature variations swing quickly from cut to cut in the process and cause the formation of cracks that are evenly spaced.

3. 4 Surface Roughness

Figure 10 demonstrates the results for average surface roughness, Ra for the three machining conditions. Comparison of the Ra results show the lowest Ra was produced under MQL using Karanja oil condition and followed by chilled air condition. Dry condition shows the highest Ra with the value of 1.680µm which is 37.8% and 46.7% higher than the hole drilled with chilled air and MQL using Karanja oil conditions, respectively. This result is supported by a previous study conducted by Hamidon et al. (2021). The rapid tool wear and catastrophic failure in dry machining condition can cause increased friction and chip adhesion. This, in turn, can lead to poor surface finish and increased surface roughness. Furthermore, due the excessive heat formed at cutting zone in dry condition, a material can undergo a phase transformation, which can cause changes in the microstructure of the material (Mustafa et al. 2024). These changes can result in residual stresses, surface cracks, and other forms of surface damage that can lead to increased surface roughness. In contrast, using the MQL using Karanja oil condition resulted in a decrease in chip temperature by reducing their adherence to the cutting tool's edge through misting an air-fluid mixture. This, in turn, led to an improved surface quality of the machined surface when compared to dry machining. Surface roughness result using MQL with Karanja oil is 14.8% better than chilled air. MQL provides a better result compared to chilled air, due to its ability to reduce friction and heat generation more effectively.

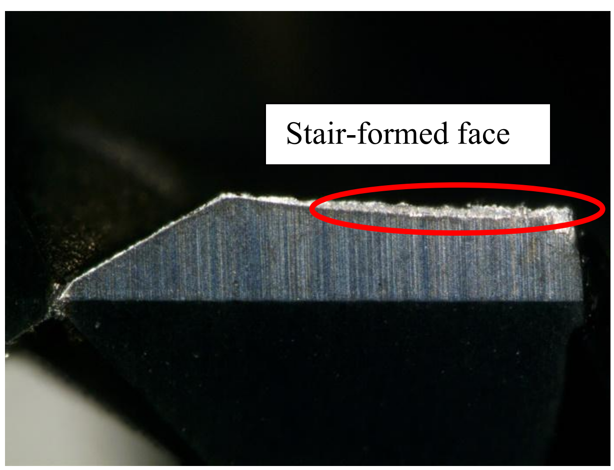


Figure 9: Catastrophic failure in chilled machining condition.

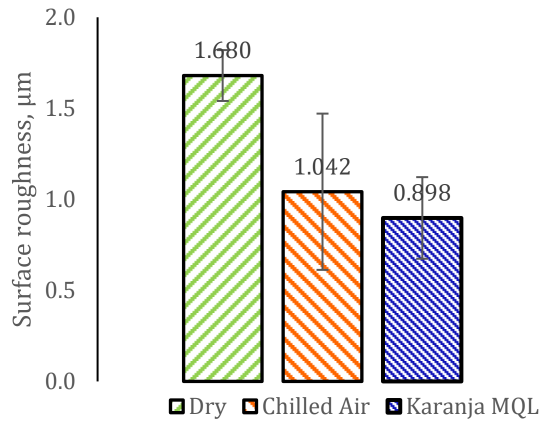


Figure 10: Average surface roughness against different machining conditions.

Figure 11 shows the trend of R_a for each hole in different machining conditions. For dry machining condition, the value of Ra is between 1.48µm and 1.84µm. There is not much difference between the values of Ra between each hole. Compared to chilled air condition, the lowest value of Ra was 0.4µm and the highest value was 1.92µm. The fluctuated trend of surface roughness in chilled air condition shows that chilled air is able to cool down the cutting zone, however, temperature variations swing quickly from cut to cut affected the value of surface roughness of the hole. The consistency of air jetted to the cutting zone is also varied, resulting in some areas not being properly covered. On the other hand, the result of surface roughness for MQL using Karanja oil condition is more consistent with the highest value is 1.61µm and the lowest value is 0.62µm. For the first four holes, the value of R_a is higher compared to the rest. This can be explained by a new cutting tool typically has sharper cutting edges, which can lead to higher cutting forces and more significant tool-part interactions during the initial machining operations. This can result in increased tool-part friction and potential micro-level vibrations, leading to higher surface roughness. In spite of that, most of the Ra values in this condition is lower compared to dry and chilled air condition.

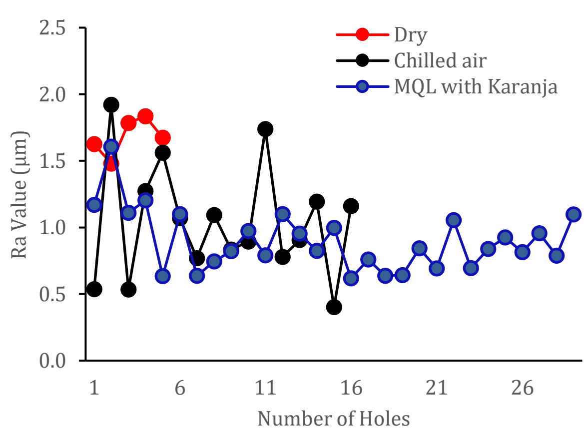


Figure 11. Average surface roughness for each hole.

3.5 Hole Diameter and Deviation

The characteristics of hole quality not only depends on surface roughness; hole diameter, deviation or circularity error also plays an important role. Any machined part's performance is significantly affected by the diameter deviation from the nominal size. For example, the tolerance for rivets and bolts required in the aerospace industry using a standard twist drill is as low as ±0.025 mm (Aamir et al., 2020). Figure 12 shows the result of circularity deviation for different machining condition at entry, middle and exit part of the holes. In average, dry machining shows the highest value of deviation for the three parts of the holes. At high temperature, the formation of Built -Up- Edge (BUE) is common. The drill's geometry would undergo changes with the existence of a significant BUE resulting in an enlargement of the drill diameter that causes high deviation in dry machining. Cooling from chilled air helps to reduce temperature and could decrease the formation of BUE. Typically, the extent of hole deviation was more noticeable when MQL using Karanja oil was utilized. The hole diameter is close to nominal value for the three parts of holes which is less than 0.1 mm for the whole depth. The hole shape at entry, middle and exit of the holes under different conditions are demonstrated in Figure 13.

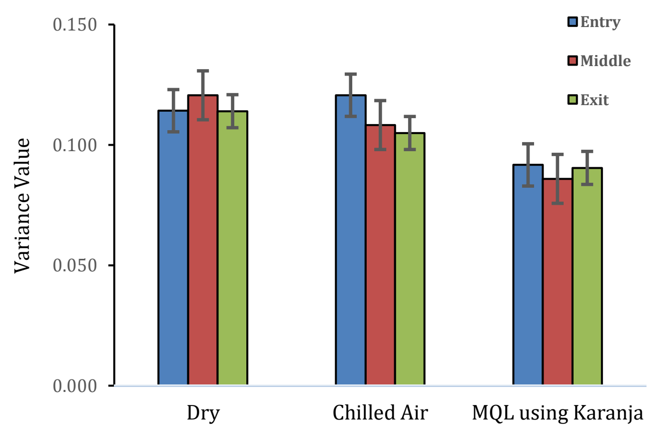


Figure 12: Circularity variation of the drilled holes.

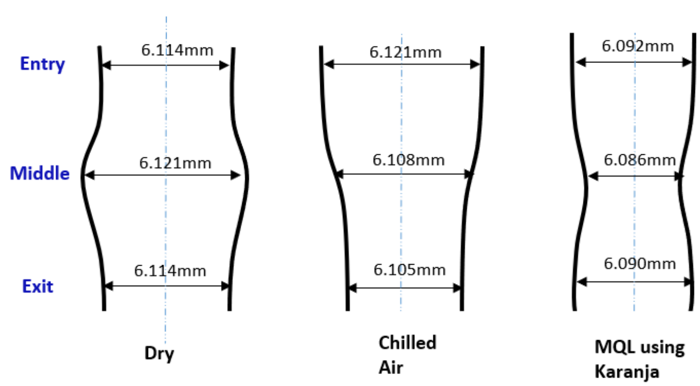
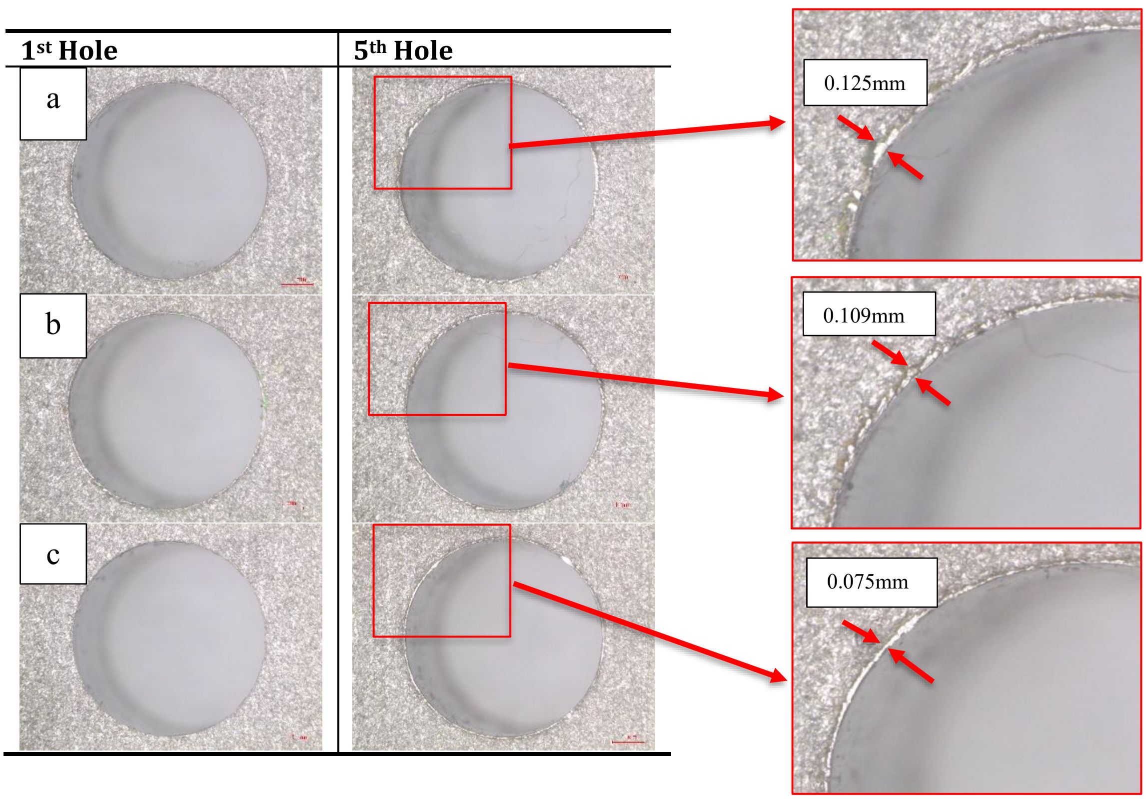


Figure 13: Hole shape under different machining conditions.

3. 6 Burr Formation

In drilling process, the burr formation occurs at the entrance and exit of the hole. The presence of burrs at the entry and exit points of the holes can cause challenges during part assembly and potentially result in the rejection of the part (Shanmugam et al.,2024). In this study, the burr width around the holes were observed at the hole entrance only. The burr formation in dry cutting, chilled air and MQL using Karanja oil is shown in Table 3 as denote a, b and c respectively. The width of the burr obviously showed at the 1st hole of dry cutting and chilled air machining conditions. At the 5th hole, the burr width become larger for both machining conditions. Conversely, for MQL using Karanja oil shows smooth shape around the hole at the 1st hole. The uniform burr width can be seen at 5th hole; however, the size of burr width is smaller compared to the other two conditions. The formation of the burr is closely related to the wear of cutting tools (Costa et al., 2009). The presence of cooling agent helps to reduce tool wear as well as the present of burr.

Table 3: Burr width for the three machining conditions.



CONCLUSIONS

In summary, from the analysis of different machining conditions; MQL using Karanja oil, chilled air, and dry machining applied to the drilling of cobalt chromium, the results obtained can be summarized below:

(a) Chilled air and MQL using Karanja oil machining condition show the reduction of average flank wear by 72% and 76% respectively compared to dry condition at 5th hole.
(b) The number of holes increase 200% and 360% in chilled air condition and MQL using Karanja oil respectively, compared to dry condition.
(c) Dry condition shows the highest Ra with the value of 1.680µm which is 37.8% and 46.7% higher than the hole drilled with chilled air and MQL using Karanja oil conditions, respectively.
(d) Dry machining and chilled air show more than 0.1mm of deviation for the entry, middle and exit part of the hole. However, for MQL using Karanja oil, the hole diameter is close to nominal value for the three parts of holes which was less than 0.1 mm for the whole depth.
(e) MQL using Karanja oil provides a better result compared to chilled air, due to its ability to reduce friction and heat generation more effectively. The property of high flash point and viscosity index make Karanja oil an effective and sustainable choice for lubrication in drilling process.

While acknowledging the limitations inherent in this study, such as the need for further exploration into specific operational parameters, the results unmistakably highlight MQL as the preferred machining condition for drilling cobalt chromium. Other types of vegetable oil such as neem, castor, linseed and jatropha are also known to have their benefit in lubrication purpose. Future investigations could explore deeper into optimizing cutting parameter and MQL using other types of vegetable oil.

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REFERENCES

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

Allegri, G., Colpani, A., Ginestra, P.S. & Attanasio, A. (2019). An Experimental Study on Micro-Milling of a Medical Grade Co-Cr-Mo Alloy Produced by Selective Laser Melting, Materials, 12(13):2208.

Altan Özbek, N., Özbek, O., Kara, F., & Saruhan, H. (2022). Effect of Eco‐friendly Minimum Quantity Lubrication in Hard Machining of Vanadis 10: a High Strength Steel. Steel Research International, 93(7), 2100587.

Balaji, M., Murthy, B. S. N. and Rao, N. M. (2016). Multi response optimization of cutting parameters in drilling of AISI 304 stainless steels using response surface methodology.

Proceeding of the Institution Mechanical Engineer s, Part B: Journal od Engineering Manufacture, vol. 232, no. 1, pp. 151-161.
Baron, S., Desmond, D. & Ahearne, E. (2019). The fundamental mechanisms of wear of cemented carbide in continuous cutting of medical grade cobalt chromium alloy (ASTM F75). Wear, 424–425, 89-96.
Chen, B., Xiong, F, Tang, H., He, L. & Hu, S. (2020). Effect of cooling method on small diameter blind-hole drilling of new. β-type dental Ti-Zr-Nb alloy. Journal of Manufacturing Process, 59, 421–431.
Costa, E.S., Silva, M. & Machado Á.R. (2009). Burr produced on the drilling process as a function of tool wear and lubricant-coolant conditions. Journal of The Brazilian Society of Mechanical Sciences and Engineering, 31, 57-63.
Das, A., Das, S.R., Panda, A. & Patel, S.K. (2022). Experimental investigation into machinability of hardened AISI D6 steel using newly developed AlTiSiN coated carbide tools under sustainable finish dry hard turning. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 236(5).
Dawood, A., Arbuckle, G. K. & Jahan M. P. (2015). A comparative study on the machinability of Ti-6Al-4V using conventional flood coolant and sustainable dry machining. International Journal of Machining and Machinability of Materials, 17(6), 507-528,
Deshpande, S. & Deshpande. Y. (2019). A review on cooling systems used in machining processes, Materials Today: Proceeding, 18 (7), 5019-5031.
Devgan, S., Mahajan, A. & Mahajan, V. (2023). Machining Performance of Cobalt-Chromium and β-Type Titanium Biomedical Alloy. Materials for Biomedical Simulation. Materials Horizons: From Nature to Nanomaterials. Springer, Singapore, 85-91.
Elbah, M., Laouici, H., Benlahmidi, S., Nouioua, M. & Yallese, M.A. (2019). Comparative assessment of machining environments (dry, wet and MQL) in hard turning of AISI 4140 steel with CC6050 tools. International Journal of Advanced Manufacturing Technology, 105, 2581–2597.
Gupta, K. and Laubscher, R. (2018). An Experimental Study on MQL Assisted High Speed Machining of NiTi Shape Memory Alloy, Proceedings of 16th international conference on manufacturing research, pp. 80-85.
Hamidon, R., Zulkefli, N.A., Saravanan, R., Zailani, Z., Bahari, M.S., Zakaria, S. & Azmi, H. (2021). Effect of Different Cutting Conditions on Tool Wear and Chip Formation in Drilling of Cobalt Chromium Molybdenum, Lecture Notes in Mechanical, Intelligent Manufacturing and Mechatronics, 391–400.
Husshini, N.H.N., Kasim, M.S. & Mohamad, W.N.F. (2022). Tool Life and Surface Roughness of Inconel 718 During End Milling Under Dry, Chilled Air and Chilled MQL. Lecture Notes in Mechanical Engineering. SympoSIMM 2021: Intelligent Manufacturing and Mechatronics, 415–423.
Kumar, S. & Gandotra, S. (2021). Effect of cooling air on machining performance during hard turning. Materials Today: Proceedings. Volume 38(5), 2213-2216.
Mahboob, A.M.A., Azmi A.I. &Khalil A.N.M. (2018). Specific cutting energy of Inconel 718 under dry, chilled-air and minimal quantity nanolubricants, Procedia CIRP, 77, 429–432.
Mustafa, G., Li, B. & Zhang, S. (2024). Cutting condition effects on microstructure and mechanical characteristics of Ni-based superalloys—a review. Int J Advanced Manufacturing Technology 130, 3179–3209.

Nazma, S.M., Ranjan, D.N. & Binte Z.P. (2019). A Review on Different Cooling/Lubrication Techniques in Metal Cutting, American Journal of Mechanics and Applications, 7 (4), 71–87.
Özbek, O., Altan Özbek, N., Kara, F., & Saruhan, H. (2023). Effect of Vibration and Cutting Zone Temperature on Surface Topography during Hybrid Cooling/Lubrication Assisted Machining of Vanadis 10. Materials Testing, 65(9), 1437-1452.
Pradeep, K.G. & Samuel, R.D. (2022). Analysis of high-speed drilling AISI 304 under MQL condition through a novel tool wear measurement method and surface integrity studies. Tribology International, 176, 107871.
Pimenov, D. Y., da Silva, L. R. R., Machado, A. R., França, P. H. P., Pintaude, G., Unune, D. R., Kuntoglu, M. & Krolczyk, G. M. (2024). A comprehensive review of machinability of difficult-to-machine alloys with advanced lubricating and cooling techniques. Tribology International, 109677.
Rahim E.A. & Sasahara, H. (2011). A study of the effect of palm oil as MQL lubricant on high-speed drilling of titanium alloys, Tribology International. 44 (3), 309–317.
Rahman, M., Kumar, A.S., Manzoor, U.S. and Ling, M.S. (2003). Effect of Chilled Air on Machining Performance in End Milling. The International Journal of Advance Manufacturing Technology, 21, 787–795.
Revuru, R.S., Zhang, J.Z. & Posinasetti, N.R. (2020). Comparative performance studies of turning 4140 steel with TiC/TiCN/TiN-coated carbide inserts using MQL, flooding with vegetable cutting fluids, and dry machining. The International Journal of Advanced Manufacturing Technology, 108, 381–391.
Roy, S., Kumar, R., Kumar, S. A. & Kumar, D. R. (2019). A Brief Review on Effects of Conventional and Nano Particle Based Machining Fluid on Machining Performance of Minimum Quantity Lubrication Machining. Materials Today: Proceedings, 18, 5421–5431.
Said, Z., Gupta, M., Hegab, H., Arora, N., Khan A.M, Jamil, M. & Bellos, E., (2019). A comprehensive review on minimum quantity lubrication (MQL) in machining processes using nano-cutting fluids. The International Journal of Advance Manufacturing Technology, 105, 2057–2086.
Salur, E., Kuntoğlu, M., Aslan, A. & Pimenov, D. Y. (2021). The Effects of MQL and Dry Environments on Tool Wear, Cutting Temperature, and Power Consumption during End Milling of AISI 1040 Steel. Metals. 11, (11), 1674.
Saravanan, R., Hamidon, R., Murad, N.M. & Zailani, Z. A. (2021). Machining of Cobalt Chromium Molybdenum (CoCrMo) Alloys: A Review. Lecture Notes in Mechanical Engineering, 413–424.
Shanmugam, R., Baloor, S.S., Koklu, U., Polishetty, A. & Bolar, G. (2023). Machining Temperature, Surface Integrity and Burr Size Investigation during Coolant-Free Hole Milling in Ti6Al4V Titanium Alloy. Lubricants,11(8).
Sharma, V. S., Dogra, M., and Suri N. M. (2009). Cooling techniques for improved productivity in turning, International Journal of Machine Tools & Manufacture vol. 49, pp. 435–453.
Sun, J., Wong, Y. S., Rahman, M., Wang, Z.G., Neo, K. S., Tan, C. & Onozuka, H. (2006). Effects of coolant supply methods and cutting conditions on tool life in end milling titanium alloy. Machining Science and Technology, 10 (3), 355–370.
Swain, S., Patra, S.K., Roul, M.K. & Sahoo, L.K. (2022). A short review on cooling process using compressed cold air by vortex tube in machining. Materials Today: Proceeding, 64(1), 382-389.
Yugeshwar, C., Prasad M.V.R.D. & Ramana, M.V. (2023). Dry machining of alloy steels – A review. Materials Today: Proceedings.

Zailani, Z.A., Ruslia N. S. N., Shuaib N. A. (2021). Effect of Cutting Environment and Swept Angle Selection in Milling Operation. International Journal of Engineering, 34 (12), 2578-2584.
Zainal, A. Z., Tarisai M. P. & Harrison, G. (2020). Chilled Air System and Size Effect in Micro-milling of Nickel−Titanium Shape Memory Alloys. International Journal of Precision Engineering and Manufacturing-Green Tech, 7, 283–297.
Zaman, H. A., Sharif, S., Kim, D. W., Idris M. H., Suhaimi M. A. & Tumurkhuyag, Z. (2017). Machinability of Cobalt-based and Cobalt Chromium Molybdenum Alloys - A Review. Procedia Manufacturing, 11, 563–570.