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The influence of Graphene-enhanced minimum quantity lubrication and swept angle on machinability of Aluminum alloy 1050

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KEYWORDS

Milling
Dry cutting
Swept angle
MQL
Graphene nanoparticles
Machinability

ABSTRACT

Cutting fluids usage is a significant concern due to their impact on health footprint and the environmental effects throughout its lifecycle. Both industry and research institutions seek ways to reduce the use of cutting fluid for ecological and economic reasons. This study investigates alternative methods, including dry machining, minimum quantity lubrication (MQL) and MQL augmented with graphene nanoparticles on machinability of Aluminum Alloy 1050. Two ranges of stepover; 30% and 60% of the cutting tool diameter were applied in milling process. Their impact on tool wear, surface roughness, burr and chip formation were studied. Results indicated that the dispersion of graphene nanoparticles in minimum quantity lubricant significantly reduced the tool wear, decreased the burr formation and chip size, as well as enhanced surface quality of the milled slots as compared to dry machining and minimum quantity lubrication alone. The findings emphasize the importance of selecting proper swept angles and cutting conditions to enhance material machinability.

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1.0 INTRODUCTION

Aluminum, characterized by its inherent softness and low melting point, may not be well-suited for industrial applications due to the formation of a slippery coating during cutting or machining, posing a risk of tool damage (Hong and Zhao, 1999). To tackle this challenge, aluminum is commonly blended with alloying elements like copper, magnesium, and manganese to produce aluminum alloys (Kah et al., 2015). These alloying elements are identified by a series number, ranging from 1 to 8, indicating the purity of aluminum in the alloyed metal (Kaufman, 2000). The incorporation of alloying elements alters the mechanical and chemical properties of the alloy, making certain alloys more conducive to cutting, shaping, or milling than others. Aluminum alloys, with their malleable characteristics and high ductility, find extensive use in industries such as aerospace, automotive, and general engineering (Ulas et al., 2020). Among the widely utilized aluminum alloys is Aluminum Alloy 1050 (AA1050), known for its pliability, making it suitable for applications requiring high formability (Avcu et al., 2021).

Despite its reputation for good machinability, this material can still develop a built-up edge (BUE) during machining, potentially impacting both the surface finish and the longevity of the cutting tool (Sarikaya et al., 2021). An increase in cutting temperature to a given level will lead to microstructural adjustments, surface residual stress, tolerance errors and distortions. Normally, in machining of aluminum alloy, cutting fluids are used to avoid overheating and adherence of material to the surface cutting (Pena et al., 2018). Additionally, the cutting fluids also solve machinability issues by cooling, removing metal particles, reducing friction, and protecting the tool, workpiece, and machine tool (Rao, 2008). However, since around 85% of these fluids are either petroleum-based or mineral-based oils, which are not biodegradable, they could potentially cause major environmental pollution throughout their life cycle (Pop et al., 2008). Furthermore, this cutting fluid can have adverse effects on health, including the development of leukemia, skin cancer, lung cancer, asthma, and other associated conditions (Raza et al., 2014). Hence, driven by the needs of stringent operating conditions and environmental preservation, numerous alternatives to conventional liquid lubricants have been proposed.

Alternative lubrication techniques like dry cutting, minimum quantity lubrication (MQL), chilled air, cryogenic machining, air cooling, and the use of solid lubricants have been found effective in improving machining performance and reducing risks (Zailani and Mativenga, 2023). Opting for dry machining is a prudent choice to avoid the use of potentially risky cutting fluids during the machining process. Dry machining eliminates the need for external lubricants or coolants, relying solely on the inherent properties of the cutting tool and workpiece material (Goindi and Sarkar, 2017). While it may lead to increased tool wear and higher temperatures, proper tool selection and control of cutting parameters can mitigate these effects. In situations where complete removal of cutting fluids is not feasible, minimum quantity lubrication (MQL) is employed. It involves applying a minimal amount of lubrication, precisely targeted to specific points during machining (Mia et al., 2022). This technique enhances surface finish quality, extends tool life, reduces lubrication costs, and mitigates tool wear and cutting temperature. Recently, the use of graphene nanoparticles to augment minimum quantity lubrication was found to be the most significant factor in reducing flank wear, burr formation and cutting force. The theory is that the property of graphene including its easy rolling and sliding action improves the contact condition and friction in machining (Zailani and Mativenga, 2022).

Swept angle, also known as tool engagement, plays a crucial role in machining processes. It refers to the portion of the cutting tool that interacts with the workpiece during milling. The swept angle significantly impacts several key factors, including tool wear, surface roughness, chip formation, and burr formation (Zainal et al., 2021). In addition, it also holds significance in mechanical machining operations as it links the parameters of the cutting tool, workpiece materials, and the process itself (Balogun and Edem, 2017). That is the reason why it has been recognized as one of the selection criterions for tool life (Boothroyd, 1988). Hence, the cutting tool and workpiece engagement are significant in influencing machining performance (Adesta et al., 2018). So, the objective of this research is to conduct an experimental study investigating the impact of swept angle selection under various cutting conditions during the milling process. Subsequent sections will delve into a detailed explanation of the study's findings and implications.

2.0 EXPERIMENTAL PROCEDURE

2.1 Experimental Setup and Machining Conditions

The material of the workpiece was an Aluminum Alloy 1050 plate, measuring 150 mm in length, 150 mm in width, and 4 mm in height. The composition of AA1050 was verified through arc spark analysis. The outcomes of the arc spark experiment affirmed the identification of the tested specimen as AA1050. Following this, the results of the arc spark experiment were presented in Table 1, detailing the weight percentage of the specific composition of AA1050. A 4-flutes high speed steel (HSS) end mill cutter with 4.0 mm diameter was used. This experiment was conducted using a Tongtai EZ–5A CNC Milling Machine. A constant cutting velocity of 63 m/min, table feed rate of 440 mm/min, and depth of cut of 1 mm were used as established from pilot tests.

Table 1: Specimen Component Percentage.

Element	**Composition (%)**
Aluminium, Al	99.43
Silicon, Si	0.084
Iron, Fe	0.367
Copper, Cu	0.063
Manganese, Mn	0.019

Three different cutting conditions were studied, namely dry, minimum quantity lubrication (MQL) with base lubrication (Solcut oil) and MQL dispersed with graphene nanoparticles. For MQL, the nozzle was placed at the tool entry point to enhance oil entrapment (Zainal Abidin et al., 2020). The flow rate was 40 ml/hr with a compressed air pressure of six bar. In this experiment, two values of swept angle were used for each condition: 30% and 60% of tool diameter stepover which were 66.4° and 101.5°, respectively. Each condition was repeated three times using new cutting tools. Figure 1 shows the schematic view of experimental setup.

A swept angle refers to the angle formed by the cutting edge of a milling tool and the direction of the feed motion during the machining operation. In milling operations, having the right swept angle is important for achieving proper chip evacuation, minimizing tool wear, and obtaining the desired surface finish on the machined part (Zainal et al., 2021). The values will be chosen using equation (1):

$$Swept\ angle = \frac{tool\ step\ over\ (\%)}{100} \times\ tool\ diameter \tag{1}$$

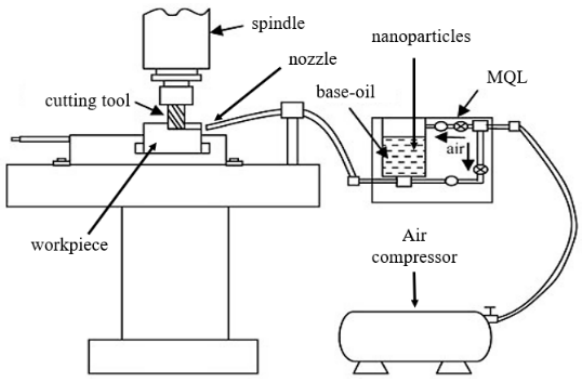

Figure 1: Schematic view of experimental setup.

Figure 3 shows the swept angle of the cutting tool on the workpiece which consists of 66.4° (30% tool diameter stepover) and 101.5° (60% tool diameter stepover). Both stepovers were selected to indicate high and low angle of engagement. Figure 2 shows the swept angle of the cutting tool on the workpiece which consists of 66.4° (30% tool diameter stepover) and 101.5° (60% tool diameter stepover). Both stepovers were selected to indicate high and low angle of engagement.

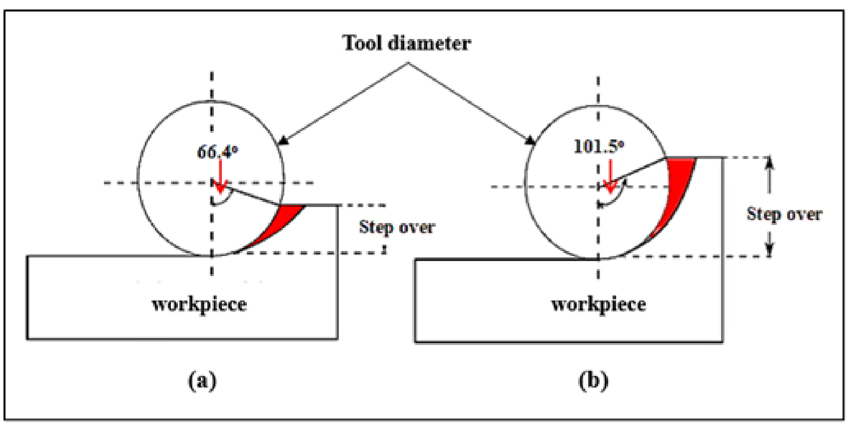

Figure 2: Swept angles of the cutting tool on the workpiece, (a) Ø = 66.4° and (b) Ø = 101.5°.

2.2 Cutting Fluid Preparation

In this experiment, graphene nanoplatelet was used as an additive in base oil. It was supplied by US Research Nanomaterials. Inc. Figure 3 shows image of the graphene nanoplatelet at 10 μm scale under scanning electron microscope (SEM). The nanofluids were prepared by mixing the nanoplatelet particles with Solcut oil. Sodium dodecyl sulfate with 0.1% weight of the nanoparticles was added to stabilize the particles and enhance the uniformity. Then, the mixtures were stirred for five minutes in a AM4 Multiple Heating Magnetic Stirrer machine before sonicated for one hour using a Branson Digital Sonifier Ultrasonic Liquid Processor.

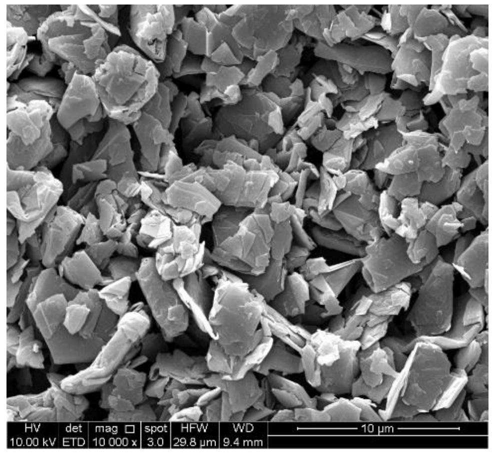

Figure 3: SEM image of graphene nanoplatelet.

2.3 Tool Wear, Cutting-Edge Radius, Surface Roughness, Burr Formation and Chip Length

Every tool and workpiece for each cutting condition was then examined using a Xoptron XST60 Stereo Microscopy System to capture tool wear, burr and chip formation. Flank wear (V_B) was measured on the side flank face, and cutting-edge radius (r_e) was determined by placing the best-fitting circle at the tool flank face intersection. While the width of burr formation (W_b) was measured for top burr. Then, the length of chip formation (L_c) was also quantified. For all measurements, a Java-based image processing, Image J software was used concurrently. A Mitutoyo F-3000 surface roughness tester was used to measure surface roughness using arithmetical mean (R_a) value. Systematic uncertainties were minimized by first calibrating the equipment to be used. In addition, random vagueness was addressed by performing each measurement at least five times.

3.0 RESULTS AND DISCUSSION

3.1 Tool Wear Modes

Optical images were used to identify the wear modes. Figure 4 depicts various types of wear and damage on a cutting tool after milling ten consecutive slots. These include material adhesion, where material has stuck to the tool's surface; flank wear, which occurs when the tool's flank is worn down due to friction during cutting; outer corner wear, affecting the tool's edges; and chipping, where small pieces of the tool have broken off. Each type of wear impacts the tool's performance and longevity. Among all wear modes, the most dominant was flank wear. The primary cause of these occurrences lies in the intense force and persistent contact between the cutting tool and the workpiece during penetration. This interaction results in heat generation through frictional action.

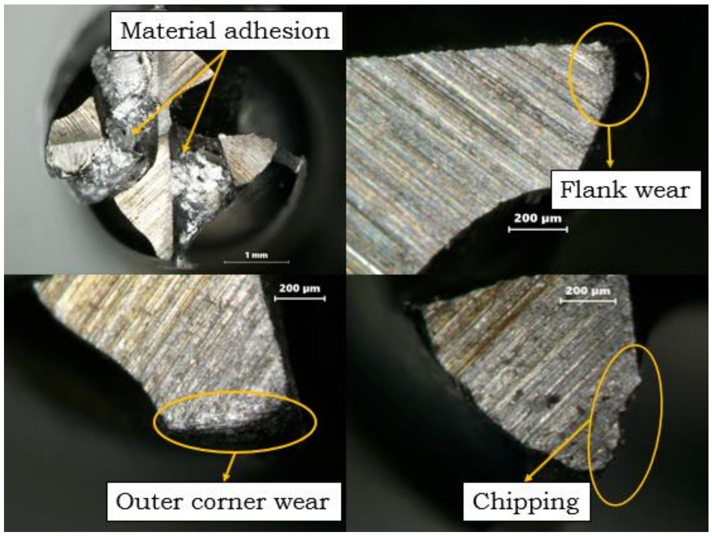

Figure 4: Tool wear modes after milling ten consecuties slots.

In addition, when machine aluminum alloy 1050, the material adhesion is crucial due to the sticky and soft characteristics of the alloy. These properties make the alloy susceptible to adhering to the tool rake face during the cutting process. The occurrence of material adhesion is predominantly influenced by temperature. This situation would soften the workpiece material thus resulting in welded chips or material adhesion that cause build-up in the flute area specifically under dry cutting (as shown in Figure 5). As temperature varies, both the evolution of adhesion and changes in the friction coefficient are significantly impacted. Abidin et al. (2024) also observed comparable outcomes, noting that tool burn marks were detected during dry cutting, leading to flute clogging. That is why almost no adhesion was found under MQL and when MQL dispersed with graphene nanoparticles (Figure 6).

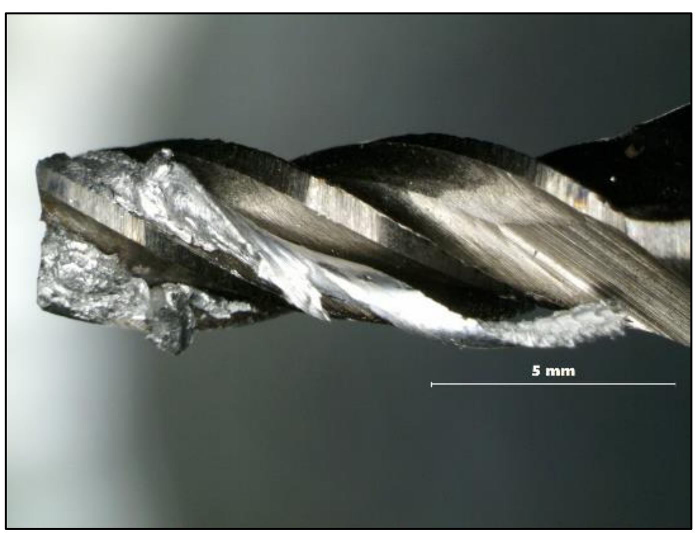

Figure 5: Welded chips and material adhesion under dry cutting.

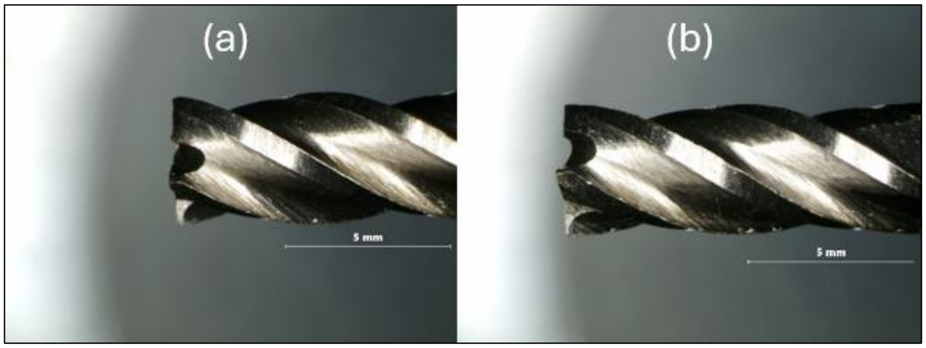

Figure 6. Flute condition under MQL and MQL dispersed with graphene.

3.2 Tool Flank Wear

For the flank wear measurements, the tools were imaged from the bottom face to focus on each cutting edge. The magnitude of flank wear was determined according to ISO 8688-2 [19]. Lines were drawn from the cutting edge to the end of the worn land and the average of these lines used as the average flank wear. Figure 7 shows the average flank wear growth for different swept angles and cutting conditions. The results pointed that the flank wear was significantly affected by the swept angles and cutting conditions. The highest flank wear was attained under swept angle 101.5° for all cutting conditions. The higher swept angle contributes to higher wear during machining due to the increased contact area between the tool and the workpiece, leading to more friction and heat generation. Additionally, the higher swept angle can lead to more significant forces acting on the cutting tool, accelerating wear and reducing tool life. This finding aligns with the research conducted by Bologun and Edem, who found that increased specific cutting energy, corresponding to a higher swept angle, resulted in greater power requirements for the machine tool (Balogun and Edem, 2017). It is clearly seen that the surface material is pushed to the sides of the scratch, as well as the formation of wear debris expelled to the edge of the scar. The scar presents a typical aspect of ploughing wear.

It can be seen clearly that machining under dry cutting condition shows a substantial amount of wear on the flank surface in both swept angles. Figure 8 shows example of flank wear for lower swept angle. Together MQL and MQL with graphene nanoparticles have increased wear in higher swept angle but remain much lower than dry cutting. Meanwhile, machining under MQL confronts lesser values under similar parametric settings condition. This is since the oil which acts as a cooling and lubricating agent could significantly reduce the temperature and frictional forces between the cutting tool and workpiece. Additionally, the inclusion of graphene nanoparticles further enhances MQL. Graphene is renowned for its exceptional properties, including high thermal conductivity and efficient lubrication. When dispersed in MQL, it forms a nanofluid that offers several benefits that minimizes surface roughness, reduces cutting temperature, improves tool life, and decreases tool wear. This finding seems to be consistent with Wang et al. reported that by adding graphene as additive in canola oil, the cutting temperature and wear was significantly reduced (Wang et al., 2022). Naresh et al. (2019) reported that the properties of graphene eliminate heat generated at the cutting zone and tool wear through formation of thin film. Notably, under MQL with dispersed graphene nanoparticles, the cutting-edge shape remains relatively sharper compared to both dry cutting and MQL alone, where the edges tend to be more rounded.

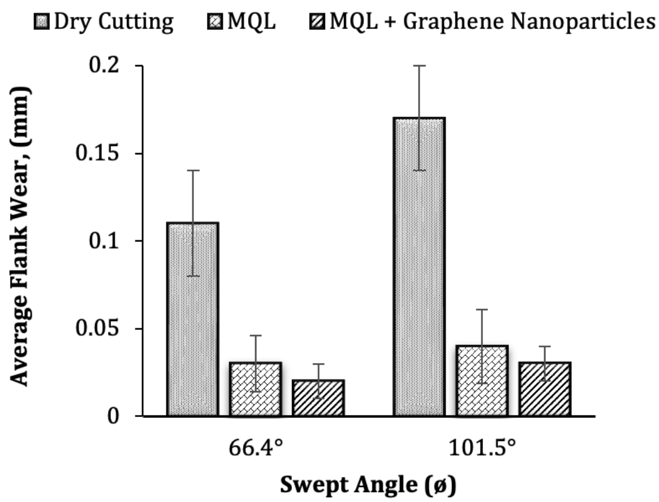

Figure 7: Average flank wear under different swept angles and cutting conditions.

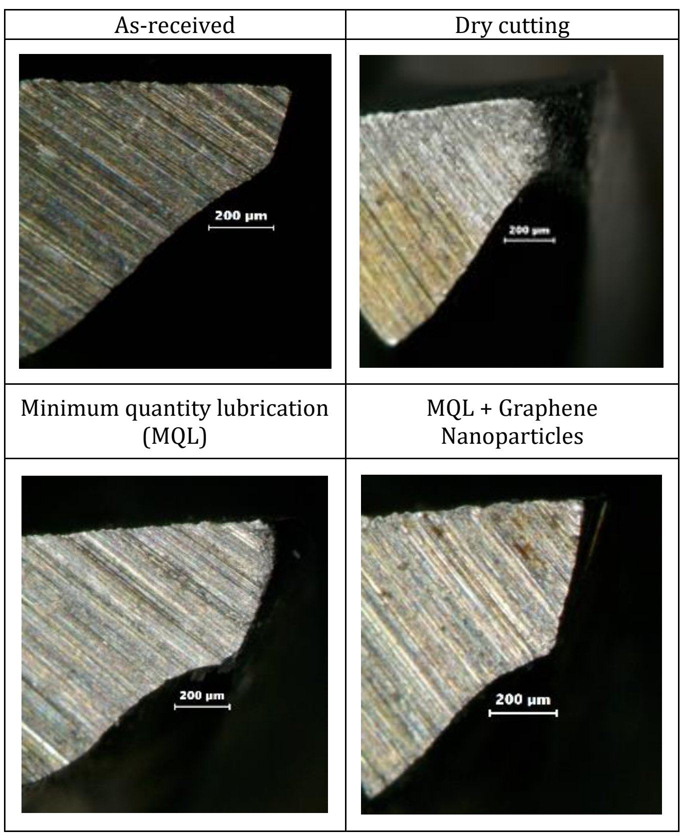

Figure 8: Tool wear growth for lower swept angles under different cutting conditions.

3.3 Surface Roughness

Surface roughness is a crucial quality indicator in machining processes. Figure 9 illustrates how average surface roughness varies with different swept angles and cutting conditions. The evaluation is based on the arithmetic mean value (Ra). Notably, roughness quality is closely tied to feed per tooth and tool edge radius. Since feed per tooth values remain fixed across all cutting conditions, any impact from tool wear directly affects the overall roughness quality.

In this experiment, average surface roughness was measured at three main points, i.e. entry, middle, and exit of milled slot. Surface roughness could be improved by using MQL and nanoparticles instead of dry cutting, especially under lower swept angle. Figure 10 shows surface roughness pattern under different cutting conditions and swept angles. Rougher surface was found under dry cutting, especially with adhered or sticky material. Under dry cutting conditions, particularly when materials become adhered or sticky, a rougher surface was observed. This can occur due to chips becoming welded to the cutting tool or workpiece surface, resulting in surface defects and a less refined finish (Kasim et al., 2023). In contrast, the adhered material was eliminated in other conditions. This might be due to the application of MQL, and nanoparticles reduce the tool wear by retaining the sharp edges and hence, improve the surface quality.

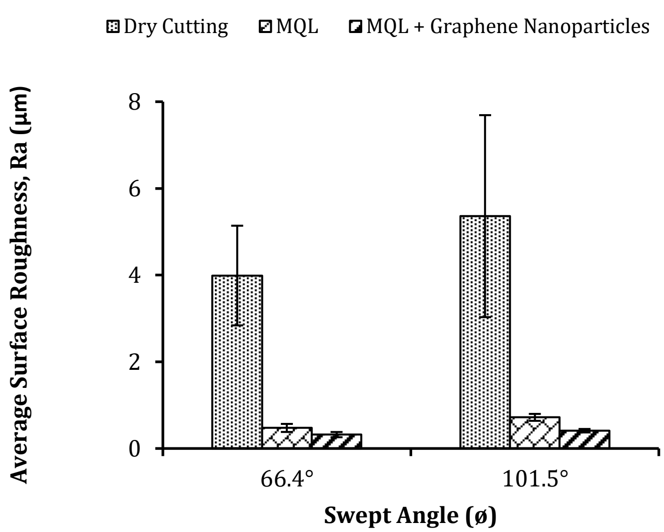

Figure 9: Average comparisons for surface roughness, Ra.

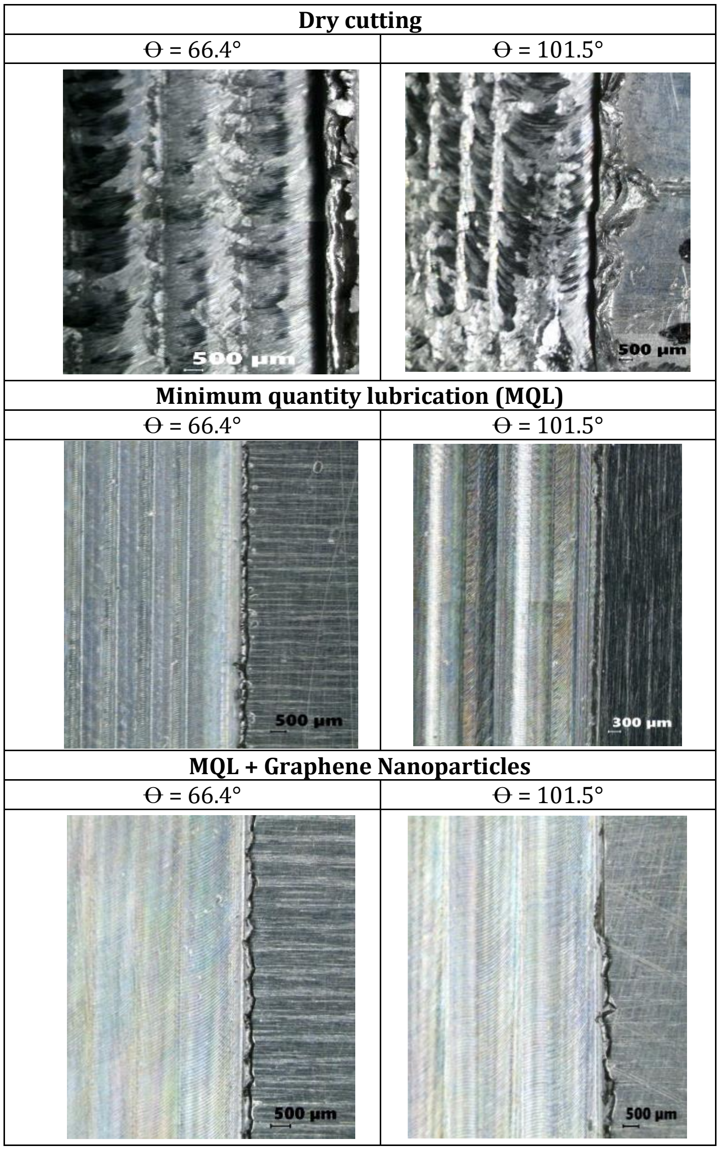

Figure 10: Surface pattern for both swept angles and cutting conditions.

3.4 Burr Formation

It is important to note that due to the high ductility of aluminium, it could promote serious formation of burr on the slot side. There were four types of burrs created which were top burr, exit burr, entrance burr, side burr, and bottom burr. They were designated through their cross-sectional area. It was found that the most dominant burr was the top burr which formed on top of the workpiece surface. Figure 11 shows the top burr formation varies under different swept angles and cutting conditions. Dry cutting results in wider top burrs with substantial curvature, while MQL (minimum quantity lubrication) produces thinner burrs. The addition of nanoparticles to MQL enhances the shearing process by improving lubrication and reducing chip adhesion, ultimately leading to reduced burr size.

Figure 12 shows the average burr width under different cutting conditions and swept angles. A significant reduction in burr width values was obtained under MQL and MQL dispersed with graphene nanoparticles. This improved performance was possibly due to their ability to maintain the sharpness of the tools. Under dry cutting, as the tool wears down, its cutting edges become less sharp and more prone to producing burrs on the workpiece. The wear on the tool affects its ability to maintain a clean cutting action, contributing to ploughing effect, resulting in increased burr formation (Ning et al., 2001). The observed phenomenon shows a direct correlation, as a higher swept angle leads to increased tool wear, larger cutting-edge radius, heightened ploughing effect, and ultimately, the formation of a prominent top burr.

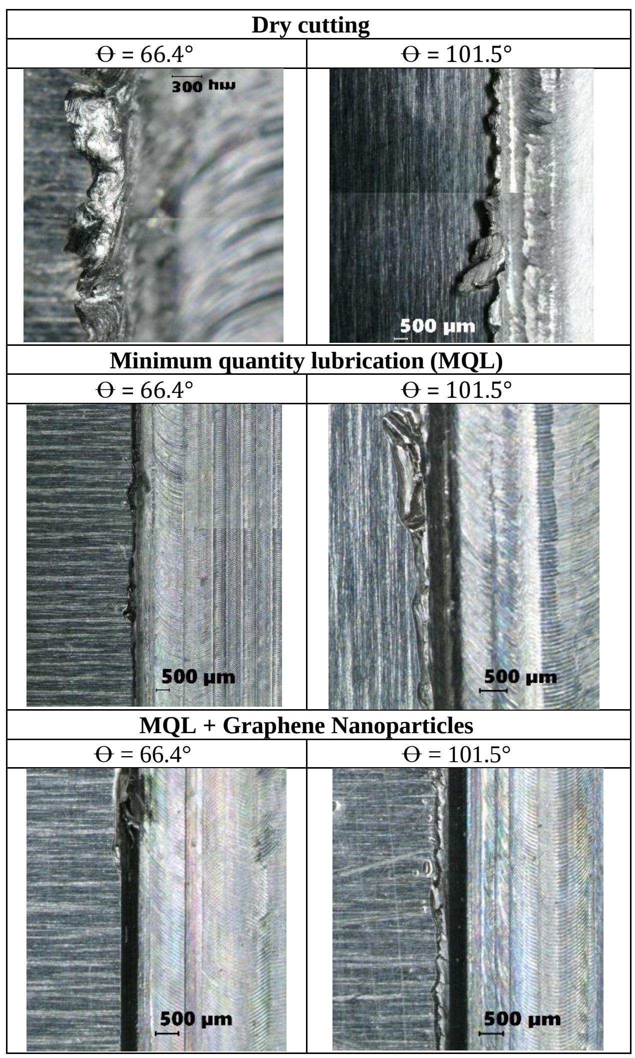

Figure 11: Burr formation under different swept angles and cutting conditions.

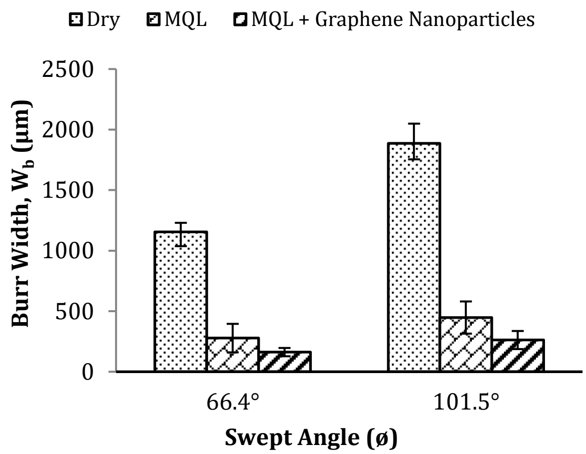

Figure 12: Average burr width under different swept angles and cutting conditions.

3.5 Chip Formation

Chips are formed heavily relying on strain deformation, wherein partial fracturing is induced by internal cracking or voiding within or adjacent to the primary shear zone. In this experiment, the most dominant chip produced is discontinuous chips, which are breaks into small and irregular long and short fragments in size. Figure 13 shows the average chip length under different swept angles and cutting conditions. Dry condition created longer chips especially when a higher swept angle was applied. This finding agrees with theory where the higher value of swept angle applied during operation, the longer the chips.

Figure 14 compares chip patterns under various cutting conditions. It is prominent to note that small well-broken chips are preferred in machining. This will facilitate better heat dissipation, exert less force and easier to evacuate from the cutting zone. Under dry cutting, for a lower swept angle, the shapes are long, thin, and curled compared to more fragmanted and irregular at a swept angle of 101.5°. The chips experienced intense heat, which caused them to undergo significant plastic deformation. Ning et al. (2001) reported that thermal stresses will cause the chip to curl. In other words, the high temperature made the chips change shape and become distorted. Regardless of the swept angle, MQL produces shorter and flat chips compared to dry cutting. The addition of graphene nanoparticles to MQL further enhances the process. Chips become even shorter and more compact than in MQL alone. The texture differs noticeably from the other conditions. The research findings consistently support the idea that lubrication through MQL (minimum quantity lubrication) and MQL with graphene nanoparticles is beneficial for chip formation during machining. Specifically, these lubrication methods result in shorter chips compared to dry machining. In summary, proper lubrication enhances chip behavior and contributes to more efficient and controlled machining processes.

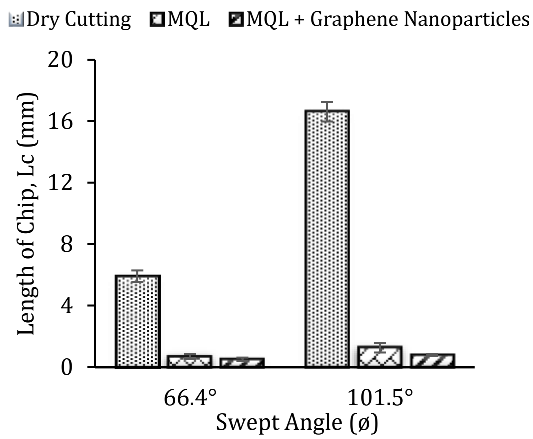

Figure 13: Average chip length under different swept angles and cutting conditions.

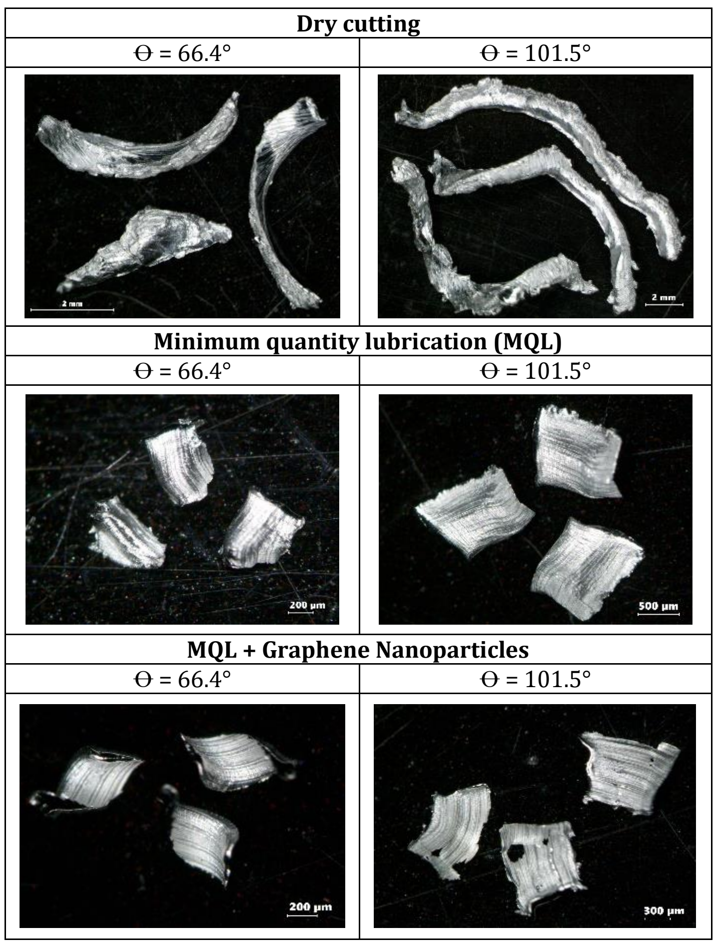

Figure 14: Chips pattern under different swept angles and cutting conditions.

CONCLUSIONS

This study highlights the advantages of using minimum quantity lubrication (MQL) as an alternative to conventional metalworking fluids in machining. The inclusion of graphene nanoparticles in MQL further enhances its effectiveness. Additionally, the study explores the impact of swept angle selection across different cutting conditions. Notably, opting for a lower swept angle consistently leads to favorable outcomes, including reduced tool wear, minimized burr formation, improved surface roughness, and enhanced chip formation. Overall, the results emphasize the potential of MQL with dispersed graphene nanoparticles, particularly at a swept angle of 66.4°, where minimal tool wear and superior surface quality are demonstrated.

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REFERENCES

Abidin, Z. Z., Ariffin, N. I., Shuaib, N. A., Hamidon, R., Harun, A., & Sultan, A. A. M. (2024, March). Enhancement on the surface quality in machining of aluminum alloy using graphene nanoparticles. In AIP Conference Proceedings (Vol. 2934, No. 1). AIP Publishing. https://doi.org/10.1063/5.0180573.

Adesta, E. Y. T., Hamidon, R., Riza, M., Alrashidi, R. F. F. A., & Alazemi, A. F. F. S. (2018). Investigation of tool engagement and cutting performance in machining a pocket. In IOP Conference Series: Materials Science and Engineering (Vol. 290, No. 1, p. 012066). IOP Publishing. https://doi.org/10.1088/1757-899X/290/1/012066.

Avcu, Y. Y., Gönül, B., Yetik, O., Sönmez, F., Cengiz, A., Guney, M., & Avcu, E. (2021). Modification of surface and subsurface properties of AA1050 alloy by shot peening. Materials, 14(21), 6575. https://doi.org/10.3390/ma14216575.

Balogun, V. A., & Edem, I. F. (2017). Optimum swept angle estimation based on the specific cutting energy in milling aisi 1045 steel alloy. International Journal of Engineering, Vol. 30, No. 4, 1-4.

Boothroyd, G. (1988). Fundamentals of metal machining and machine tools (Vol. 28). Crc Press.

Goindi, G. S., & Sarkar, P. (2017). Dry machining: a step towards sustainable machining–challenges and future directions. Journal of cleaner production, 165, 1557-1571. https://doi.org/10.1016/j.jclepro.2017.07.235.

Hong, S. Y., & Zhao, Z. (1999). Thermal aspects, material considerations and cooling strategies in cryogenic machining. Clean Products and Processes, 1(2), 107-116. https://doi.org/10.1007/s100980050016.

ISO, I. (1989). International Standard ISO 8688: Tool-life Testing in milling.

Kah, P., Rajan, R., Martikainen, J., & Suoranta, R. (2015). Investigation of weld defects in friction-stir welding and fusion welding of aluminium alloys. International Journal of Mechanical and Materials Engineering, 10, 1-10. https://doi.org/10.1186/s40712-015-0053-8.

Kasim, M. S., Ngah, N., Mohamed, S. B., Rahman, Z. A., Haron, C. H. C., Yusof, S. N. A., & Mohamad, A. (2023). Machining surface quality evaluation of Inconel 718: a comparative study of various coolant and lubrication strategies in milling process. Jurnal Tribologi, 39, 17-35.

Kaufman, J. G. (2000). Introduction to aluminum alloys and tempers. ASM international.
Mia, M., Rahman, M. A., Gupta, M. K., Sharma, N., Danish, M., & Prakash, C. (2022). Advanced cooling-lubrication technologies in metal machining. In Machining and tribology (pp. 67-92). Elsevier. https://doi.org/10.1016/B978-0-12-819889-6.00010-1.
Naresh Babu, M., Anandan, V., Muthukrishnan, N., Arivalagar, A. A., & Dinesh Babu, M. (2019). Evaluation of graphene based nano fluids with minimum quantity lubrication in turning of AISI D3 steel. SN Applied Sciences, 1, 1-15. https://doi.org/10.1007/s42452-019-1182-0.
Ning, Y., Rahman, M., & Wong, Y. S. (2001). Investigation of chip formation in high speed end milling. Journal of materials processing technology, 113(1-3), 360-367. https://doi.org/10.1016/S0924-0136(01)00628-8.
Rao, P. N. (2009). Manufacturing Technology Volume 2—Metal cutting and Machine Tools.
Pena, A. E., Anania, F. D., & Mohora, C. (2018, August). Methodology for optimizing cutting parameters on milling process. In IOP Conference Series: Materials Science and Engineering (Vol. 400, No. 2, p. 022044). IOP Publishing. https://doi.org/10.1088/1757-899X/400/2/022044.
Pop, L., Puşcaş, C., Bandur, G., Vlase, G., & Nuţiu, R. (2008). Basestock oils for lubricants from mixtures of corn oil and synthetic diesters. Journal of the American Oil Chemists' Society, 85, 71-76. https://doi.org/10.1007/s11746-007-1156-z.
Raza, S. W., Pervaiz, S., & Deiab, I. (2014). Tool wear patterns when turning of titanium alloy using sustainable lubrication strategies. International journal of precision engineering and manufacturing, 15, 1979-1985. https://doi.org/10.1007/s12541-014-0554-z.
Sarikaya, M., Gupta, M. K., Tomaz, I., Danish, M., Mia, M., Rubaiee, S., ... & Khanna, N. (2021). Cooling techniques to improve the machinability and sustainability of light-weight alloys: A state-of-the-art review. Journal of Manufacturing Processes, 62, 179-201. https://doi.org/10.1016/j.jmapro.2020.12.013.
Ulas, M., Aydur, O., Gurgenc, T., & Ozel, C. (2020). Surface roughness prediction of machined aluminum alloy with wire electrical discharge machining by different machine learning algorithms. Journal of Materials Research and Technology, 9(6), 12512-12524. https://doi.org/10.1016/j.jmrt.2020.08.098.
Wang, B., Yang, Q., Deng, J., Hou, N., Wang, X., & Wang, M. (2022). Effect of graphene nanoparticles and sulfurized additives to MQL for the machining of Ti-6Al-4 V. The International Journal of Advanced Manufacturing Technology, 119(5), 2911-2921. https://doi.org/10.1007/s00170-021-08348-w.
Zailani, Z. A., & Mativenga, P. T. (2022). Boron and graphene nanoparticles as solid lubricant in micro milling of nickel titanium shape memory alloys. International Journal of Machining and Machinability of Materials, 24(3-4), 262-279. https://doi.org/10.1504/IJMMM.2022.125199.
Zailani, Z. A., & Mativenga, P. T. (2023). Machinability of nickel-titanium shape memory alloys under dry and chilled air cutting conditions. The International Journal of Advanced Manufacturing Technology, 126(9), 4675-4684. https://doi.org/10.1007/s00170-023-11373-6.
Zainal Abidin, Z., Tarisai Mativenga, 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 Technology, 7, 283-297. https://doi.org/10.1007/s40684-019-00040-5.

Zainal, Z. A., Rusli, 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. https://doi.org/10.5829/IJE.2021.34.12C.02.