Contents lists available at ScienceDirect





CIRP Annals - Manufacturing Technology

journal homepage: https://www.editorialmanager.com/CIRP/default.aspx

# A low temperature nano-lubrication method for enhancing machinability in ultra-precision grinding of binderless tungsten carbide (WC)



Fan Zhang<sup>a</sup>, Yanbin Zhang<sup>a,c</sup>, Chi Fai Cheung (2)<sup>a,\*</sup>, Alborz Shokrani (2)<sup>b</sup>, Stephen T. Newman (1)<sup>b</sup>

<sup>a</sup> State Key Laboratory of Ultra-precision Machining Technology, Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hong Kong, China

<sup>b</sup> Department of Mechanical Engineering, University of Bath, UK

<sup>c</sup> School of Mechanical and Automotive Engineering, Qingdao University of Technology, China

#### ARTICLE INFO

Article history: Available online 18 April 2023

Keywords: Grinding Lubrication Low temperature

### ABSTRACT

This paper presents a low temperature nano-lubrication method, using a vortex tube to generate a low temperature grinding environment for increasing heat transfer with a mixture of nanoparticles as a nano-lubricant for reducing friction in ultra-precision grinding of tungsten carbide. The results show the method significantly reduces wheel deterioration and improves workpiece surface integrity. The arithmetical mean height (*Sa*) and maximum height (*Sz*) were reduced by 50.8% and 65.3% respectively, with wheel deterioration 57.8% lower than traditional minimum quantity lubrication. These results were obtained by optimized low temperature gas at -20 °C and MoS<sub>2</sub>/Fe<sub>3</sub>O<sub>4</sub> nano-lubricant with mix-ratio 1:2.

© 2023 The Author(s). Published by Elsevier Ltd on behalf of CIRP. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)

#### 1. Introduction

Binderless Tungsten carbide (WC) is a key material of a mould and tool, and is close to diamond in hardness and expansion coefficient. It's excellent properties also bring challenges in manufacturing and especially in ultra-precision machining technology for WC mould manufacturing. You [1] reported that WC surfaces produced through diamond turning are covered in craters and pits due to brittle chip formation. They suggested using laser-assisted diamond turning to reduce surface damage. Nevertheless, feed marks and additional waveforms due to sintering of chips to the cutting edge diminished shape accuracy. Ultra-precision grinding (UPG) is a promising process that can take into account machining accuracy, surface quality and machining efficiency. However, Guo et al. [2] noted that the high friction at the grinding zone cause increased grinding wheel wear and a brittle material removal mode rather than a ductile grinding regime. In conventional grinding, Hosseini et al. [3] investigated the effects of nano-lubricant in the grinding process of tungsten carbide and found that it was an effective method to improve the machining efficiency. Brinksmeier et al. [4] revealed fundamentals of metalworking fluidchemistry for improvement of energy and resource efficiency in the manufacturing process. Hence, reducing friction and enhanced heat transfer are crucial in realising damage free UPG of WC.

Using cooling and lubrication is an effective way of improving the grindability of WC. Many lubrication methods such as minimum quantity lubrication (MQL) [5], nano-lubricant minimum quantity

\* Corresponding author.

E-mail address: benny.cheung@polyu.edu.hk (C.F. Cheung (2)).

lubrication (NMQL) [3], cryogenic cooling [6], dry grinding, etc. have been investigated in recent years. As ultra-precision machine tools are strictly required to operate within a constant temperature and humidity environment, MQL is the prevailing method in UPG. Though, the insufficient anti-friction, anti-wear and heat transfer capabilities of MQL cannot solely solve the grinding problem of WC. A lubrication method is urgently needed.

Pušavec et al. [7] determined the cooling performance during cryogenic milling of titanium alloy, indicating that the cooling capability of liquid carbon dioxide was better than that of liquid nitrogen. Therefore, both lubrications and cryogenic gas can increase the heattransfer rate and reduce friction behaviour during machining of high hardness materials. Currently, there are no studies on the effects of low temperature nano-lubrication in UPG of WC and the Al<sub>2</sub>O<sub>3</sub> and CNT nanoparticles used in the aforementioned studies are potentially carcinogenic. This paper reports on UPG grindability of WC with a low temperature nano-lubrication method in terms of grinding wheel deterioration and workpiece surface integrity. Spiral grooves grinding experiments with linearly increased grinding depth, from 0  $\mu$ m to 10  $\mu$ m, were conducted to investigate the material removal behaviour and optimize the grinding parameters for ductile material removal. Surface grinding experiments were also conducted with constant parameters obtained from the above experiment. The cooling methods were varied in the experiment including dry grinding, MQL with pure oil, NMQL with MoS<sub>2</sub>/Fe<sub>3</sub>O<sub>4</sub> nano-lubricant, LTG coupled with MQL and LTG coupled with NMQL. To optimize the lubricant, the temperature value of LTG (0 °C, -10 °C, -20 °C) and mix ratio of MoS<sub>2</sub>/Fe<sub>3</sub>O<sub>4</sub> (1:1, 2:1, 1:2) were also set as variables.

https://doi.org/10.1016/j.cirp.2023.04.075

0007-8506/© 2023 The Author(s). Published by Elsevier Ltd on behalf of CIRP. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)

# 2. A low temperature nano-lubrication method

The low temperature nano-lubrication method makes use of a mixture of nanoparticles as additives to produce nano-lubricant for reducing friction and grinding wheel deterioration. In turn, the friction angle and material removal direction can be reduced, further minimising the critical cutting depth, brittle fracture cracks on the workpiece surface and brittle chip formation. It also makes use of a vortex tube to generate a low temperature grinding environment down to -20 °C. This increases heat transfer to minimize surface defects due to brittle chip adhesion further improving the grindability in UPG of WC.

#### 2.1. Experimental setup and cooling/lubrication systems

This research was undertaken on a Moore Nanotech 450 UPL ultra-precision grinding machine. As shown in Fig. 1, a resin-bonded diamond wheel with diameter of 20 mm, V tip angle of 120° and grain size of 1500# was used. Before each experiment, the grinding wheel was dressed by diamond pen to ensure consistency. The bind-erless WC workpiece from FUJI Die, Japan, with a dimension of  $\phi$ 15 × 3 mm and grain size of 0.58  $\mu$ m, was fixed on the spindle of the machine by a cylindrical fixture. A purposely designed disc fixture was used to prevent nano-lubricant from entering the air bearing spindle. The WC workpieces were pre-ground to ensure consistency and obtain flat and crack-free surfaces. The pre-grinding parameters include rotation speed of the grinding wheel = 20,000 rpm, rotation speed of workpiece = 500 rpm, feed rate = 0.5 mm/min, cutting depth = 1  $\mu$ m. The nano-lubricant was supplied by an MQL device and LTG was generated using a Meech experimental vortex tube kit.



Fig. 1. Experimental setup for grinding experiments.

#### 2.2. Formulation of the mixture of $MoS_2/Fe_3O_4$ nano-lubricant

By using a mixture of nanoparticles as additives in lubricants, it can improve the lubrication and cooling performance of MQL. According to the results of preliminary tests, it was found that  $MoS_2$  can reduce surface roughness while  $Fe_3O_4$  can reduce the wheel deterioration. In this study, a mixture of nanoparticles 200 nm  $MoS_2$  and 20 nm  $Fe_3O_4$  was added in lubricant (Commercial oil) to formulate the nano-lubricant. Mechanical stirring and ultrasonic vibration dispersion methods were used to improve dispersion and stability. The mix ratio of  $MoS_2/Fe_3O_4$  were set as discussed in Section 3. The mass fraction of nano-lubricant is 6%.

#### 2.3. Generation of low temperature gas (LTG)

The low temperature gas ranges from -20 °C to 0 °C were generated using a vortex tube. Unlike cryogenic temperatures generated by liquid nitrogen or liquid carbon dioxide, LTG is harmless to an ultra-precision machine tool and beneficial to improve heat transfer performance of the nano-lubricant. It is noted that the temperature value is positively correlated with input pressure of high pressure gas as shown in Fig. 2. Due to the rapid heat absorption from the environment, the temperature value is negatively correlated with the distance between the measurement point and nozzle exit. At normal working conditions, the grinding zone is 5 mm away from the nozzle exit. The temperatures reached at -20 °C and 0 °C when input pressure are 9.5 bar and 3 bar, respectively.



Fig. 2. The temperature control and adjustment methods of the LTG.

# 3. Experimental evaluation

In order to evaluate the performance of the low temperature nanolubrication method, two groups of experiments were designed: Group A (Setup 1) and Group B (Setup 2). As shown in Fig. 3, Group A experiments using Setup 1 are related to the spiral grooves grinding experiments which have been designed and undertaken to obtain confirmatory results of lubrication conditions and optimize grinding parameters for ductile material removal in UPG. From the start point to end point, the grinding depth was increased linearly from 0  $\mu$ m to 10  $\mu$ m. The other parameters were kept constant, i.e. grinding wheel speed  $n_1 = 20,000$  rpm, workpiece speed  $n_2 = 500$  rpm, feed rate f = 100 mm/min. Different lubrication conditions (i-1 to i-4) were used. For Group B using Setup 2, surface grinding experiments were carried out to obtain optimized lubrication/cooling parameters which include different cooling temperatures and different mix ratio of MoS<sub>2</sub>/Fe<sub>3</sub>O<sub>4</sub> nano-lubricant. Similar grinding parameters were used under constant surface speed (CSS) mode: grinding wheel speed  $n_1 = 20,000$  rpm, cutting speed v = 10 m/min, feed rate f = 0.5 mm/min. Eight groups of experiments were conducted with lubrication/ cooling by ii-1 to ii-8.



Fig. 3. Schematic view of experimental scheme and grinding parameters.

# 4. Results of spiral grooves grinding experiments in Group A

### 4.1. Material removal rate

As shown in Fig. 4, the groove depth is built up from outside towards the centre of the workpiece. On one side of the cross-section of the workpiece, there are 20 furrows. During grinding of WC with high hardness, there is elastic deformation of the resin bond grinding wheel which reduces the depth of material removal. The material removal area was determined by integrating the sectional profile of the grooves, which was measured by Zygo NexView white light optical profiler. The removal area was found to be 59.81  $\mu$ m<sup>2</sup> under dry grinding. With the use of lubricant, the removal area was increased by 41.5% and 120.1%



Fig. 4. Surface profile of spiral grooves and material removal of the last groove.

under MQL and NMQL conditions, respectively. The addition of lubricant reduces the friction and hence the grinding wheel deterioration. A decrease of friction coefficient reduces the friction angle of the abrasive/ workpiece interface, then increases the critical removal depth of material. This facilitates ultra-precision grinding of WC. While the material removal area was decreased by 42.9% under low temperatures as the material became harder and more difficult to be removed.

#### 4.2. Surface integrity analysis

The surface defects have always been challenging for UPG of WC. As shown in Fig. 5, there are serious brittle cracks, pull outs and micro burrs on the workpiece under dry grinding condition. It is the inevitable result of poor tribological properties and high thermal and mechanical loads at the wheel/workpiece interfaces. With the use of lubricant, defects were significantly reduced. Each lubrication condition shows a varied impact on minimizing different defects. Whilst anti-friction and anti-wear properties of nanoparticles were effective in reducing brittle cracks in NMQL, the improved heat transfer resulted in reduced adhesion and plastic flow under low temperature grinding conditions.



Fig. 5. SEM images of the last groove under different lubrication conditions.

#### 4.3. The size of brittle cracks

Within the defects presented, brittle cracks were the most important defect which adversely affected the surface integrity in UPG of WC. The size of brittle cracks was found to relate to cutting depth and lubrication conditions. To quantitatively characterize the effect of the new method, the length of brittle cracks (regular shape) was measured on an SEM as shown in Fig. 6.



Fig. 6. Crack length tendency under different lubrication conditions.

Although four conditions nearly show the similar trend, there appears two stages (Stage lwith steady increase and Stage II with rapid increase) as shown in Fig. 6 during grinding of WC after comparing the crack size of ground surface. Firstly, the crack length increases as the depth of cut increases. After the 13th groove, the crack size presents a rapid upward trend, which indicates the precipitous deterioration. As a result, the parameters of surface grinding experiments could be chosen before this point. Furthermore, the largest value and standard deviation were obtained with a dry condition, compared with other conditions. Although the crack value decreased in MQL grinding, the standard deviation shows the instability of dry condition. Both crack height and its standard deviation are reduced significantly by NMQL and LTG conditions. For example, the crack size of the two conditions obtained the same value 0.6  $\mu$ m on the 13th groove, which is a 31% decrease from the dry condition (0.87  $\mu$ m). The results from spiral groove grinding tests clearly indicate that the lubrication methods NMQL and LTG are effective in suppressing surface defects. However, the parameters of nano-lubricant and temperature value of LTG can be further optimized. The combination of low temperature and nano-lubrication may have a complementary synergic effect for improving the machinability in UPG of WC. The grinding depth was increased to 6.5  $\mu$ m at the 13th groove and so 6.5  $\mu$ m was chosen as the grinding depth in surface grinding experiment by comprehensive consideration to improve efficiency and reduce grinding wheel deterioration.

#### 5. Results of surface grinding optimization in Group B

#### 5.1. Wheel deterioration

The grinding wheel deterioration was determined by comparing the 3D profile between the dressed wheel and the worn wheel, using the iterative closest point (ICP) method [8]. The maximum wheel deterioration value is shown in Fig. 7. Compared with MQL grinding, applying both nano-lubricant and coolant air can significantly reduce wheel deterioration. The wheel deterioration was reduced with the decrease in temperature of the LTG and reached the lowest value at -20 °C (4.71  $\mu$ m). At low temperature, the chips are more likely to be carried out at the grinding zone rather than adhere to the wheel porosity. The mix ratio of MoS<sub>2</sub>/Fe<sub>3</sub>O<sub>4</sub> nano-lubricant also plays an important role in reducing the wheel deterioration and achieved the lowest wheel deterioration at the mix ratio of 1:2. The presence of MoS<sub>2</sub>/Fe<sub>3</sub>O<sub>4</sub> nanolubricant between the abrasive and the workpiece reduces contact and wear time of the wheel. When it comes to LTG+MoS<sub>2</sub>/Fe<sub>3</sub>O<sub>4</sub>, the wheel deterioration attained the lowest value 2.71  $\mu$ m, which is 57.8% lower than MQL grinding. This inferred that LTG and NMQL perform complementary roles in reducing grinding wheel deterioration.



**Fig. 7.** Wheel deterioration under different lubrication conditions (a) Wheel surface matching by ICP, (b) Wheel deterioration under different temperatures, (c) Wheel deterioration under varied mixed ratios of nano-lubricants.

#### 5.2. Surface roughness

As shown in Fig. 8, the surface roughness was found to reduce with decreasing grinding temperature. At -20 °C, surface roughness reached the lowest values of Sa = 14 nm and Sz = 130 nm, which are 42.6% and 46.9% lower than that for grinding with MQL at 20 °C. This shows that temperature contributes significantly to the surface quality in UPG of WC. Combined with the results in Fig. 5, it is possible that the reduction of surface roughness is due to the reduction of material removal rate which infers a reduction in processing efficiency. Fig. 9 shows that the mix ratio of MoS<sub>2</sub>/Fe<sub>3</sub>O<sub>4</sub> is a significant factor affecting surface roughness. The lowest Sa (17 nm) and Sz (151 nm) were obtained with a mix ratio of 1:2. In fact, the lubrication effect of laminated MoS<sub>2</sub> in grinding is stronger than that of other shapes of nanomaterials. There exists a typical laminated structure of MoS<sub>2</sub> particles (see Fig. 1) working as the slippery role to reduce the friction behaviour between the wheel and the workpiece [9]. However, the speed of film extension of laminated nanoparticles is not advantageous, which limits its lubrication performance [10]. Spherical Fe<sub>3</sub>O<sub>4</sub> nanoparticles provide a rolling effect at the cutting zone further intensifying the lubrication between the surface and the grinding wheel. This advantage is apparent when the number of spherical Fe<sub>3</sub>O<sub>4</sub> is more than that



Fig. 8. Surface roughness under different temperature of LTG.



Fig. 9. Surface roughness under different mix ratios of MoS<sub>2</sub>/Fe<sub>3</sub>O<sub>4</sub>.

of layered MoS<sub>2</sub>. The coupling effect with the use of LTG (-20 °C) and MoS<sub>2</sub>/Fe<sub>3</sub>O<sub>4</sub>(1:2) obtained the lowest surface roughness of *Sa* (12 nm) and *Sz* (85 nm). At low temperatures, the 'plate-rolling' structure is well maintained because the movement of nanoparticles is weakened with high viscosity oil.

# 5.3. Surface integrity

As shown in Fig. 10(a)-(d), it was found that the chips adhesion points on the workpiece surface are reduced which is attributed to better heat transfer performance of LTG. From Fig. 10(e) to (g), the plastic flow phenomenon was alleviated. As analysed above, the decrease of friction coefficient reduces the friction angle of the abrasive/workpiece interface. Thus, the ploughing phenomenon was alleviated and the thickness of undeformed chips was also reduced. The "polishing effect" of nanomaterials occurs under high-speed air flow, and micro burrs were removed. This was confirmed by the reduction of the variation of the surface topographies in Fig. 11. Furthermore, the fracture cracks were avoided due to lower friction.



Fig. 10. SEM images under different lubrication conditions.

However, the chip adhesion still exists by using MoS<sub>2</sub>/Fe<sub>3</sub>O<sub>4</sub>(1:2) alone, due to its poor heat transfer performance. Therefore, the LTG was coupled to use with MoS<sub>2</sub>/Fe<sub>3</sub>O<sub>4</sub>(1:2) to address this problem. It is evident from Fig. 10(h) that, the smoothest surface, with the fewest surface defects, was obtained through coupled use of LTG(-20 °C) and MoS<sub>2</sub>/Fe<sub>3</sub>O<sub>4</sub>(1:2). On the one hand, the better heat transfer performance of LTG and better anti-friction performance of NMQL work were obtained simultaneously. On the other hand, the viscosity of MoS<sub>2</sub>/Fe<sub>3</sub>O<sub>4</sub> lubricant became larger at low temperatures, which resulted in the adsorbed oil layer or tribo layer possessing higher strength and better lubrication properties [9]. This advantage is substantiated by the smallest variation of surface topography obtained in Fig. 11(h).



Fig. 11. Surface topographies under different lubrication conditions.

# 6. Conclusion

In this paper, a low temperature nano-lubrication method is proposed to enhance the machinability in ultra-precision grinding (UPG) of binderless tungsten carbide (WC). Experiments were undertaken in UPG of WC under different cooling and lubrication conditions. The LTG, NMQL and LTG+NMQL were tested by considering material removal rate, wheel deterioration, brittle cracks, chips adhesion, plastic flow, and surface roughness and SEM. It is concluded that LTG and NMQL lubrication methods work well on improving machinability in UPG of WC. Using LTG+MQL is helpful for increasing heat transfer, which results in reducing chips adhesion. NMQL is effective in reducing friction, which results in reduced fracture cracks and plastic flow. The processing efficiency is significantly improved compared to LTG +MQL. The surface quality of the ground surfaces (Sa and Sz were reduced by 50.8% and 65.3%, respectively), wheel deterioration (reduced by 57.8%) and grinding efficiency in UPG of WC are significantly optimized by a combination mixture of MoS<sub>2</sub>/Fe<sub>3</sub>O<sub>4</sub>(1:2) and lower grinding temperature as compared to traditional MQL.

#### **Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Acknowledgement

The work described in this paper was mainly supported by a grant from the Hong Kong Scholars (project codes: XJ2021022).

#### References

- You KY, Fang FZ, Yan GP (2021) Surface Generation of Tungsten Carbide in Laser-Assisted Diamond Turning. International Journal of Machine Tools and Manufacture 168:103770.
- [2] Guo B, Zhao QL, Jackson MJ (2013) Precision Grinding of Binderless Ultrafine Tungsten Carbide (WC) Microstructured Surfaces. The International Journal of Advanced Manufacturing Technology 64(5):727–735. J.
- [3] Hosseini SF, Emami M, Sadeghi MH (2018) An Experimental Investigation on the Effects of Minimum Quantity Nano Lubricant Application in Grinding Process of Tungsten Carbide. Journal of Manufacturing Processes 35:244–253.
- [4] Brinksmeier E, Meyer D, Huesmann-Cordes AG, Herrmann C (2015) Metalworking Fluids-Mechanisms and Performance. Annals of the CIRP–Manufacturing Technology 64:605–628.
- [5] Yang G, Fang F (2019) Fabrication of Optical Freeform Molds Using Slow Tool Servo with Wheel Normal Grinding. Annals of the CIRP–Manufacturing Technology 68:341–344.
- [6] Olsson M, Akujärvi V, Ståhl JE, Bushlya V (2021) Cryogenic and Hybrid Induction-Assisted Machining Strategies as Alternatives for Conventional Machining of Refractory Tungsten and Niobium. *International Journal of Refractory Metals and* Hard Materials 97:105520.
- [7] Pušavec F, Grguraš D, Koch M, Krajnik P (2019) Cooling Capability of Liquid Nitrogen and Carbon Dioxide in Cryogenic Milling. Annals of the CIRP–Manufacturing Technology 68:73–76.
- [8] Besl P, McKay N (1992) A Method for Registration of 3-D Shapes. IEEE Transactions on Pattern Analysis and Machine Intelligence 14(2):239–256.
- [9] Zheng X, Xu Y, Geng J, Peng Y, Olson D, Hu X (2016) Tribological Behavior of Fe<sub>3</sub>O<sub>4</sub>/MoS<sub>2</sub> Nanocomposites Additives in Aqueous and Oil Phase Media. *Tribology International* 102:79–87.
- [10] Cui X, Li CH, Ding WF, et al. (2022) Minimum Quantity Lubrication Machining of Aeronautical Materials Using Carbon Group Nanolubricant: From Mechanisms to Application. Chinese Journal of Aeronautics 35/11:85–112.