



Article

# An Experimental Study on SiC Nanofluid-Assisted MQL in Hard Milling of AISI D2 Tool Steel

Ngo Minh Tuan <sup>1</sup>, Tran Minh Duc <sup>2</sup>, Nguyen The Doan <sup>1</sup>, Tran Ngoc Diep <sup>3</sup>, Vu Nhu Nguyet <sup>1</sup>  
and Tran The Long <sup>1,\*</sup>

<sup>1</sup> Department of Manufacturing Engineering, Faculty of Mechanical Engineering, Thai Nguyen University of Technology, Thai Nguyen 250000, Vietnam; minhantuan@tnut.edu.vn (N.M.T.); ntdoan@tnut.edu.vn (N.T.D.); vuhunguyet@tnut.edu.vn (V.N.N.)

<sup>2</sup> Academic Affairs Department, Thai Nguyen University of Economics and Technology, Thai Nguyen 250000, Vietnam; minhduc@tnut.edu.vn

<sup>3</sup> Faculty of Mechanical Engineering, Hanoi Vocational College of High Technology, Tay Mo Ward, Nam Tu Liem District, Hanoi 10000, Vietnam; dieptn@hht.edu.vn

\* Correspondence: tranthelong@tnut.edu.vn; Tel.: +84-985-288-777

## Abstract

The new technological solutions supporting hard machining processes are becoming an up-to-date research area. The enhancement of cooling lubrication efficiency in the cutting zone plays a crucial role in improving cutting performance. This paper investigates the effectiveness of Minimum Quantity Lubrication (MQL) using SiC nanoparticle-enhanced oil in the hard milling process of AISI D2 tool steel. The results are compared with dry and pure MQL modes based on criteria including cutting force components, surface roughness, tool wear, and tool life. The research results show that compared to dry and pure MQL, the SiC nanofluid MQL environment provides the best performance with reductions in feed force  $F_x$  (22.3–23.8%), thrust force  $F_y$  (20.5–55.3%), tangential force  $F_z$  (26.5–34%), surface roughness (37–62.3%), tool wear (46.1–73.3%), and increased tool life (80–200%). These findings demonstrate that the lubrication and cooling efficiency of the base oil is improved with the addition of SiC nanoparticles. The deep penetration of oil droplets into the cutting zone and the formation of the oil film significantly contributed to reducing friction and cutting heat. SiC nanoparticles not only improved the lubricating and cooling capabilities of the base cutting oil but also created secondary mechanisms within the cutting zone. Furthermore, monitoring cutting forces and surface roughness can be suggested as supplementary criteria for evaluating tool wear and tool life. This research will provide important technological guidance and a theoretical basis for the improvement of hard milling and application of the SiC nanofluid MQL technique.

**Keywords:** hard machining; hard milling; Minimum Quantity Lubrication; SiC nanofluid; AISI D2 tool steel; surface roughness; cutting force; tool wear; tool life

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## 1. Introduction

In industrial production, molds are essential tools for mass-producing products necessary for daily life with consistent specifications. In fact, there are many types of molds, such as stamping molds, plastic injection molds, pressure die casting molds, forging molds, powder metallurgy molds, ceramic molds, etc., made from various materials [1]. Cold stamping molds in sheet metal processing are a system of many closely coordinated

parts that perform operations such as cutting, punching, bending, or drawing [2]. Molds are usually divided into two main parts: the upper and lower parts. The upper part includes the punch—the part that directly impacts the material, the punch holder plate to secure the punch, and the top plate used to connect to the sliding head of the press. The lower part includes the die—which has a shape corresponding to the punch to shape or cut the material, along with the base plate to support and attach to the machine table [3]. In addition, the die also has other parts such as guide bushings, guide bearings, pressing plates, springs, locating pins, stoppers, ejector pins or ejector plates, etc. In cold stamping dies, the die block is the hollow part with the shape used to shape or cut the material, and the corresponding part. This is a part which is located at the bottom of the mold and machined with a profile suitable for the product to be created. It is a very important part of the mold, shaping the shape, size and surface of the final product, determining product quality and mold life [4]. The material used to manufacture cold stamping molds must meet many stringent requirements due to working under high pressure, high friction and continuous repeated impact. First of all, the material needs to have high hardness, good wear resistance, good strength and impact toughness. In addition, the material needs to have good hardenability to achieve uniform hardness from surface to core, as well as high dimensional stability after heat treatment to ensure the accuracy of the mold.

Non-stick and plastic deformation resistance are also crucial, preventing the mold surface from sticking or deforming during prolonged use. Simultaneously, the material should have good machinability (cutting, grinding, polishing) for ease of mold manufacturing and repair. Therefore, some commonly used materials for cold stamping molds are tool steels and alloy steels such as AISI H13, AISI D2, AISI O1, etc.

The typical mold cavity machining process has several main stages. Rough machining is the first step of removing most of the material to create the basic shape on CNC machines. Cutting tools such as flat milling cutters, end milling cutters, and ball end milling cutters are commonly used. After that, the steel is hardened to increase strength and load capacity. Stress relief annealing is a heat treatment designed to remove internal residual stresses and helps stabilize the steel structure, preventing cracking or deformation during the injection molding of plastic products. Commonly, finish machining is the hard milling on CNC machines using coated carbide cutters to machine the complex curved surfaces of the mold cavity.

During the finishing stage of mold cavities by hard milling, the cost of cutting tools is high because in machining heat-treated steel, the milling inserts wear out quickly, caused by crater wear and chipping, which negatively affects the machined surface quality [5,6]. In addition, surface thermal stress is caused by large friction between the cutting edge and hardened steel, which generates very high local heat [7]. If the cooling condition is not done well, the mold cavity surface may be burned or its structure may change, easily causing surface cracking after product pressing. Therefore, selecting the appropriate cutting mode and using the appropriate lubrication and cooling conditions are urgent requirements.

During the dry hard milling process, high cutting forces and enormous cutting temperatures are often generated, accelerating tool wear, reducing tool life, and declining surface quality [8]. The implementation of hard milling under flood coolant faces difficulty due to the discontinuous cutting process, easily causing thermal shock, chipping or tool failure [9]. To overcome these problems, some advanced cooling lubrication technologies have been researched and developed. Among them, Minimum Quantity Lubrication (MQL) is a method using a small amount of cutting oil mixed with high-pressure compressed air to create oil mist particles, which is then directly introduced into the cutting zone. Thanks to the deep penetration of oil droplets into the cutting zone, the lubrication efficiency of MQL is higher than that of dry cutting (Wang et al. [10]) and flood coolant

(Mohandas et al. [11]). López de Lacalle et al. [12] concluded that the MQL technique, that reaches the inner zones of the tool teeth, causes the formation of the micro-drop spray coolant. Du et al. [13] found that MQL helps improve the efficiency of the milling process of 316 L stainless steel by reducing cutting forces (10–25%), cutting temperature (9%), and the friction coefficient (16%) in comparison with the dry mode. Cönger et al. [14] investigated singular and dual MQL nozzles in the milling process of Al6061-T651 alloy. The surface roughness values, cutting forces, flank wear, total consumed energy, and machining cost were significantly lower than those in dry condition. However, when applying MQL mode to machining difficult-to-cut materials like hardened steels and superalloy, the results are not really different due to limited cooling capacity [15,16]. Pereira et al. [17] suggested that cooling alone or lubrication alone is insufficient when machining these materials.

To overcome the limited cooling capacity, the two main research directions being pursued and developed include cryogenic cooling-assisted MQL and MQL using nano-cutting oils. Pereira et al. [17] indicate the positive machining outputs of the turning process of AISI 304 under a cryogenic cooling-assisted MQL environment. The CryoMQL condition achieved tool life improvement (over 50%) and the increase in cutting speed (over 30%) compared to dry cutting. Pereira et al. [18] used cryogenic cooling with MQL (CryoMQL) with CO<sub>2</sub> as an internal coolant for milling Inconel 718. The obtained results indicate the improvement of cutting length and reduction in cutting forces under internal CryoMQL when compared to MQL and external CryoMQL conditions. González et al. [19] found the outstanding benefits in the application of CO<sub>2</sub> cryogenic cooling combined with MQL for milling the integral blade rotors made in Ti6Al4V. This technique enables the effective use of PCD inserts by mitigating issues associated with the chemical reactivity between Ti6Al4V alloy and this type of cutting tool, which is closely linked to the cutting temperature.

Meanwhile, the use of nano-enhanced cutting oils as base fluids in MQL technology represents a second approach, owing to their ability to improve thermal conductivity and enhance the lubricating performance of conventional cutting oils. Moreover, a significant advantage of this method is that it does not require any additional cryogenic support equipment. Hence, it has become an up-to-date topic that has attracted special attention from scientists worldwide. Das and his colleagues [20] studied the effect of MQL using nano-cutting oil compared to MQL using conventional cutting oil for hard turning of AISI 4340 steel. Experimental results showed that MQL using nano-cutting oil yielded better results in reducing tool wear and cutting force. Khatai et al. [21] studied the effect of MQL using ZnO nano-enhanced oil on the hard turning performance of AISI D2 steel. The lowest cutting temperature and noise level were recorded with the nanofluid MQL mode. Cutting speed has a significant effect on tool wear and cutting temperature, while feed rate has the greatest effect on surface roughness. Şirin and Kivak found that the thermal conductivity and lubricating ability of nano-cutting oils were higher than those of based cutting oil [22].

In recent years, the use of the nanofluid MQL technique applied for hard machining and difficult-to-cut materials has yielded positive results. The lubrication and cooling efficiency in the cutting zone resulting from nano-cutting oils has been improved, thereby reducing cutting forces, cutting heat, tool wear and improving machined surface quality [16,23]. However, the effectiveness of using nano-cutting oils depends on parameters such as morphology (Duc et al. [24]), grain size, and the type of nanoparticles (Pryazhnikov et al. [25]). In addition, the concentration of nanoparticles [23] and the type of base cutting oil also have a significant effect [25]. Some common types of nanoparticles used for the MQL technique include Al<sub>2</sub>O<sub>3</sub>, MoS<sub>2</sub>, graphite, graphene, CuO, SiC, SiO<sub>2</sub>, TiO<sub>2</sub>, hBN, carbon nanotubes (CNTs), and so on. Each type of nanoparticles has its own characteristics,

so they create different cooling lubrication mechanisms when penetrating the cutting zone (Sharma et al. [26]). Abbas et al. [27] pointed out a higher thermal conductivity coefficient of  $\text{Al}_2\text{O}_3$  nano-cutting oil compared to base cutting oil. The friction coefficient is reduced in hard turning of AISI 1045 steel due to the “rolling effect” of  $\text{Al}_2\text{O}_3$  nanoparticles (Luo et al. [28]). Eltaggaz et al. [29] compared dry, flood, MQL and nanofluid MQL modes in turning ADI alloy steel. Among the different conditions investigated, the obtained experimental results indicated better surface quality and reduced cutting force in case of MQL using nano-cutting oil. Similar results were also recorded in the study by Kara [30]. Hegab et al. [31] showed a strong correlation between nanoparticle concentration and the machining outputs in turning Inconel 718 alloy under the MQL condition. Nevertheless, studies on the milling process under the nanofluid MQL environment are limited. Günan et al. [32] studied the MQL mode using  $\text{Al}_2\text{O}_3$  nano-cutting oil with different nanoparticle concentrations for milling Hastelloy C276 alloy. Experimental results showed that nanoparticle concentration had a significant effect on tool wear and tool life. With an  $\text{Al}_2\text{O}_3$  nanoparticle concentration of 1%, the results were better than 0.5% and 1.5%. In addition, adhesive wear was reduced because  $\text{Al}_2\text{O}_3$  nano-cutting oil improved cooling lubrication efficiency in the cutting zone. Hassanpour and his colleagues [33] studied the micro-milling process of Ti6Al4V alloy under MQL mode using  $\text{MoS}_2$  and  $\text{CuO}$  nano-cutting oils. The authors found that the surface quality was improved and the thickness of the white layer was reduced. Zhang et al. [34] studied the effect of SiC MQL on hard turning performance of 40Cr steel ( $48 \pm 2\text{HRC}$ ) and found that compared to dry cutting, ceramic tool wear, cutting temperature, and surface roughness were significantly reduced, by 55.1%, 41.5% and 19.2%, respectively. These led to the extension of tool life by 44.4–46.7%. Thakur et al. [35] showed the better turning performance of EN-24 steel under MQL using SiC soluble-oil-based nanofluid compared to pure MQL mode. In addition, SiC nanoparticle concentration is the most significant input variable.

From previous studies, it was found that several related works have been done on the machining performance under MQL and SiC nanofluid MQL environments. In the literature, limited knowledge is available on the effectiveness of MQL using SiC nano-cutting oil for the hard milling process of AISI D2 tool steel under dry, pure MQL, and nanofluid MQL conditions. Several parameters were used as evaluation criteria, including active cutting force, surface roughness, tool wear, and tool life.

## 2. Materials and Methods

### 2.1. Experimental Devices

In order to study the effect of MQL using nano-enriched cutting oil on the hard milling process of AISI D2 steel, an experimental system was constructed with workpiece material, the CNC milling machine, cutting tool, MQL system, cutting force measuring device, surface roughness measuring device, and tool-wear monitoring system. The workpiece material used in the study was high-alloy AISI D2 tool steel (US standard governed by ASTM A681-08R22-Standard Specification for Tool Steels Alloy, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, 19428-2959 USA, 2022), which is a high-chromium (Cr) cold-forged die steel characterized by good wear resistance, high mechanical strength, and dimensional stability after heat treatment. AISI D2 steel samples were initially machined and then hardened to the hardness of 58–60 HRC (Figure 1). The chemical composition and mechanical properties of AISI D2 steel are shown in Tables 1 and 2. The hard milling trials were performed on Mazak 530C vertical milling center (Yamazaki Mazak Corporation, 1–131 Takeda, Oguchi-cho, Niwa-gun, Aichi-Pref, Japan). The APMT1604PDTR carbide inserts with a PVD TiAlN coating, flank angle ( $11^\circ$ ), and nose radius (0.66 mm) were used (Figure 2).

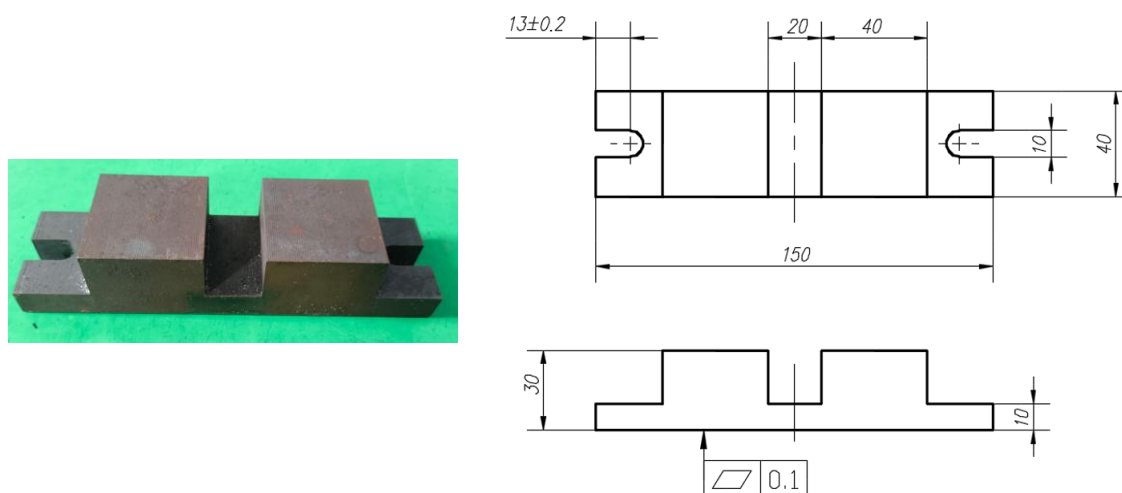


Figure 1. AISI D2 workpiece sample used for hard milling experiments.



Figure 2. APMT1604PDTR LT30 milling inserts.

Table 1. Chemical composition of AISI D2 steel.

| Chemical Composition (%) |     |     |     |           |         |         |       |       |       |       |
|--------------------------|-----|-----|-----|-----------|---------|---------|-------|-------|-------|-------|
| C                        | Si  | Mn  | Ni  | Cr        | Mo      | W       | V     | Cu    | P     | S     |
| 1.4–1.6                  | 0.4 | 0.6 | 0.5 | 11.0–13.0 | 0.8–1.2 | 0.2–0.5 | ≤0.25 | ≤0.25 | ≤0.03 | ≤0.03 |

Table 2. Mechanical properties of AISI D2 steel.

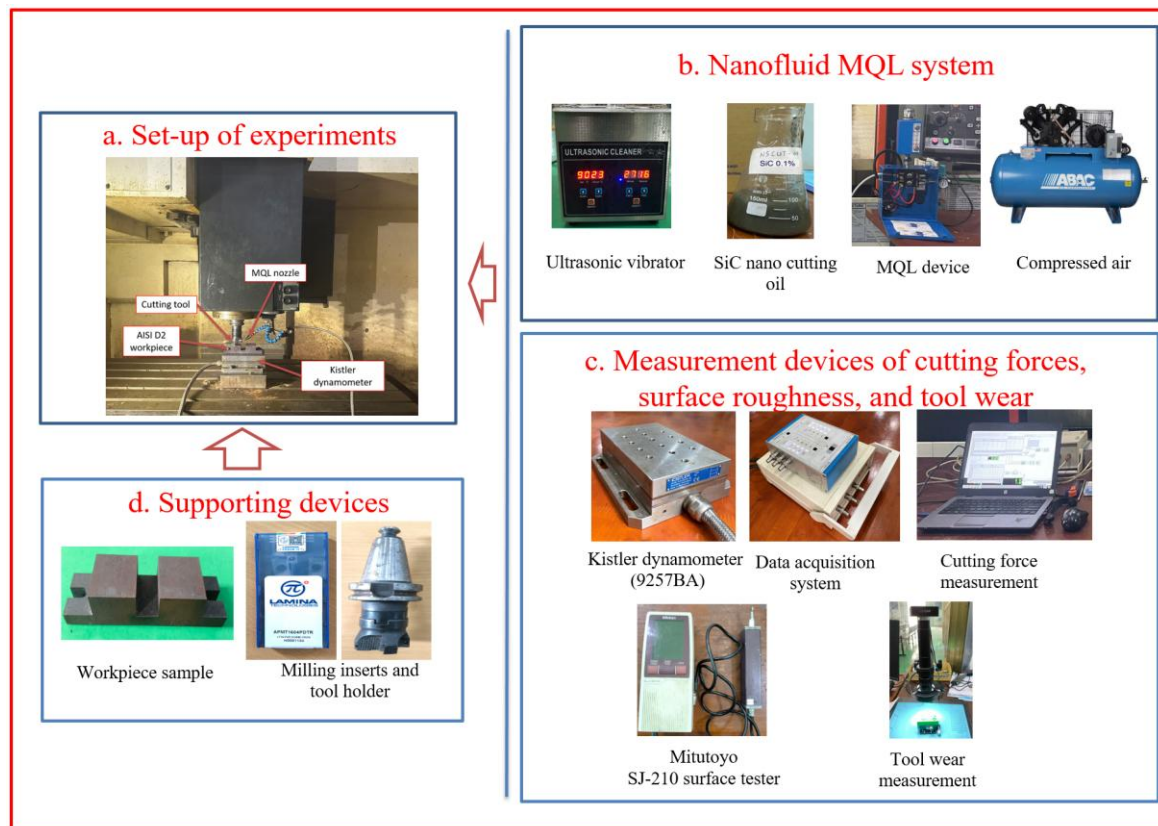
| Tensile Strength (MPa) | Shear Strength (MPa) | Elongation (%) | Modulus of Elasticity (GPa) | Poisson's Ratio |
|------------------------|----------------------|----------------|-----------------------------|-----------------|
| 1510                   | 1160                 | 5              | 190–210                     | 0.28            |

## 2.2. Experimental Set-Up

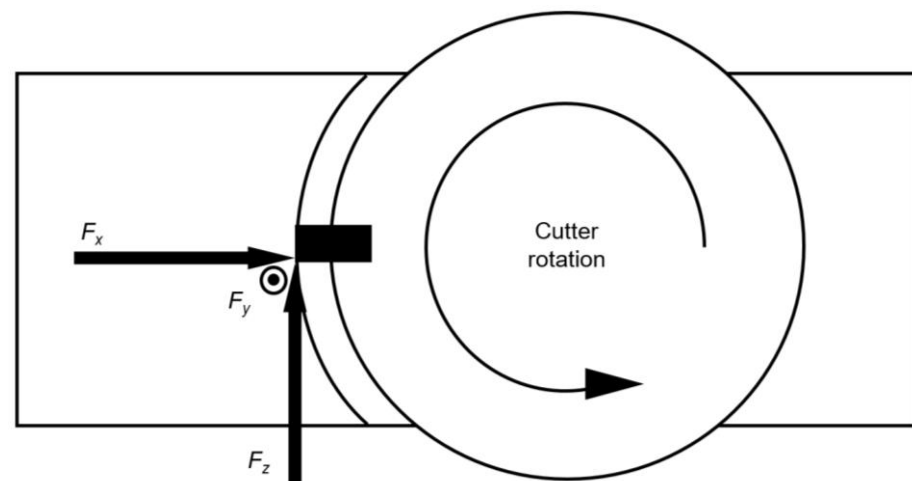
The experimental setup was established on a Mazak 530C vertical milling center. Kistler 9257BA multicomponent dynamometer (Kistler Instruments (Pte) Ltd., Midview, Singapore) was mounted on the machine table and interfaced with a DQA N16210 A/D data acquisition system (National Instruments, Austin, TX, USA) connected to a computer (Figure 3). The data acquisition and processing procedures were fully synchronized by using DasyLab 10.0 software, enabling the direct measurement of the three cutting force components,  $F_x$ ,  $F_y$ , and  $F_z$ . The cutting parameters are fixed at a cutting speed of 110 m/min, feed rate of 0.05 mm/tooth, and cutting depth of 0.15 mm, which are based on previous works [32,36].

Figure 4 presents the designation of cutting force directions in single-insert face milling. The force component  $F_x$  acts in the direction of tool motion, whereas  $F_y$  acts along the tool's main axis, perpendicular to the workpiece surface. This component tends to push the tool away from the workpiece and is therefore referred to as the thrust force. The force component  $F_z$ , also known as the tangential force, lies in the plane of the workpiece and

is perpendicular to the tool's direction of motion. It represents the primary cutting force and plays a key role in determining the cutting power.



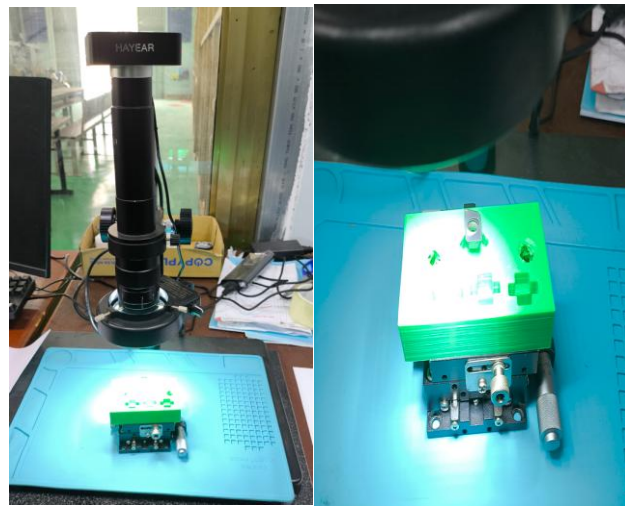
**Figure 3.** Diagram of the set-up of hard milling experiments and measurement.



**Figure 4.** Cutting force components acting on the cutting tool in single-insert face milling with the tangential force  $F_z$ , feed force  $F_x$ , and axial force  $F_y$  (directed out of the page).

The YSHT-MQL2551A external MQL system (Yongshenghetuo Intelligent Equipment Co., Ltd., Foshan, Guangdong, China) is used and consists of an oil reservoir, oil flow valves, air pressure regulator, and a flexible directional nozzle. Compressed air is supplied at a pressure of 6 bar, while the oil flow rate is adjusted within the range of 30 mL/hour [37]. The MQL nozzle is adjusted to direct the contact area between the tool flank face and the workpiece surface. The MQL nozzle distance to the cutting zone is 30 mm and the nozzle angle is  $45^\circ$  [13,16]. The system operates on the principle of mixing cutting

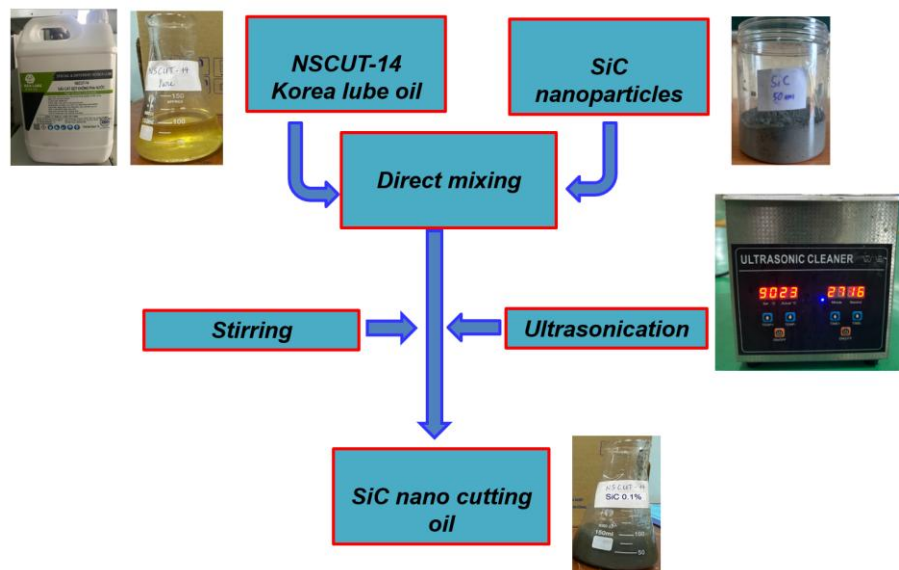
oil with compressed air to create oil mist. Surface roughness was measured by using a Mitutoyo SJ-210 surface roughness tester (Mitutoyo Corporation, Kawasaki, Kanagawa, Japan). The probe was positioned perpendicular to the feed direction to ensure the accurate recording of the undulation characteristics created by the milling process. After each pass, measurements were taken in at least three different locations on the same machined surface, and then the surface roughness  $R_a$  values were recorded and averaged. Tool wear was observed under a Hayear digital microscope (Shenzhen Hayear Electronics Co., Ltd., Shenzhen, China) to assess the wear amount and the wear mechanism occurring on the cutting edge (Figure 5). The types of wear recorded included flank wear, rake face wear, chipping, and micro-cracks.



**Figure 5.** Hayear digital microscope system used to observe and assess tool wear.

### 2.3. Preparation Process of SiC Nano-Cutting Oil

To create the nano-enhanced cutting oil, SiC nanoparticles with a particle size of 50 nm were suspended in the NSCUT-14 Korea Lube base cutting oil (Korea Lube Vietnam CO., LTD, 4th floor, 622A An Phu street, An Phu ward, District 2, HCM city). The formulation process consisted of two main stages: mechanical stirring and ultrasonic dispersion. Initially, nanoparticles at a surveyed concentration of 0.1% by weight were precisely weighed according to Equation (1) and added to the NSCUT-14 Korea Lube base cutting oil. The mixture was stirred mechanically for 30 minutes to pre-disperse the nanoparticles in the oil medium [38]. The mechanical stirring process helped break up large aggregates, facilitating the subsequent fine dispersion stage. After mechanical stirring, the solution was placed in an Ultrasonic Cleaner (TB-50) (AG Sonic Technology Limited, Shenzhen, China). Ultrasonic waves at a frequency of 40 kHz broke down any remaining nanoparticle clusters and dispersed them evenly throughout the base oil. Ultrasonication was maintained for approximately 1 hour [32] to ensure the stability of the nano-cutting oil (Figure 6). The obtained nano-cutting oil was immediately used for the MQL system.



**Figure 6.** Diagram of the preparation process of SiC nano-cutting oil.

The concentration of nanoparticles in the base oil is determined as the weight percent (wt%) and is calculated by the following formula:

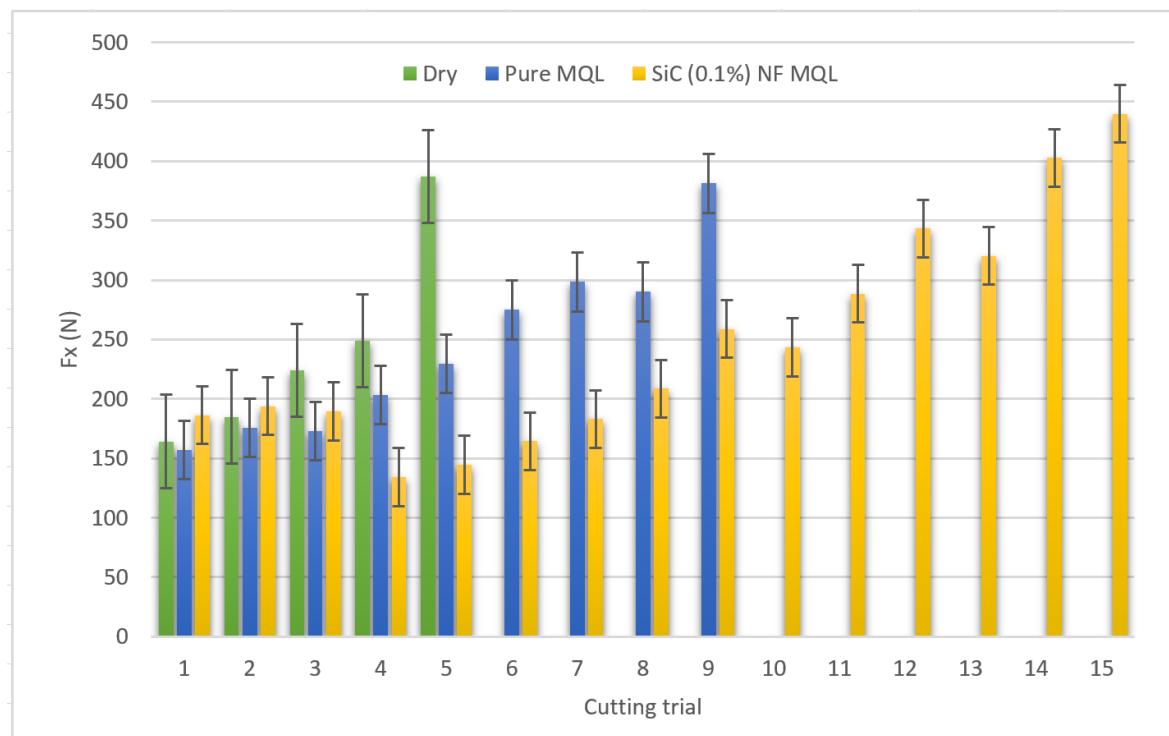
$$\text{Weight percentage concentration (wt\%)} = \frac{\text{Weight of solute (g)}}{\text{Weight of solution (g)}} \times 100\% \quad (1)$$

### 3. Results and Discussion

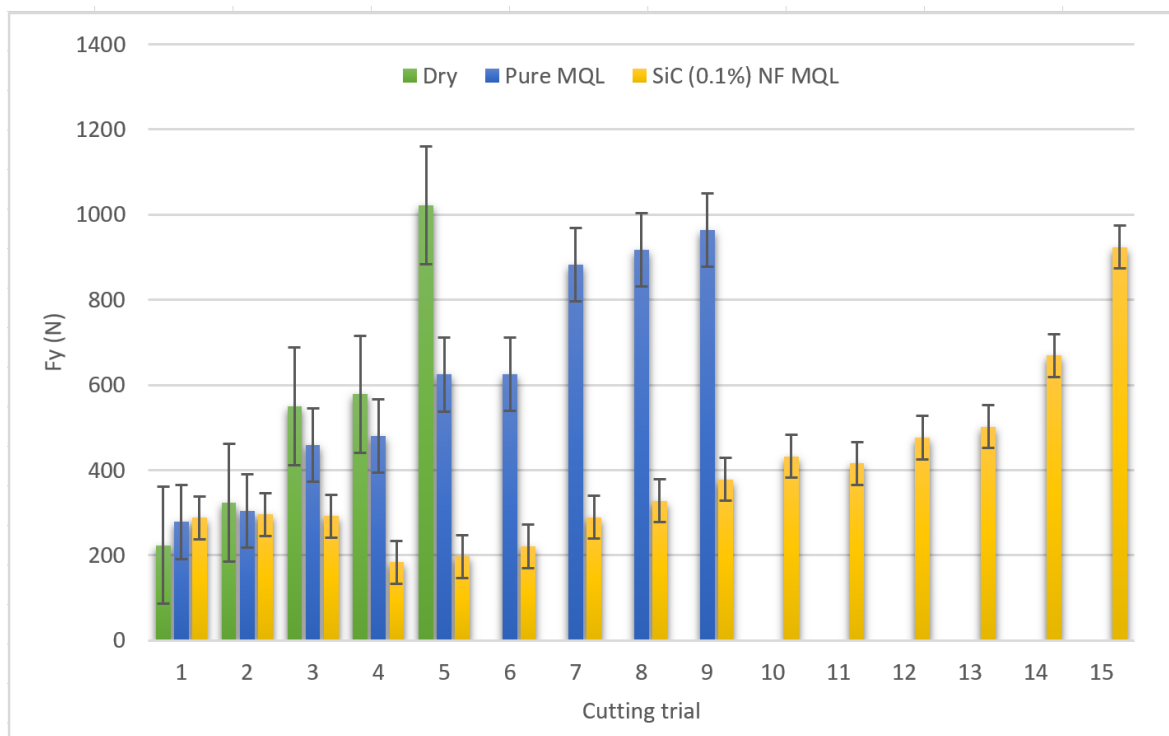
Hard milling experiments on AISI D2 tool steel were conducted under three different lubrication regimes: dry, pure MQL, and MQL using SiC nano-cutting oil at a concentration of 0.1%. The measured parameters included the three cutting force components ( $F_x$ ,  $F_y$ ,  $F_z$ ), surface roughness  $R_a$ , and tool wear. The experimental results were analyzed to evaluate the influence of cooling lubrication condition on cutting forces, surface quality, tool wear, and tool life.

#### 3.1. Influence of Cooling Lubrication Modes on Cutting Forces

In hard milling, cutting force is one of the important parameters reflecting the working state of the cutting tool as well as the friction conditions in the cutting zone, significantly influencing tool performance through interconnected mechanical and thermal mechanisms. High cutting force raises the stress acting on the cutting edge, leading to higher normal and shear stresses at the tool–chip and tool–workpiece interfaces. This elevated stress can cause plastic deformation, micro-chipping, or even fracture of the cutting tool, particularly in brittle materials such as carbide or ceramics [5,6]. Figures 7–9 show the change in cutting force with the number of cuts for three different cooling lubrication modes. The cutting force is analyzed in terms of three orthogonal components,  $F_x$ ,  $F_y$ , and  $F_z$ . The error bars with standard error in Figures 7–9 represent the uncertainty, variability, or possible error in the data values. They help understand how precise or reliable each data point is.



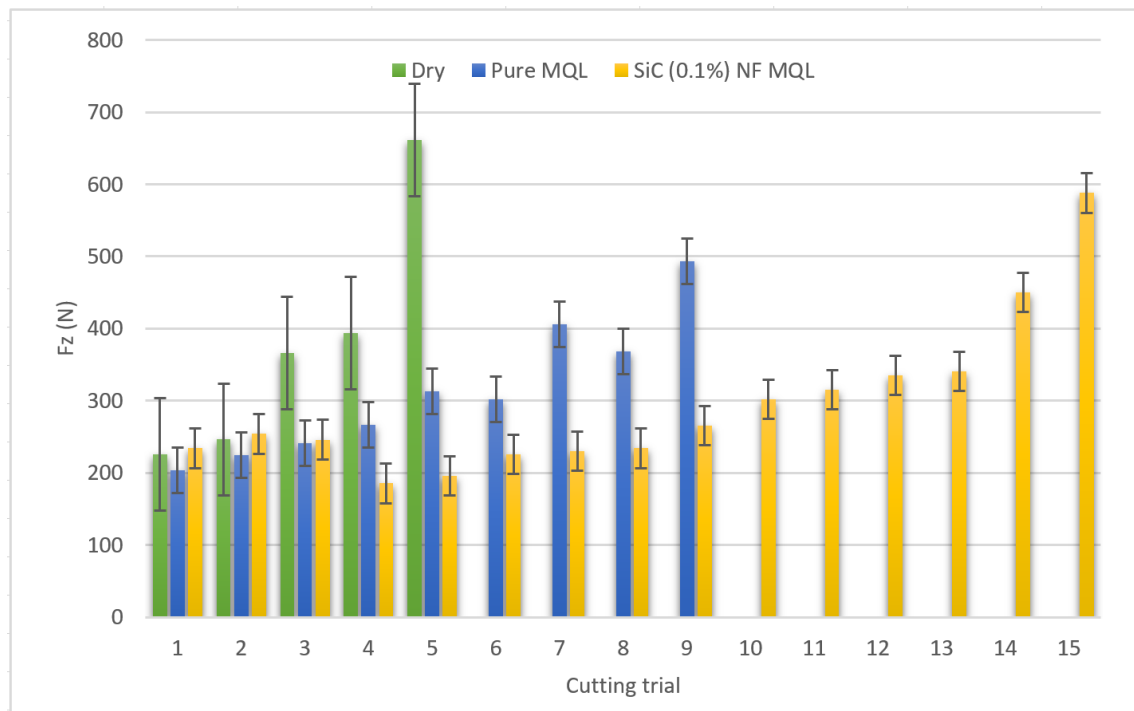
**Figure 7.** Results of measuring the cutting force  $F_x$  (feed force) in the number of cuts with different cooling lubrication conditions.



**Figure 8.** Results of measuring the cutting force  $F_y$  (thrust force) in the number of cuts with different cooling lubrication conditions.

Experimental results indicate that all three components of the cutting force gradually increase with the number of cuts in all surveyed cooling lubrication conditions. This trend can be attributed primarily to progressive tool wear during the hard machining process. As the cutting tool wears, the contact area between the tool and the workpiece expands,

leading to higher friction in the cutting zone. Consequently, the cutting forces become significantly greater in subsequent cutting trials.



**Figure 9.** Results of measuring the cutting force  $F_z$  (tangential force) in the number of cuts with different cooling lubrication conditions.

Under dry machining conditions, the cutting force exhibits the most rapid increase and reaches the highest magnitude compared to other machining modes. After only about five cuts, the cutting force  $F_x$  increases from approximately 150 N to nearly 400 N, the cutting force  $F_y$  increases from approximately 200 N to over 1000 N, and the cutting force  $F_z$  increases from approximately 220 N to approximately 670 N. This behavior indicates that, in the absence of cooling and lubricating environment, friction and temperature in the cutting zone become extremely high, causing rapid tool wear and leading to a sudden increase in cutting force. Notably, the  $F_y$  component consistently shows higher values than the two force components along the feed force  $F_x$  and the tangential force  $F_z$ , suggesting that the substantial pressure is exerted on the tool's flank face and the machined surface during the hard milling process. As a result, the micro-chipping along the main cutting edge and severe crater wear on the flank face shown in Section 3.4 reduce the machinability of the coated carbide tool.

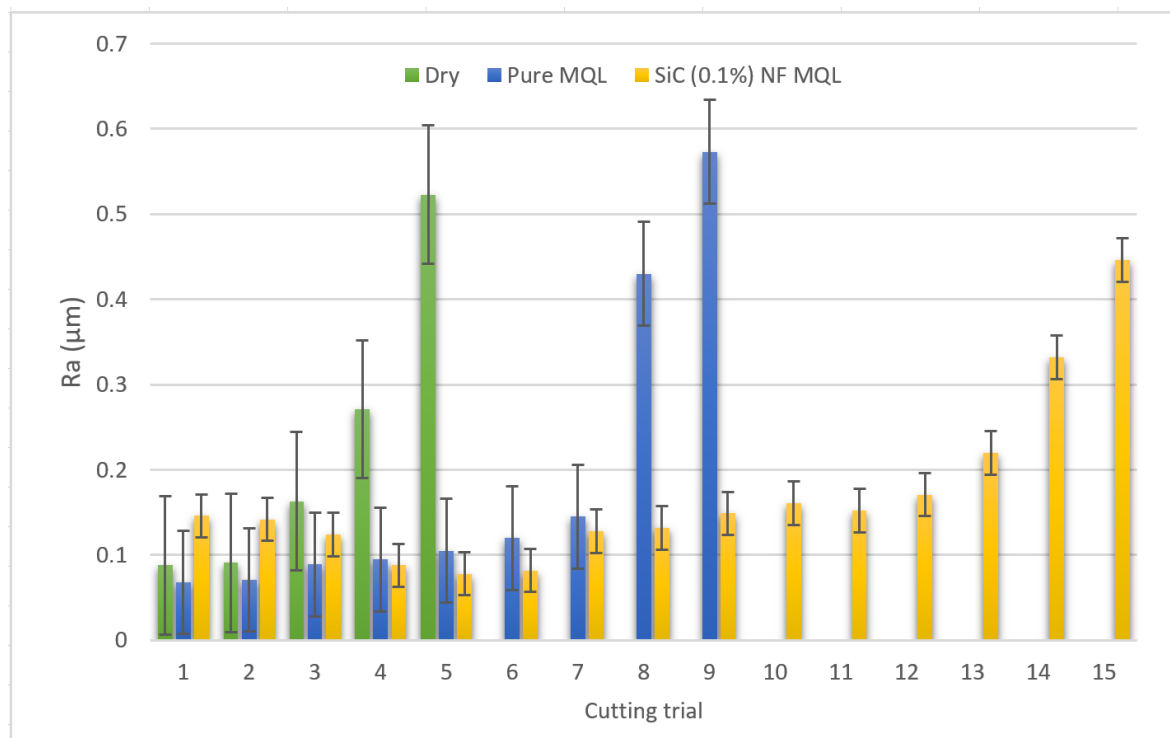
Under a pure MQL environment, the cutting force is markedly lower than in dry machining. The cutting fluid is delivered directly into the cutting zone, creating a lubricating film at the interfaces between the tool and the chip, as well as between the tool's flank face and the machined surface. This lubrication reduces friction and facilitates chip formation. As a result, the increasing rate of cutting forces is more gradual, allowing the tool to sustain a greater number of passes, approximately nine, before the cutting forces increase sharply. The frictional force increases proportionally with normal force or thrust force, further amplifying heat generation. The resulting high temperature accelerates various tool wear mechanisms. Moreover, elevated temperatures lead to thermal softening of the tool material, reducing its hardness and wear resistance [5]. These effects collectively create a feedback loop in which increased wear further elevates cutting force, thereby accelerating tool degradation. Consequently, when flank wear approaches the permissible limit, the cutting force exhibits a sharp increase.

The most noticeable improvement was observed when using SiC nanofluid MQL. In this case, the cutting force in all three components remained consistently lower than in the other two lubrication modes for most of the machining process. The tool was able to perform up to approximately 15 cuts before a noticeable increase in cutting force occurred. This enhancement can be attributed to the presence of SiC nanoparticles, which generate a rolling effect at the contact interfaces, thereby reducing the coefficient of friction [26,39]. Simultaneously, the high thermal conductivity of SiC enhances heat dissipation in the cutting zone [25,40], leading to lower temperatures and reduced tool wear.

Overall, the application of MQL with SiC nano-cutting oil leads to a substantial reduction in cutting forces (approximately 20–40% compared to dry machining) and slows down the growing rates in all the cutting force components over time. These results clearly demonstrate the superior performance of nano-enhanced cutting fluids in improving tribological conditions within the cutting zone and enhancing machining efficiency [26].

### 3.2. Influence of Cooling Lubrication Modes on Surface Roughness

Surface roughness is a key indicator of the quality of the machining process. In hard milling, it is influenced by various factors such as cutting parameters, the tool wear condition, lubrication modes, and chip evacuation in the cutting zone. In order to evaluate the influence of different lubrication conditions on the machined surface quality during hard milling of AISI D2 tool steel, surface roughness  $R_a$  is measured three times after each cut, and the average values are taken. Figure 10 shows the variation in surface roughness value  $R_a$  with the number of cuts under different lubrication regimes.



**Figure 10.** Surface roughness  $R_a$  in the number of cuts with different cooling lubrication conditions.

The results show that the surface roughness value tends to increase gradually with the number of cuts in all three machining modes. The main reason is that tool wear changes the shape of the cutting edge, increases friction, and reduces cutting efficiency, thereby degrading the quality of the machined surface.

Under dry machining conditions, the roughness increased most rapidly, from about 0.09  $\mu\text{m}$  to about 0.53  $\mu\text{m}$  after only five cuts. This indicates that tool wear occurs quickly and strongly affects surface quality when there is no lubrication medium.

Compared to dry cutting, surface roughness under pure MQL remained lower in the initial stages due to a better lubricating effect, but increased significantly as the number of cuts increased, reaching approximately 0.58  $\mu\text{m}$  at the 9th cut. Meanwhile, under the MQL condition using SiC nano-cutting oil, surface roughness remained lower and more stable. The  $R_a$  values in the initial stages were only about 0.08–0.15  $\mu\text{m}$  and increased more slowly compared to the other two modes. Even in the final cuts, the roughness remained significantly lower than in MQL without nano-cutting oil. These results show that SiC nano-cutting oil improves surface quality by reducing friction, heat, and tool wear. Surface roughness can be reduced by approximately 37–62.3% compared to pure MQL and dry machining. The main reason lying behind this is that SiC nanoparticles contribute to a surface polishing effect by smoothing the contact interfaces during machining, resulting in a micro-polishing action that enhances the surface finish of the machined workpiece [26,39].

### 3.3. Tool Life Investigation

Tool life is a critical indicator for evaluating machining efficiency. In hard milling, tool wear results from the combined effects of cutting forces, cutting zone temperature, and friction between the tool and the workpiece. When the tool wears down to a certain limit, machined surface quality deteriorates rapidly and the cutting force increases significantly. Therefore, determining tool life is necessary to evaluate the effectiveness of different cooling lubrication conditions.

In hard milling, tool life is determined based on the total accumulated cutting time until the tool no longer guarantees machining quality and is taken according to the ISO 3685 standard for tool-life testing (International Organization for Standardization ISO Central Secretariat, 1214 Vernier (Geneva), Switzerland, 1993) of the flank wear criteria  $VB = 0.3$  mm. The cutting time for each machining operation is calculated using the formula:

$$T_m = \frac{L + A}{f_r} \quad (2)$$

where:

- $T_m$ —Cutting time (min),
- $L$ —Cutting length (mm),
- $A$ —Approach distance (mm),
- $f_r$ —Feed rate (mm/min).

The approach distance  $A$  to reach full cutter depth is given by

$$A = 0.5(D - \sqrt{D^2 - w^2}) \quad (\text{mm}) \quad (3)$$

where:

- $D$ —Diameter of the milling cutter (mm),
- $w$ —Workpiece width (mm).

The feed rate per minute is calculated using the formula

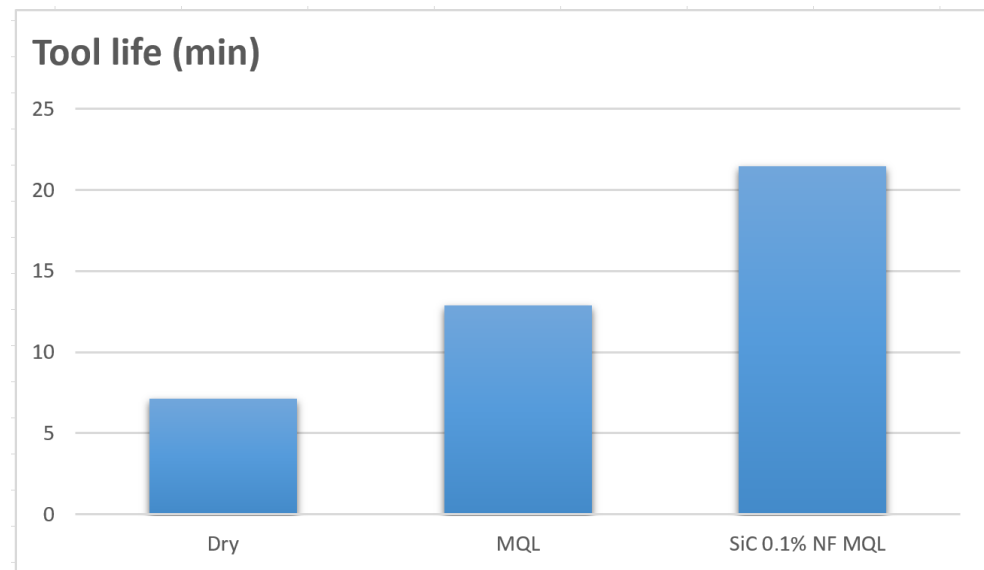
$$f_r = N \cdot n_t \cdot f \quad (\text{mm/min}) \quad (4)$$

where:

- $N$ —Spindle speed (rev/min),
- $n_t$ —Number of teeth on the cutter,
- $f$ —Feed rate (mm/tooth).

In this work, for the cutting speed  $V_c = 110$  m/min,  $D = 50$  mm,  $w = 40$  mm,  $f = 0.05$  mm/tooth, and the cutting time for each pass is  $T_m = 1.43$  (min). Hence, the cutting time

for different cooling lubrication conditions will be  $T_{\text{dry}} = 7.15$  (min),  $T_{\text{pure MQL}} = 12.87$  (min), and  $T_{\text{NF MQL}} = 21.45$  (min), which are illustrated in Figure 11.



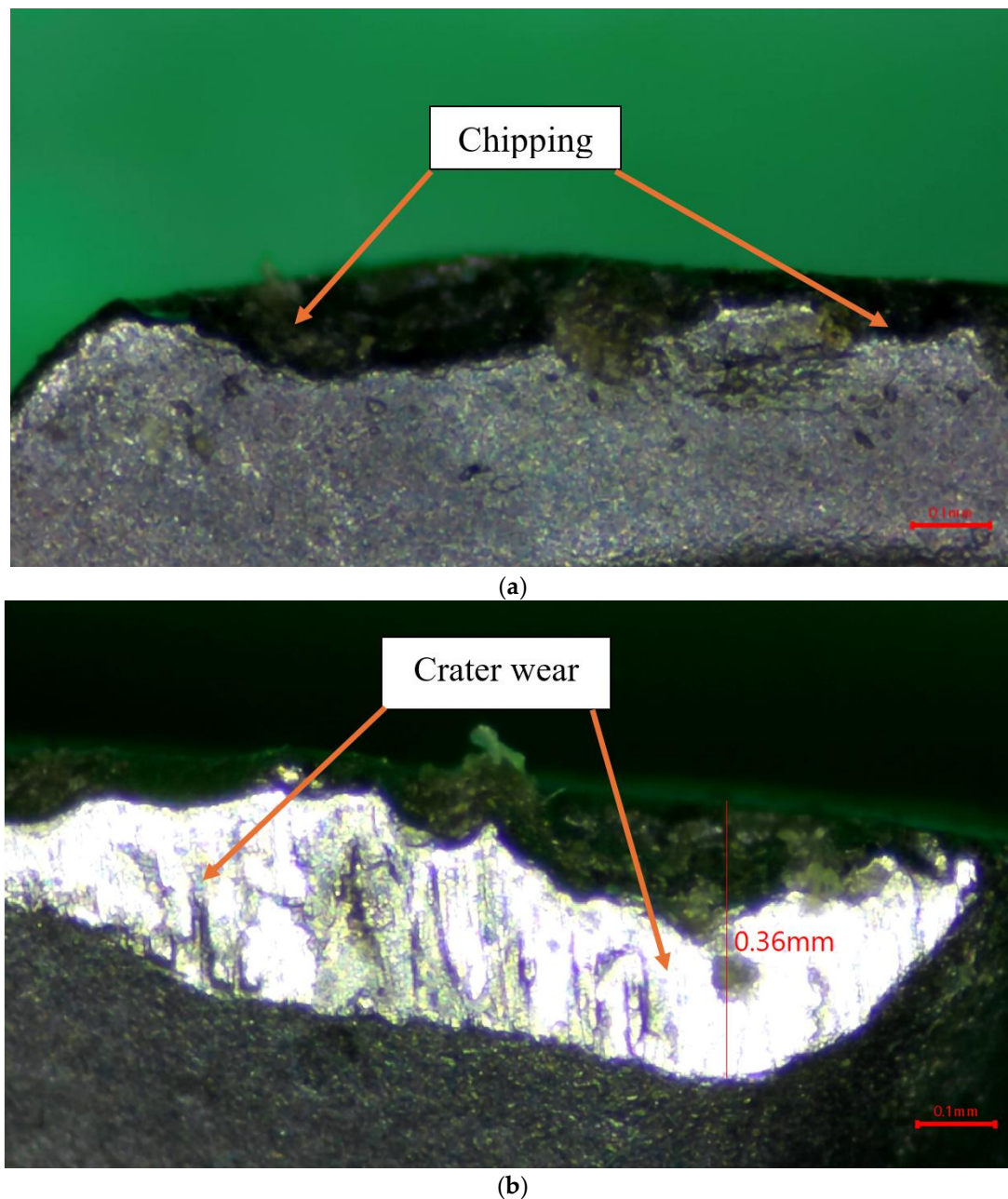
**Figure 11.** Tool life under different cooling lubrication conditions.

In Figure 11, compared to dry machining, it can be seen that tool life increased significantly under pure MQL mode and nanofluid MQL modes. The tool life in dry cutting reaches the end at about 7.15 minutes. Under a pure MQL condition, tool life increased to about 12.87 minutes. Notably, with MQL using SiC nano-cutting oil, the tool life prolongs to about 21.45 minutes. Thus, tool life in case of nanofluid MQL increased by about 1.8–3 times compared to dry machining. The reason lying behind this is that SiC nanoparticles improve lubrication through a “rolling effect,” where spherical or near-spherical particles act as “ball rollers” in the contact zones, reducing friction and shear stress [34]. Also, these nanoparticles form a protective tribofilm on the contact surfaces, minimizing direct contact and thereby suppressing adhesive wear. Regarding temperature, the high thermal conductivity of SiC nanoparticles is an outstanding property [25], which enhances heat dissipation from the cutting zone, effectively lowering cutting temperature [35]. Temperature reduction is critical in machining hardened materials like AISI D2 tool steel, where excessive heat accelerates diffusion and oxidation wear.

### 3.4. Investigation of Wear Mechanism

To clarify the effectiveness of pure MQL and nanofluid MQL conditions, it is necessary to analyze the tribological and thermal transfer mechanisms occurring in the contact zone when nanoparticles are involved. Tool wear images in Figures 12–14 show that lubrication conditions have a significant impact on the degree of tool wear. Under dry machining conditions, friction between the tool and chip occurs primarily as direct sliding friction, resulting in a high coefficient of friction and increased cutting zone temperature. This accelerates tool wear, particularly flank wear and chipping on the main cutting edge, leading to a reduction in the machinability of the cutting insert. Hence, a rapid increase in cutting force and a degradation of machined surface quality occur. The wear land on the rake and flank faces of the tool under dry cutting developed significantly, exhibiting precise cutting stripes and an irregular wear zone profile. At the edges, the flank wear width was about 0.36 mm after five cutting passes (Figure 12), which indicates the end of tool life and was the largest among the three different cooling lubrication modes. The wear

mechanism here is a grasshopper-like pattern. This is found in conditions without lubrication and cooling, where damage and temperature at the cutting zone are very high, leading to excessive wear and rapid tool chipping.

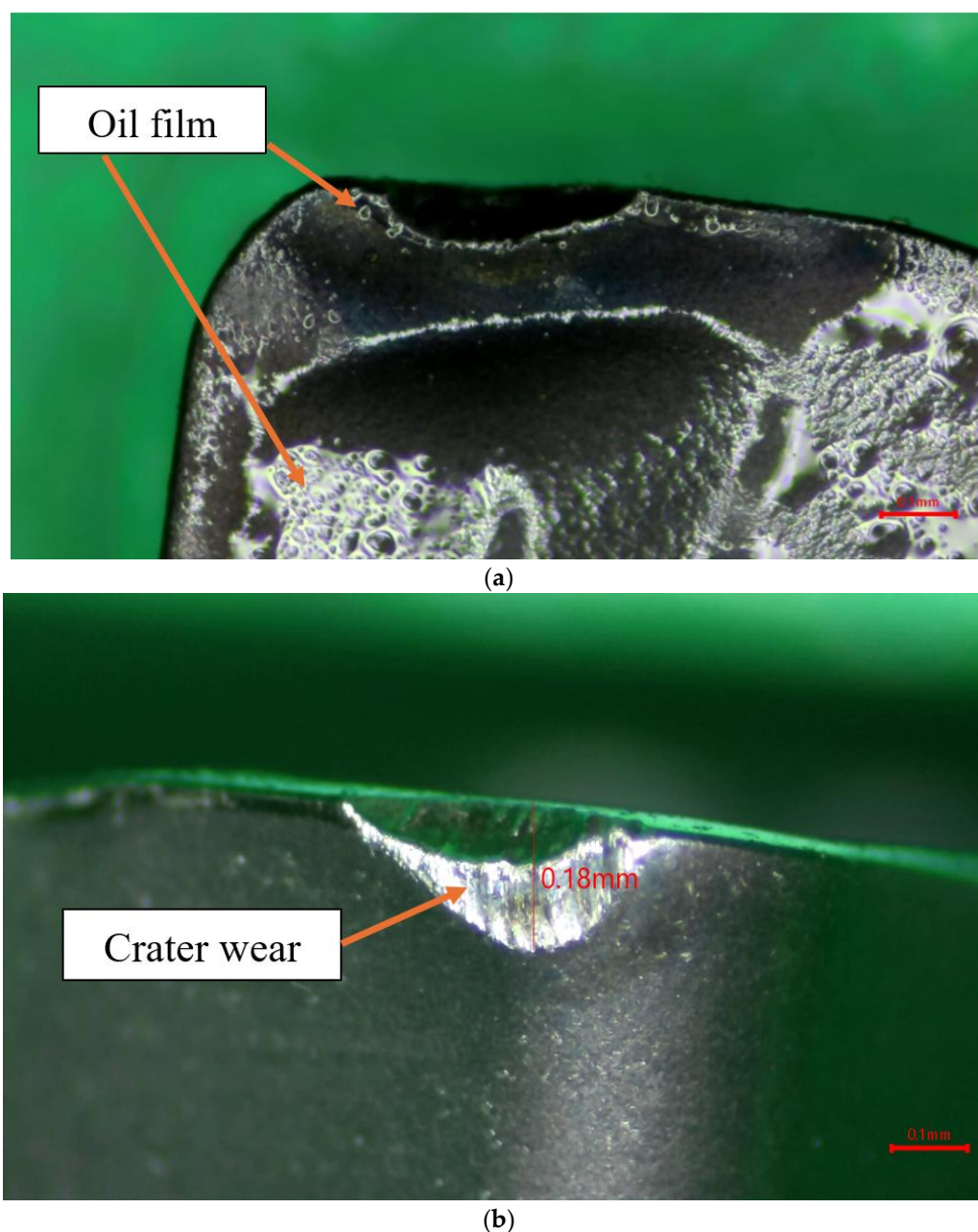


**Figure 12.** Tool wear images during hard milling under dry mode (after five cuts): (a) rake wear, (b) flank wear.

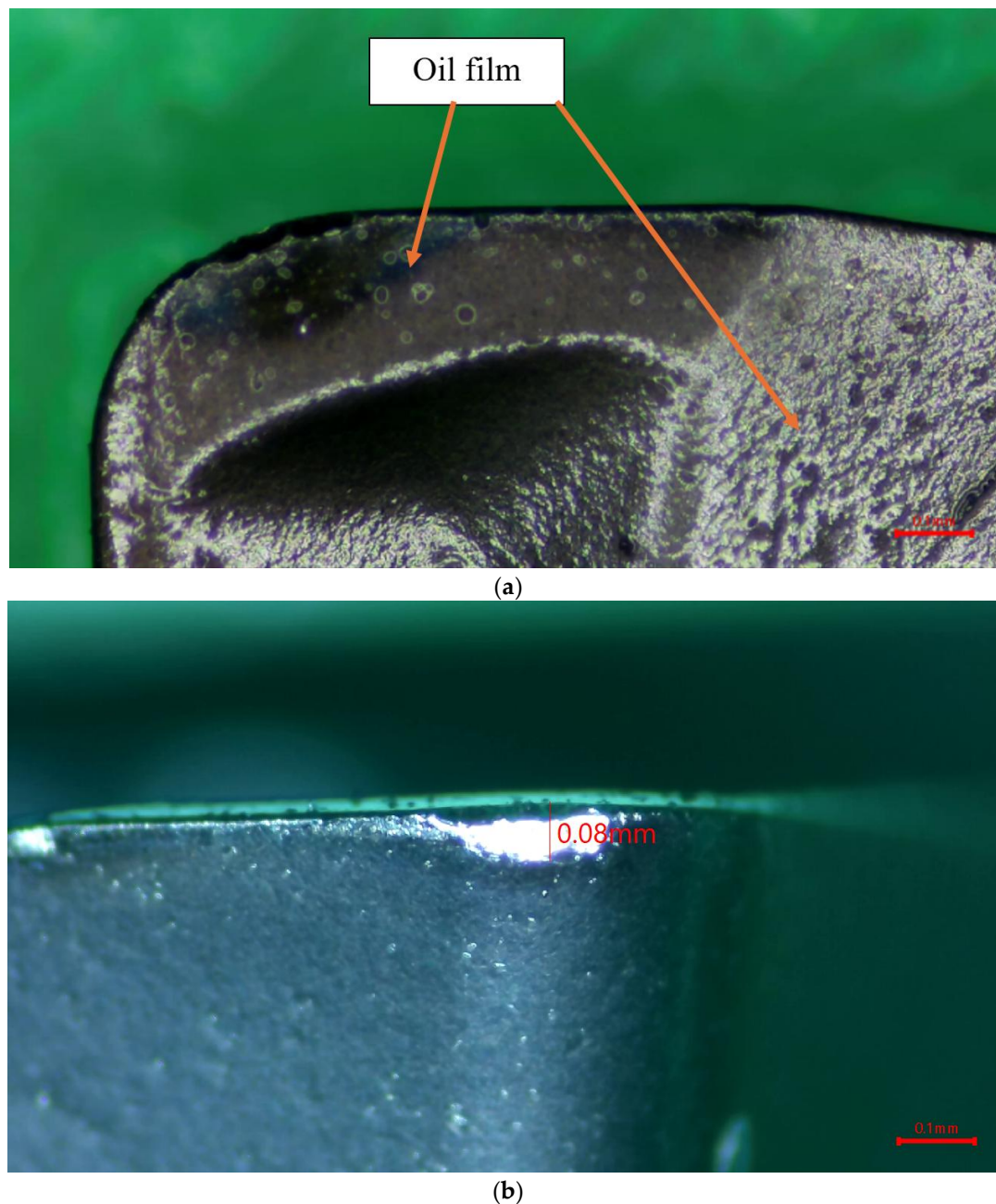
In pure MQL mode, tool wear is significantly reduced when compared to dry machining. The flank wear and cutting edge chipping still occur, but the wear area is smaller and the wear profile is relatively more stable. The width of flank wear  $VB_{MQL}$  is 0.18 mm. Thanks to the MQL technique, oil mist is created and penetrates deep into the cutting area to form the tribofilm (Figure 13), contributing to the reduction in friction and tool wear rate.

The most significant improvement was observed in the MQL condition using 0.1% SiC nano-cutting oil. The tool wear images show significantly smaller wear zones on the rake and flank faces, and less severe tool chipping compared to the other two modes (Figure 14). The width of flank wear  $VB_{NFMQL}$  is 0.08 mm. This demonstrates that the formation of oil droplets containing SiC nanoparticles improved cooling lubrication efficiency in the cutting zone,

thereby slowing down tool wear. SiC nanoparticles possess very high hardness, but are often angular in shape and not easily deformed [39]. Therefore, when entering the tool–chip contact zone, they enhance lubrication through rolling and tribofilm effects. Firstly, acting as nano ball-bearings, SiC nanoparticles reduce friction at the tool–chip interface, while also forming a protective tribofilm that minimizes direct metal-to-metal contact [26]. Secondly, they improve heat dissipation due to their high thermal conductivity ( $370 \text{ W/m}\cdot\text{K}$ ) [25], which facilitates efficient heat transfer away from the cutting zone [40]. This leads to a reduction in cutting temperature, a critical factor in hard milling where thermal loads are typically severe [41]. The improvement in cooling lubrication resulted from pure MQL and nanofluid MQL can be indirectly evaluated through the measured flank wear. Compared to dry cutting, the pure MQL mode reduced flank wear by approximately 50%, while MQL using SiC nano-cutting oil reduced it by approximately 77.8%. These results are consistent with the trends in cutting force, surface roughness, and tool life presented in the previous sections.



**Figure 13.** Tool wear images during hard milling under pure MQL mode (after five cuts): (a) rake wear, (b) flank wear.



**Figure 14.** Tool wear images during hard milling under SiC 0.1% nanofluid MQL mode (after five cuts): (a) rake wear, (b) flank wear.

Figure 15 shows the flank wear across the cutting passes with different cooling lubrication modes. It is clearly evident that the flank wear rate during dry cutting is higher when compared to the pure MQL and 0.1% SiC nanofluid MQL conditions. It is reflected by the slope of the dry cutting graph, while the slope of the pure MQL graph is lower; however, it is still higher than that of the 0.1% SiC nanofluid MQL mode. After five cuts, the flank wear during dry cutting reached the allowance limit, while the flank wear of the pure MQL and 0.1% SiC nanofluid MQL modes was lower, ranging from 0.21 to 0.25 mm, but only at the 9th and 14th cuts. These results demonstrate that the cooling lubrication efficiency in the cutting zone of pure MQL and 0.1% SiC nanofluid MQL is better than the dry condition. Among them, 0.1% SiC nanofluid MQL showed the best efficiency and a stable flank wear graph, leading to the longest tool life. Furthermore, although the flank wear did not reach the allowance limit (according to the flank wear criteria,  $VB = 0.3$  mm

of ISO 3685), the cutting force and surface roughness values increased dramatically. Therefore, when evaluating tool life in hard milling, monitoring the cutting force directly during cutting or measuring surface roughness values can be used as supplementary criteria to assess the wear status and tool life [29,42]. They play significant roles in research as well as in production practice, as measuring tool wear after each cut is difficult due to the need to stop the machine, remove the insert, and set up the cutting process.

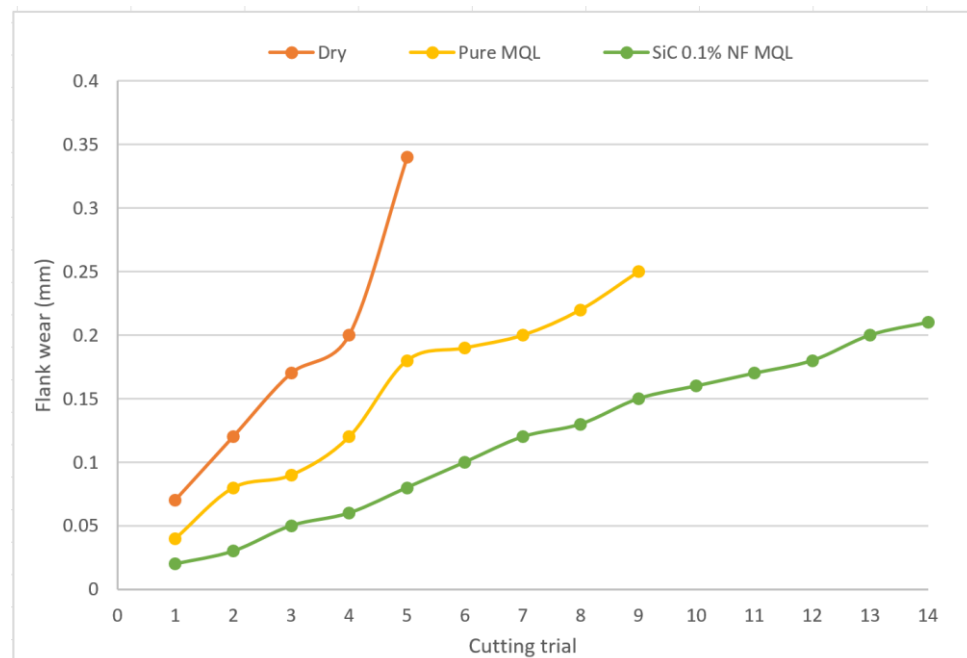


Figure 15. Flank wear under different cooling lubrication conditions.

#### 4. Conclusions

This work investigates the effects of Minimum Quantity Lubrication (MQL) enhanced with SiC nanoparticles in cutting oil on the hard milling performance of AISI D2 tool steel. The results are compared with those obtained under dry and conventional MQL conditions. The evaluated response variables include cutting force components ( $F_x$ ,  $F_y$ ,  $F_z$ ), surface roughness ( $R_a$ ), tool wear, and tool life. The main contributions of this study are summarized as follows:

Hard milling performance and cutting tool machinability were improved by using pure MQL and SiC nanofluid MQL conditions in comparison with dry mode.

The SiC nanofluid MQL environment reduces cutting forces, surface roughness and tool wear more effectively than dry and pure MQL methods, resulting in a significant improvement of tool life. More precisely, compared to dry cutting, the pure MQL condition contributes to reduced feed force  $F_x$  (22.3%), thrust force  $F_y$  (20.5%), tangential force  $F_z$  (34%), surface roughness  $R_a$  (62.3%), and flank wear (46.1%), and extends the tool life by 80%. In addition, compared to the pure MQL method, the SiC nanofluid MQL environment results in the reduction in feed force  $F_x$  (23.8%), thrust force  $F_y$  (55.3%), tangential force  $F_z$  (26.5%), surface roughness  $R_a$  (37%), and flank wear (55.6%) and prolongs the lifespan of the cutting tool by approximately 200%.

Notably, SiC nano-cutting oil significantly reduces the thrust component  $F_y$ , indicating that the ball-bearing mechanism of SiC nanoparticles improves lubrication through a “rolling effect,” leading to a reduction in friction and shear stress. This plays a crucial role in reducing cutting force, cutting heat, and flank wear, leading to an improvement in cutting performance and extension of tool life. At the same time, these nanoparticles form a protective tribofilm on the contact surfaces, reducing direct metal-to-metal interaction and

thereby limiting adhesive wear. In terms of thermal behavior, the inherently high thermal conductivity of SiC nanoparticles is a notable property, which promotes efficient heat dissipation from the cutting zone and consequently reduces the cutting temperature.

The research results indicate that the flank wear criterion for evaluating tool life in hard machining should be used in conjunction with monitoring changes in cutting forces and surface roughness.

Despite the promising results obtained, several limitations remain. This study was conducted on a single workpiece material under fixed machining conditions, which may limit the generalizability of the findings. Future research should focus on optimizing SiC nanoparticle concentration as well as some important MQL parameters (oil flow rate, nozzle angle, and nozzle positioning). In addition, a more in-depth investigation of the surface microstructure is required to better understand and validate the cooling and lubrication mechanisms of SiC nanoparticles. In addition, other cutting parameters and nanoparticle concentrations will be studied in terms of optimization. Furthermore, a comprehensive cost analysis comparing nano-enhanced cutting fluids with dry machining is necessary to evaluate their practical feasibility for industrial applications.

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