Experimental Evaluation of the Lubrication Performance of Milling Al7075 with Different Nano-fluids MQL

Wei Gao¹,²*, Qiang Qi¹,², Lan Dong¹,², Xiaojie Lv¹,² and Wei Huang¹,²

¹School of Mechanical and Electrical Engineering, Qingdao Binhai University, Qingdao, Shandong, 266555, China
²Engineering and Technology R&D center of Mechanical and Electrical in Colleges of Shandong, Qingdao Binhai University, Qingdao, Shandong, 266555, China

*Corresponding author e-mail: gaowei1923@qdbhu.edu.cn

Abstract. The addition of nano-fluids with different nano-particles into the biodegradable vegetable oil base has an effect on the wetting contact angle of Al7075, the cutting force and the lubrication performance, and the surface morphology of the workpiece and chip. In Milling Al7075, the lubrication performance of six different nano-fluids was evaluated. In this paper, the contact angle, cutting force and SEM morphology of aircraft Al7075 were evaluated under the lubrication conditions of Al₂O₃, MoS₂, SiO₂, CNTs, SiC and Graphite. The experimental results show that the cutting force in x direction of milling under so₂ nano-fluid lubrication is obviously smaller than that under so₂ nano-fluid lubrication. The cutting force in x direction under Al₂O₃ nano-fluid lubrication is 109.6% larger than that under so₂ nano-fluid lubrication, the cutting force of other nano-fluids in x direction is 2%-5% higher than that of Al₂O₃ nano-fluids in x direction. The rolling of SO₂ spherical micro-particles can reduce the wear and the cutting force, improve the surface quality. The results show that the SO₂ nano-fluid has good lubrication and wear-reducing performance.

Keywords: Nano-Fluids, Contact Angle, Cutting Force, Milling, Experimental Evaluation

The tool wear is very fast when milling high strength and high toughness aeronautical aluminum alloy whose tensile strength is over 600MPA, so it is necessary to study the lubrication and wear reduction of milling high strength aluminum alloy. The nano-fluid is sprayed into the cutting zone after atomization to lubricate and reduce friction [1]. Reducing Lubrication deficiency in milling high strength aluminum alloy and Solving the problem of tool failure too fast [2,3].

The results of high speed milling of Al7050 by Aixing et al show that the main effective mechanisms are adhesive wear, diffusion wear and oxidation wear [4]. He Ning, Li Liang, Su Yu [5, 6] et al mainly conducted research on systematic low-temperature MQLM of aviation materials, and concluded that MQL effectively improves the frictional contact state between the tool and the workpiece. Malaysian scholar Sayuti organized [7, 15, 16] to study the performance parameters of SiO₂ NMQLM Al6061-T6, and found that the surface roughness is the smallest when the air pressure...
is 2 bar and the nozzle angle is 30°. The research team of Iranian scholar Rahmati et al. [8, 14] used MoS$_2$ NMQLM aviation Al6061-T6, and the results showed that the surface quality of the workpiece was optimal when the mass fraction of Mo$_2$ nano-particles was 0.5%. Professor Li Changhe et al. [9-13] studied the MQL cutting mechanism, and the results showed that nano-particle MQL improved the heat transfer capacity and the surface quality of the workpiece was significantly improved. In this thesis, the aviation Al7075 material is milled processing using six different nano-particles and cottonseed oil MQL methods, testing different nano-fluid infiltration contact angles, measuring and analyzing the x, y, and z direction forces of the cutting process, scanning the surface of the workpiece and the surface of the chip by electron microscopy to conduct surface analysis, and comparatively discuss and analyze the lubrication performance of Al7075 milling under different NMQL.

1. Experimental Equipment and Plan

1.1 Experimental Equipment
Experimental milling machining center ML1060B, MQL system KS-2106 and experimental measurement equipment (force gauge JR-YDCL-05B, contact angle meter JGW-360A, scanning electron microscope, stylus surface roughness meter) are shown in Figure 1.

![Figure 1. Experimental equipment](image)

1.2 Experimental Materials
The experimental materials include aluminum alloy milling tools (Ø 20 toolholder, APKT1135PDER blade), aluminum alloy test workpieces (Al7075, specifications 40×30×30), experimental nano-fluids, etc., as shown in Table 1.

| No. | Name          | Specification | Quantity | Note          |
|-----|---------------|---------------|----------|---------------|
| 1   | Tool          | Ø 20 toolholder | 1        | Machining Center |
| 2   | blade         | APKT1135PDER  | 4        | MQL Lab       |
| 3   | Aluminum 7075 | 40×30×30      | 1        | MQL Lab       |
| 4   | Cottonseed oil| First level   | 500 ml   | MQL Lab       |
1.3 Experimental Plan
In the experiment, six kinds of nanoparticles and cottonseed oil were used to mill aviation Al7075, with an average particle size of 70 nm, Al₂O₃, MO₂, SiO₂, CNTs, SiC, and Graphite, with a 0.5% mass fraction ratio of cottonseed oil. For nano-fluid, the experimental plan of milling processing is shown in Table 2.

Table 2. Experimental plan

| Milling parameters          | Parameter | Note       |
|----------------------------|-----------|------------|
| Milling method             | Face milling |           |
| Milling speed Ws (r/min)   | 2500      |            |
| Feed speed Vf (mm/min)     | 500       |            |
| back engagement ap (mm)    | 0.45      |            |
| working engagement ae (mm) | 10        |            |
| MQL flow rate (mL/h)       | 50        |            |
| MQL nozzle distance (mm)   | 30        |            |
| Elevation angle of MQL nozzle (°)  | 50      |            |
| Incident angle of MQL nozzle (°) | 35      |            |
| MQL air pressure (MPa)     | 0.4       |            |

To verify the lubrication performance of different NMQL under the same milling parameter mode to process aviation Al7075, the experimental data is analyzed from the surface quality and integrity.

2. Analysis and Discussion of Experimental Results

2.1 Analysis of the Influence of Different Nano-Fluids on the Contact Angle of Al7075
Milling processing lubricating fluid affects the wettability of aviation Al7075 contact angle. Different nano-fluid droplets drop on the surface of aluminum alloy, due to the difference of the surface tension of the droplets, and the wettability characteristics of the solid surface are different, adhere to the solid surface to form different convex lens-like adhesion and wetting. The angle between the solid interface and the liquid interface is the contact angle. As shown in Figure 2, the smaller the contact angle, the liquid is easier to wet the solid, and the surface of the wetted part is easy to form an oil film. The three-phase interfacial tension satisfies the Young equation:

\[ \gamma_{lv} \cos \theta = \gamma_{lv} - \gamma_{sl} \]

\( \gamma \) is the interfacial tension, and \( \theta \) is the contact angle.
The comparison results of multiple sets of measurement of the contact angle of different nano-fluids on the aluminum alloy processing surface show that the addition of SiO$_2$ nano-fluid has the smallest contact angle on the aluminum alloy surface compared with other nano-fluids (Figure 3), which shows that the SiO$_2$ nano-particle lubricant has better wettability, and is conducive to the formation of oil film and improve lubricity.

![Figure 2. Contact angle measurement model](image)

**Figure 2.** Contact angle measurement model

2.2 **Analysis of Milling Force under Different NMQL Milling Al7075**

Under the same processing parameters (as shown in Table 3), the changes in the cutting force of milling aluminum alloys reflect the pros and cons of different nano-fluid lubricants. The effect of lubrication affects the wear of cutting tools and the quality of the processed surface. The milling processing model is established as shown in Figure 4, using the feed along the x-axis direction and the tool on the y-axis direction.

![Figure 3. Wetting contact angles of different nano-fluids to aluminum alloy materials](image)

**Figure 3.** Wetting contact angles of different nano-fluids to aluminum alloy materials

| Nano-fluid   | Contact angle (°) |
|--------------|-------------------|
| SiO$_2$     | 14.27             |
| Al$_2$O$_3$ | 33.22             |
| SiC         | 25.29             |
| Graphite    | 35.16             |
| MoS$_2$     | 34.61             |
| CNT         | 16.43             |

**Table 3.** Processing parameters

| Parameter          | Value |
|--------------------|-------|
| Milling speed Ws (r/min) | 2500  |
| Feed speed Vf (mm/min)    | 500   |
| Back engagement ap (mm)   | 0.45  |
| working engagement ae (mm)| 10    |
In the case of analyzing the performance of six different nano-fluids and aluminum alloys with different infiltration contact angles, the milling aviation aluminum 7075 under different NMQL methods was further tested to test the milling force. Establish the analysis diagram of the momentary milling force of the tool tip, as shown in Figure 5.

The experimental results of milling aluminum 7075 under six different nano-fluid lubrication methods are shown in Figure 6. The force in the x, y, and z directions is compared. The cutting force in the x direction is much greater than the y, z, which has relatively small difference in cutting force under different nano-fluid lubrication. Therefore, we mainly analyze the force in x direction. Milling under SO$_2$ nano-fluid lubrication is significantly smaller in x direction cutting force. The x-direction cutting force under Al$_2$O$_3$ nano-fluid lubrication is increased by 109.6% compared with SO$_2$ nano-fluid lubrication, and the x-direction cutting force of other nano-fluids was increased by 2%-5% compared with that of Al$_2$O$_3$ nano-fluid. The reason is analyzed. The nano-fluid lubricating fluid is added with SO$_2$ nano-particles, and its microscopic shape is spherical, which makes it transform the chip removal from sliding mode to rolling mode during cutting, further increasing lubricity and reducing friction. The Al element in Al$_2$O$_3$ nano-fluid has a certain affinity with aluminum alloy, and the rolling effect is not obvious.
2.3 Analysis of Milling Surface and Chip Surface Morphology of Milling Al7075 under Different Nano-Fluid Lubrication Methods

The milling surface of Al7075 is milled under different nano-fluid lubrication methods. The different lubrication methods have different effects on the surface quality of the workpiece. The surface quality of the workpiece is analyzed by scanning the electron microscope to observe the workpiece surface. The morphology of Al7075 was observed by scanning electron microscopy to analyze the influence of cutting force by milling Al7075 under different lubrication methods. As shown in Figure 7, the cutting surface of Al7075 was milled under different nano-fluid lubrication methods. SEM (×500), Graphite NMQL milling can form larger tool marks. SiC, MOS₂, CNTs (carbon nano-tubes) NMQL milling aluminum alloys are prone to form harder built-up tumors, which have large scratches on the surface of the workpiece, but the SiO₂, Al₂O₃ nano-fluid lubrication has rather small tool mark, which also shows that the nano-fluid has better lubricity with small cutting force.
Figure 7. SEM of cutting surface of milling Al7075 under different NMQL methods (×500)

When the cutting force is large, the milling chips will change sharply or tear. As shown in Figure 8, milling Al7075 chips under different nano-particle lubrication methods SEM (×100), Graphite, MOS$_2$, CNTs, NMQL milling Al7075, the cutting force is relatively large, the two sides of the generated chips are not uniformly torn, and one side is severely torn. SiO$_2$, Al$_2$O$_3$, SiC NMQL milling Al7075 produces symmetrical tears on both sides of the chip, and the surface of the aluminum alloy chip with Al$_2$O$_3$ NMQL milling has ripple changes.
3. Conclusion

Through six different NMQL methods, milling, analysis and comparison, and experimental research on Al7075 specimens have concluded as follows:

(1) The order of the contact angle: Graphite > MOS₂ > Al₂O₃ > SiC > CNTs > SiO₂, the size of the infiltration contact angle affects the affinity of aluminum alloy, the area of lubricating workpiece, and the effect of lubricating speed.

(2) The order of the main milling force F(x): MOS₂ > CNTs > SiC > Graphite > Al₂O₃ > SiO₂, NMQL milling Al7075, the x-direction cutting force under SO₂ nano-fluid lubrication is significantly smaller. The x-direction cutting force under Al₂O₃ nano-fluid lubrication is increased by 109.6% compared with SO₂ nano-fluid lubrication. The x-direction cutting force of other nano-fluids is increased by 2%-5% compared with the Al₂O₃ nano-fluid. The smaller the cutting force of SO₂ nano-fluid lubrication, the better the lubrication effect. The small cutting force will affect the wear of the tool and the machine tool, which can appropriately improve the cutting processing parameters, thereby improving the production efficiency.

(3) Through the analysis of the milling surface and chip surface morphology of milling aluminum 7075 under different nano-fluid lubrication methods, the surface quality of SiO₂, Al₂O₃, SiC nano-fluid milling aluminum 7075 with MQL is better, so the machining accuracy is improved, so as the production efficiency.

Through the analysis and summary of the above experimental conclusions, the lubricating fluid on the macroscopically affects the cutting force of the aluminum alloy clear and moisturizing contact angle, thereby affecting the apparent morphology. On the microscopically, the addition of nano-particles and the rolling of SO₂ spherical micro-particles have the effect of reducing wear and rolling, reduce cutting force and improve surface quality. It shows that SO₂ NMQL has good lubrication and anti-wear performance in cutting Al7075.
Acknowledgments
National Natural Science Foundation of China Project Youth Fund (51806112); Shandong Province Higher Education Research and Development Plan Project (J17KB016); Qingdao Binhai College Science and Technology Plan Research Project (2019KY02)

References
[1] Mao, C., Zou, H., Huang, Y., Li, Y., & Zhou, Z. Analysis of heat transfer coefficient on workpiece surface during minimum quantity grinding lubricant [J]. The International Journal of Advanced Manufacturing Technology, 2013, 66(1-4): 363-370.
[2] Wan Yi, Ai Xing, Liu Zhanqiang, Song Liangyu. Tool wear and damage during high-speed milling of aviation aluminum alloy 7050-T7451 [J]. Chinese Journal of Mechanical Engineering, 2007, 43(4): 103-108.
[3] Wang, T., Xie, L., Wang, XB, Jiao, L., Shen, JW, & Xu, H. Surface integrity of high-speed milling of Al/SiC/65p aluminum matrix composites[J]. Procedia CIRP, 2013, 8: 475-480.
[4] Liu Zhanqiang, Wan Yi, Ai Xing. Research on cutting force in high-speed milling [J]. China Mechanical Engineering, 2003, 14(9):734-737.
[5] Su Yu, He Ning, Li Liang, Li Xiong, Zhao Wei. The effect of low temperature nitrogen jet on high-speed milling performance of titanium alloy [J]. China Mechanical Engineering, 2006, 17(11): 1183-1187.
[6] Su Yu, He Ning, Li Liang. Experimental study on low-temperature minimum lubrication and high-speed milling of titanium alloys [J]. China Mechanical Engineering, 2010(22): 2665-2670.
[7] Sarhan AAD, Sayuti M, Hamdi M. Reduction of power and lubricant oil consumption in milling process using a new SiO2 nanolubrication system[J]. The International Journal of Advanced Manufacturing Technology, 2012, 63(5-8): 505 -512.
[8] Rahmati B, Sarhan A A D, Sayuti M. Morphology of surface generated by end milling AL6061-T6 using molybdenum disulfide (MoS2) nano-lubrication in end milling machining[J]. Journal of Cleaner Production, 2014, 66: 685-691.
[9] Jiang Zenghui, Lu Kangping, Sun Jinliang, Gao Pengcheng, Wu Zhenji. Research on the effect of tool wear on surface roughness in high-speed milling of titanium alloy [J]. Manufacturing Technology and Machine Tool, 2016(10): 126-128.
[10] Liu Zhanrui, Du Chao, Li Changhe. Overview of dry cutting and trace lubrication (to be continued) [J]. Precision Manufacturing and Automation, 2009(3): 13-17.
[11] Yang Lei. Basic research on the lubrication mechanism and application of vegetable oil-based MQL cutting fluid [D]. Jiangsu University, 2013.
[12] Zhang Yanbin, Li Changhe, Jia Dongzhou, et al. Experimental evaluation on the lubrication performance of nanoparticle jet MQL grinding of nickel-based alloys[J]. Modular Machine Tool and Automatic Processing Technology, 2015(6): 113-117.
[13] Yan Lutao, Yuan Songmei, Liu Qiang. Tool wear and chip morphology in green cutting of high-strength steel [J]. Chinese Journal of Mechanical Engineering, 2010, 46(9):187-192.
[14] Rahmati B, Sarhan AAD, Sayuti M. Investigating the optimum molybdenum disulfide (MoS2) nano-lubrication parameters in CNC milling of AL6061-T6 alloy [J]. The International Journal of Advanced Manufacturing Technology, 2014, 70(5-8): 1143-1155.
[15] Sayuti M, Sarhan AAD, Hamdi M. An investigation of optimum SiO2 nanolubrication parameters in end milling of aerospace Al6061-T6 alloy [J]. The International Journal of Advanced Manufacturing Technology, 2013, 67(1-4): 833 -849.
[16] Sayuti M, Erh OM, Sarhan AAD, et al. Investigation on the morphology of the machined surface in end milling of aerospace AL6061-T6 for novel uses of SiO2 nanolubrication system[J]. Journal of Cleaner Production, 2014, 66: 655-663.