Chapter

The Characteristics and Application of Nanofluids in MQL and MQCL for Sustainable Cutting Processes

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Abstract

Recently, there has been growing attention to nanofluids, especially in industry. More and more people nowadays see nanoparticle applications in various fields such as automotive, agriculture, medicine, machining, and so on. The addition of different nanoparticles to fluids has shown enormous advantages, particularly for improving the efficiency and therefore lowering the energy consumption of processes for addressing a wide range of global challenges related with energy and environmental problems. Nanoparticles are of great scientific interest as they are in that nanofluid with unusual effects, and ultra-small sizes will be a new area for researchers and definitely offer novel mechanisms and technologies in the future. In this chapter, the authors will mainly present the characteristics as well as latest advances in applications of nanofluids in machining practices. Nanoparticle additives contribute to reduce friction coefficient, lower the energy consumption, and significantly extend tool life by lowering thermal stress, from which the surface quality of manufactured parts improves. Moreover, the nanoparticle application in some of the green technologies as MQL and MQCL using vegetable oils not only brings out superior cooling and lubricating properties and minimizes the use of cutting fluids, but also creates new solutions for machining, especially for difficult-to-cut materials.

Keywords: nanoparticles, nanofluid, sustainable cutting, MQL, MQCL, hard machining, vegetable oil, metal cutting

1. Introduction

Climate change has become the most growing concern of people around the world. The rapid increase of population consequently leads to the use of more natural resources and giving out of more waste. The pollution in air, water, and food causes many serious human diseases. Accordingly, environmental laws are continuously tightening up to protect our Earth. Being a part of the production chain, manufacturing engineers are demanded not only to produce the products to meet the growing demand for higher quality and productivity but also to be responsible for achieving the sustainability in manufacturing. In metal cutting industries, the used cutting fluids after using for cooling and lubricating the contact zone contribute the largest amount of disposal (around 30%), which finally ends up as the contamination in the rivers leading to the water pollution [1]. Therefore, it is necessary to find the solutions to reduce or eliminate the usage of coolants. Over some last decades, there were numerous studies concerning the reduction of coolant usage in machining, and dry cutting processes, the truly environmental-friendly method, had drawn most attention and brought out the obvious cost benefits derived from the elimination and treatment of cutting fluids. However, the selection of the proper cutting tools or inserts plays a very important role to ensure the proper tool life and high precision and accuracy of machined parts [2], and it also causes a strong influence on technological and economic characteristics. Recently, to meet the continuously increasing demand for cutting difficult-to-cut materials having high-graded mechanical properties and high hardness, the tools with geometrically defined cutting edges are directly used for machining the heat-treated materials, with the typical hardness of 45–70 HRC [3]. These processes are called hard machining, which has become the research trend in mechanical applications due to high productivity and accuracy. Up to now, people have seen hard machining more in metal cutting field, and therefore many of traditional grinding processes have been replaced. The new approach not only provides the alternative solution for cutting hard materials but also improves the cutting performance, significantly reduces coolant usage, and has low machine tool investment. On the other hand, the thermal shock caused by the use of cutting fluids must be seriously considered to avoid the insert breakage, so the flood cooling is not usually used for hard machining processes, especially for interrupted cutting. Furthermore, the enormous heat and high forces arising from cutting zone are the most challenging problems of hard cutting processes, which always demand the appropriate uses of high-graded cutting tools like coated carbide, ceramic, polycrystalline cubic boron nitride (PCBN), and diamond inserts [2, 4, 5]. Accordingly, minimum quantity lubrication (MQL) technique was proposed and proven to use and exhibited the promising results in some last decades [1, 6, 7]. The cutting fluids in forms of oil mist are directly sprayed to cutting zone, so the lubricating effect is very high to decrease the friction coefficient, from which cutting forces, cutting temperature, and tool wear reduce significantly, and tool life is extended. Interestingly, the minimal use of cutting fluid makes MQL an environmental friendly technique, and the vegetable oils can be used for hard cutting, which contributes to protect environment [8]. The main drawback of MQL method is the low cooling effect, which limits the applicability and cutting performance of hard machining [9, 10]. In order to develop MQL technique, there have been many studies proposing the very promising solutions to enhance the cooling performance, which includes MQL using nanofluids, minimum quantity cooling lubrication (MQCL), and MQCL using nano additives. In this chapter, the authors mainly discuss the latest studies on those up-to-date techniques used in hard machining processes.

This chapter is divided into five sections. Section 1 of the chapter provides the literature review of new development of MQL and MQCL technology using nanofluids for sustainable cutting processes. Section 2 is dedicated to hard machining under MQL condition using nanofluid. Section 3 describes the application of MQCL condition based on the new approach for hard cutting processes. Section 4 contains the latest advances on the utilization of nano additives for improving MQCL hard machining performance. Finally, Section 5 draws out the conclusions and some suggestion for future work.

2. Hard machining under MQL condition using nanofluid

Using nano additives suspended in MQL based fluids has opened a new approach for machining difficult-to-cut materials and is also an up-to-date research topic gaining the growing concerns, especially for encountering climate change. There are many types of nanoparticles, such as Al_2O_3, MoS_2, SiO_2, ZrO_2, CuO, TiO_2, CNT, ND, and so on, proven to use for improving the tribological property, thermal conductivity, and viscosity [11].

2.1 The improvement of cutting performance

In order to apply this technique in machining practice, the parameters of MQL (the based fluid, air pressure, flow rate) and nanofluid (the type, size, and concentration of nanoparticles) are needed to study and optimize, because they have strong effects on the cutting process. If the inappropriate values of each parameter are chosen, the little effectiveness and even the negative influence may occur in machining responses.

Li et al. [12] investigated MQL grinding process for Ni-based alloy using six different types of nanofluids. The results indicated that the viscosity and thermal conductivity of nanofluids significantly improve when compared to the base fluids. The authors also pointed out that CNT nano additives exhibit the highest heat transfer coefficient. Hence, the cutting temperature and forces decrease. Another observation done by Ali et al. [13] indicated that the viscosity of Al_2O_3 and TiO_2 nano-lubricants increases while their kinematic viscosity decreases slightly. Through the experiments, the coefficient of friction, power consumption, and wear rate much reduced due to the rolling performance together with the formation of tribo-films created by Al_2O_3 nanoparticles. Moreover, the technical specification and concentration of nanoparticles play a very important role and strongly influence on the machining responses. For finish cutting, the nanoparticles with smaller grain size and higher concentration should be used to improve the surface quality and reduce the cutting forces [11]. Pashmforoush and his co-authors [14] reported that the big improvement in surface roughness in grinding process of Inconel 738 super alloy is about 62.16 and 36.36% compared to those of dry and flood conditions, respectively. The enhancement of lubricating effect was also reported in milling under MQL using MoS_2 nanofluid, from which the friction coefficient reduced to extend the tool life and improve the surface quality [15]. The presence of nanoparticles in MQL based fluid not only improves the cooling and lubricating effects but also brings out the better cutting performance for machining difficult-to-cut materials. Moreover, this approach will successfully replace the dry and flood conditions, which fulfill the technological, economic, and environmental requirements, suitable for modern manufacturing. The performance investigation of end milling of SKD 11 steel using HSS tools under nanofluid MQL was done in [16]. The experiments are set up and shown in **Figure 1**. The cutting condition includes the three values of cutting speeds of 18, 24, and 30 m/min, feed rate of 0.01 mm/tooth, and axial depth of cut of 3 mm. The diameter of end mill is 10 mm. Al_2O_3 nano additives (0.5 wt%.) are enriched in emulsion and soybean-based oil.

Through experimental results, the cutting force components F_x, F_y, and F_z when changing the cutting speeds and based fluid are shown in F**igures 2–4**. Under NFMQL with emulsion-based oil, the cutting forces F_x, F_y, and F_z reduce with the increase of cutting speed from 18 to 30 m/min. At a cutting speed of 30 m/min, the comparison between emulsion and soybean oil is made to find out the effect of the based fluid on machining responses. It can be clearly seen that the cutting forces reduce due to the better lubricating performance of soybean oil compared to emulsion fluid.

In addition, the tool life under NFMQL using soybean oil much improves and is over two times longer than that under the case using emulsion fluid (**Figure 5**). The investigation of tool wear is shown in **Figures 6–8**. They clearly reveal that notch wear and flank wear on HSS end mills increase with the rise of cutting

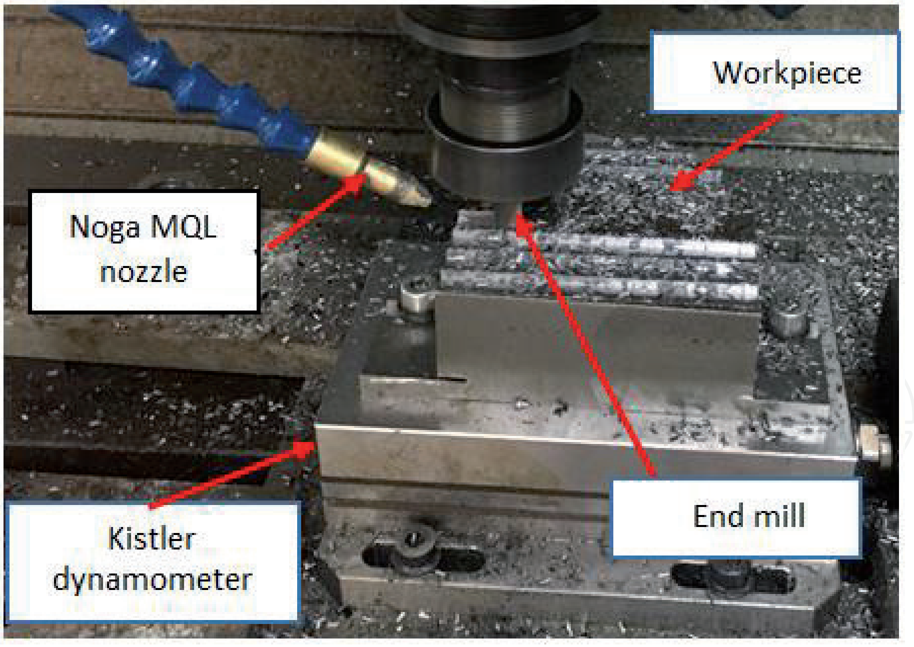

Figure 1.
Experimental setup [16].

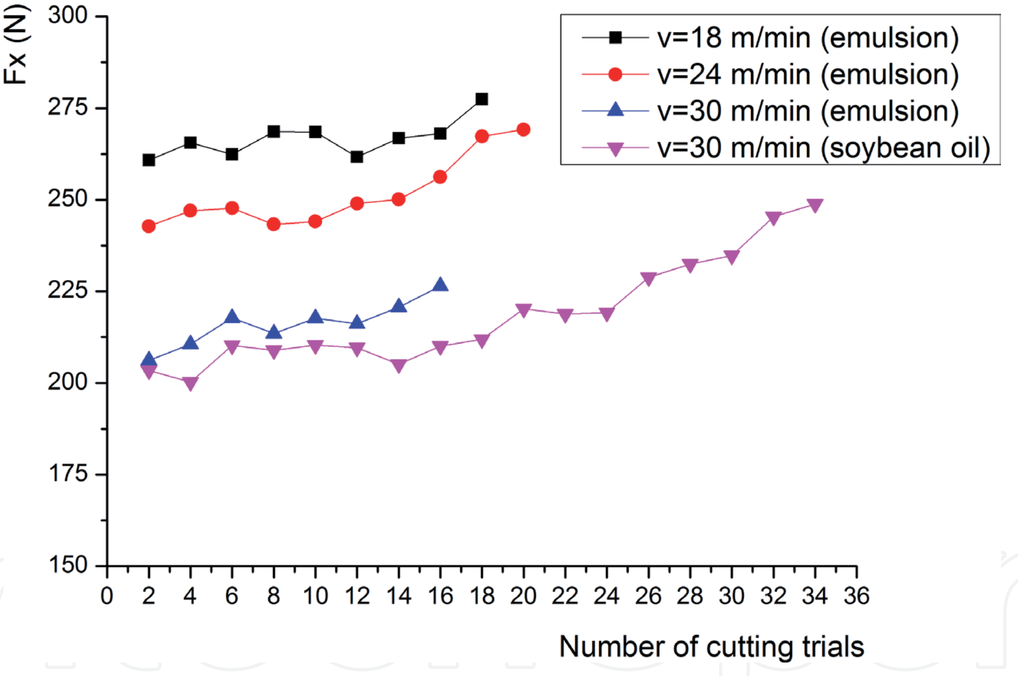

Figure 2.
The relation of cutting speeds and nanofluids to the cutting force F_x [16].

speeds from 18 to 30 m/min under MQL using emulsion. In addition to that, the burn marks caused by heat deterioration develop. It can be explained that SKD 11 tool steel has extremely high wear-resistant properties due to a high carbon and chromium (12% chrome) in chemical composition, from which it is grouped in difficult-to-cut material. In increasing the cutting speed from 18 to 30 m/min, MQL with emulsion-based fluid did not provide sufficient lubricating effects, so cutting temperature increased rapidly to damage end mills. In contrast, soybean oil has higher viscosity than that of emulsion, and the presence of Al_2O_3 nanoparticle additives contributes to improve the cooling and lubricating performance. Therefore, soybean oil-based nanofluid exhibits the superior lubricating effects to reduce friction coefficient in the cutting zone due to the easier formation of oil

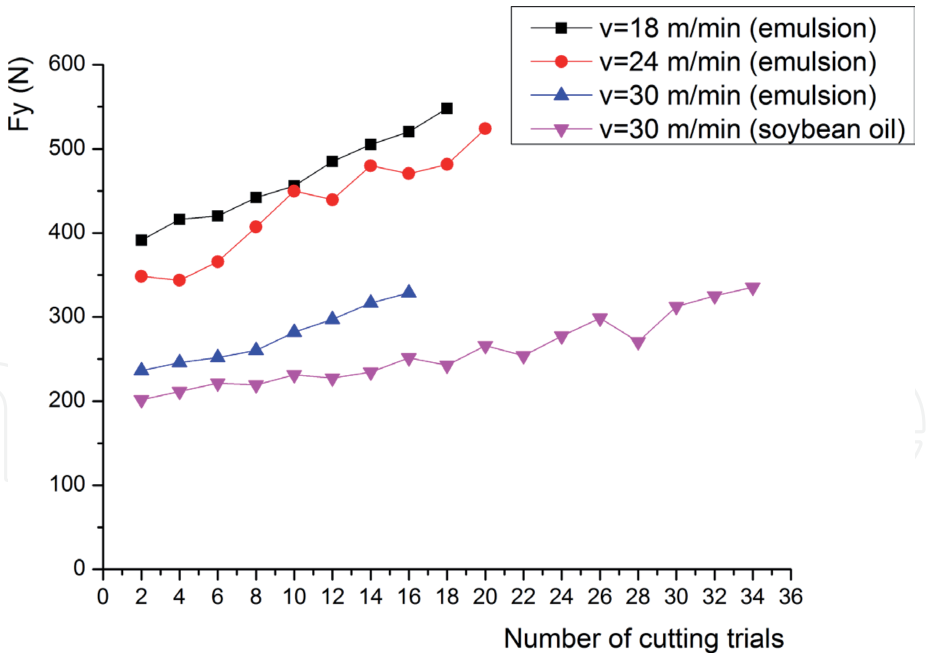

Figure 3.
The relation of cutting speeds and nanofluids to the cutting force F_y [16].

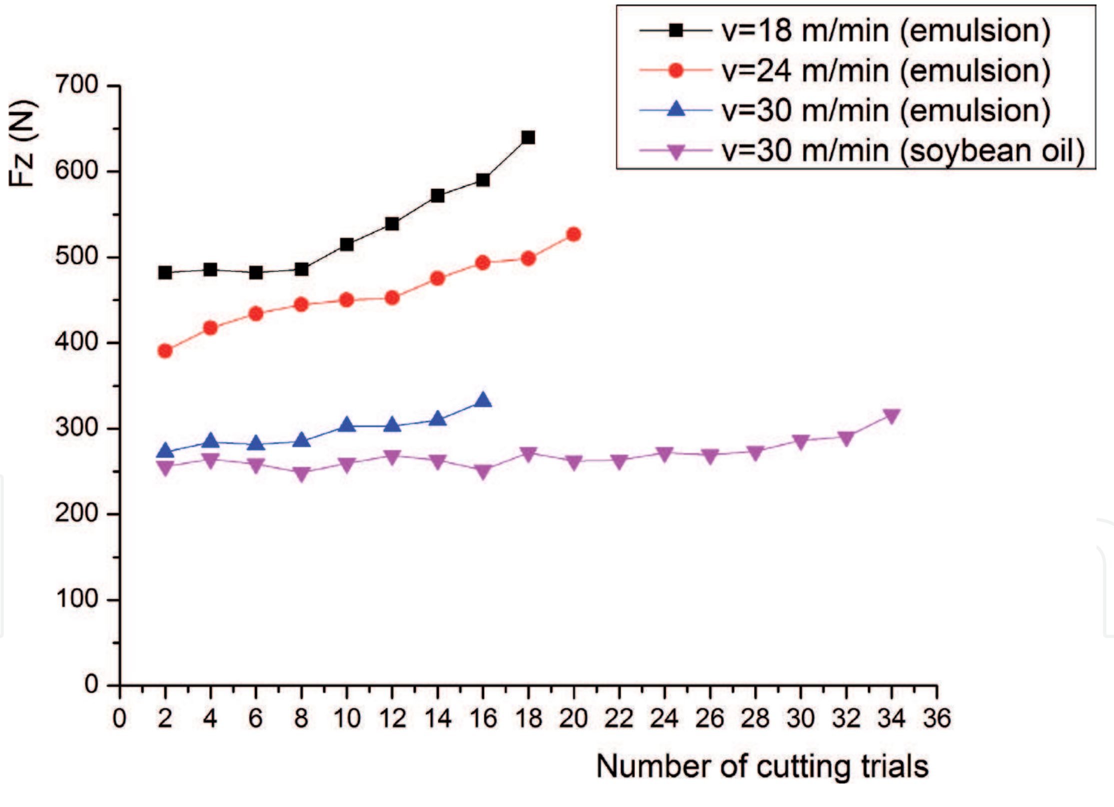

Figure 4.
The relation of cutting speeds and nanofluids to the cutting force F_z [16].

mist. In this study of end milling process of SKD 11 steel before heat treatment, cutting heat did not exceed the ignition temperature of soybean oil. That is the main reason why MQL using soybean-based nanofluid is better in this situation. Furthermore, Al_2O_3 nanoparticles with nearly sphere morphology suspended in oil mist as "the rollers" play an important role in improving cooling and lubricating effects. From those reasons, notch wear and flank wear on HSS end mills at cutting speed V_c = 30 m/min significantly reduce. Notch and flank wear lands after 85 min

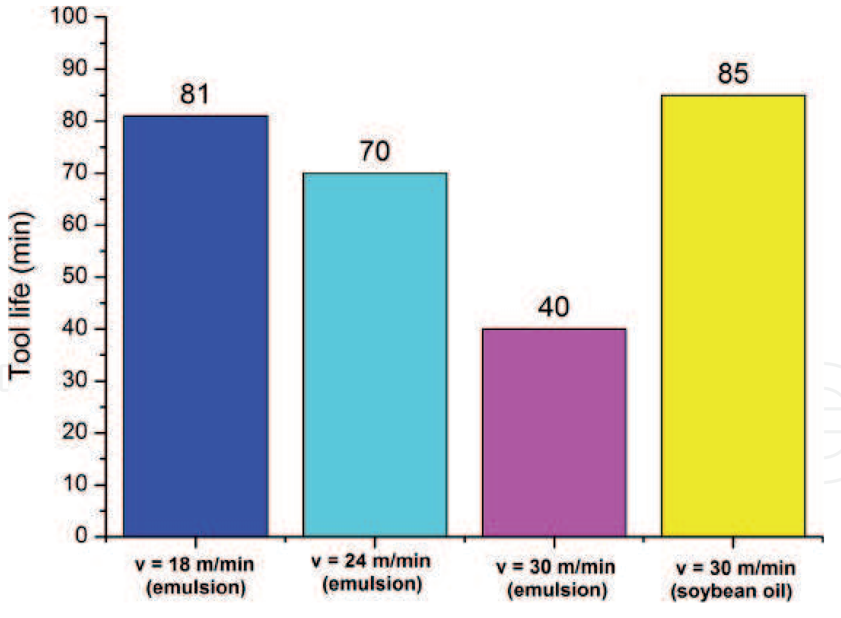

Figure 5.
The relation of cutting speeds and nano-cutting fluids to the tool life [16].

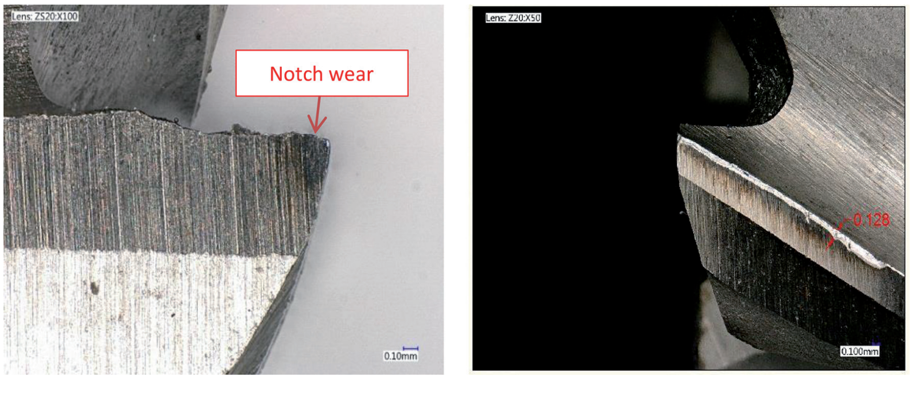

Figure 6.
Notch wear and flank wear (Vc = 18 m/min, emulsion-based nanofluid) [16].

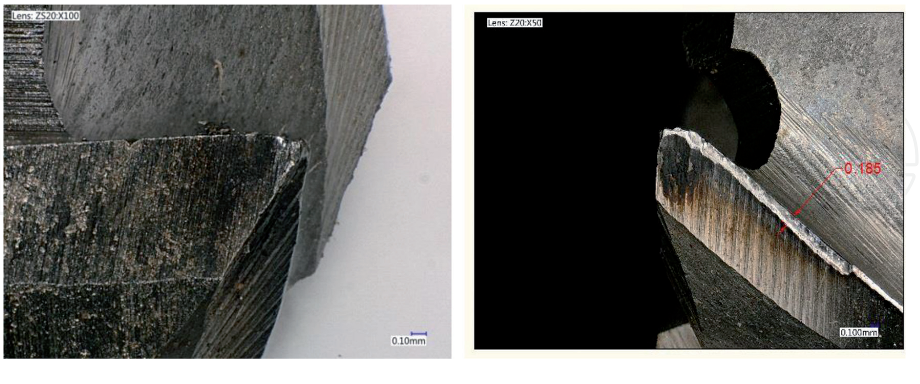

Figure 7.
Notch wear and flank wear (Vc = 24 m/min, emulsion-based nanofluid) [16].

of cutting are even lower than those of the case with MQL using emulsion-based nanofluid after 40 min of cutting (F**igures 8–9**). The significant reduction of burn marks indicates that the cooling and lubricating performance of soybean-based nanofluid is better and also suits for sustainable production due to the use of vegetable oil. Hence, tool life of end mill increases to 85 min even at cutting speed of 30 m/min, which is also higher than the manufacturers' recommendations [16]. According to ISO 8688-2:1989 (en) [17], the cutting speed for soft steels using

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Figure 8.
Notch wear and flank wear (Vc = 30 m/min, emulsion-based nanofluid) at 40 min [16].

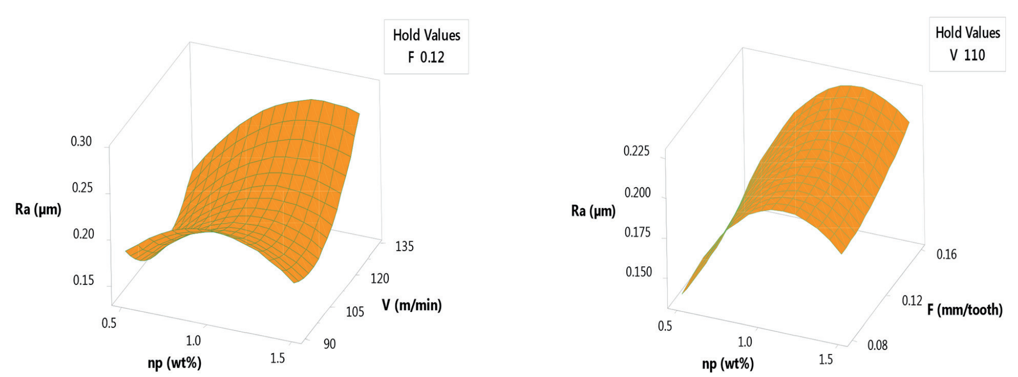
Figure 9.
Notch wear and flank wear (Vc = 30 m/min, soybean-based nanofluid) at 85 min [16].

normal HSS end mills is recommended about 30–35 m/min, but for difficult-to-cut steels like SKD 11, with hardness 200–250 HB, the cutting speed must be reduced to 14–18 m/min to ensure the proper cutting performance and tool life [18]. Moreover, the cutting speed also increases from 18 to 30 m/min by using MQL emulsion-based nanofluid, which reveals the better cooling and lubricating effects compared to the pure fluids.

2.2 The important parameter of MQL nanofluid

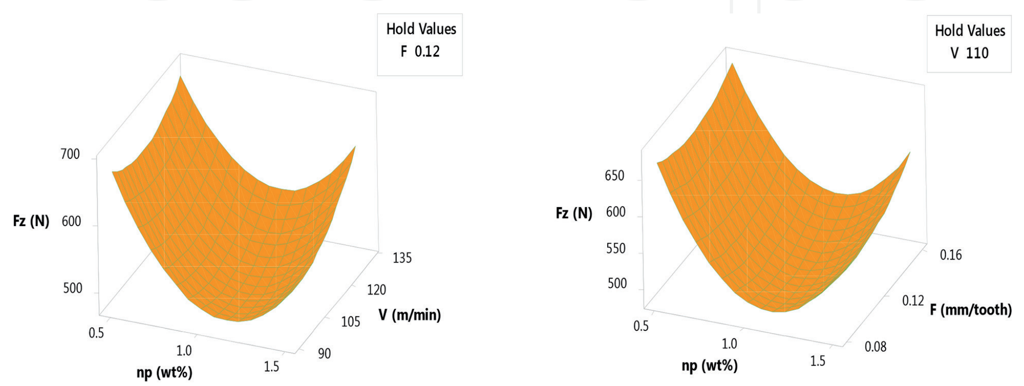
The concentration parameter of nanoparticles enriched in based fluids is among the most influential on machining outputs and costs, so it had been much studied to find out the appropriate and optimized values. Garg et al. [19] investigated the concentration effect of nanoparticles on micro-drilling process under MQL condition. The experimental results indicated that this parameter caused the significant reduction of drilling torque and power consumption. In the study of Lee et al. [20], the proper concentration of diamond nanoparticles was found with 0.05 wt%, from which the reduction of friction coefficient was observed by 23%. The authors concluded that diamond nanofluid provided the excellent anti-wear and lubricating effects. Zhang et al. [21] studied the concentration parameter of MoS_2 and CNT nano additives in MQL grinding. The improvement in lubricating performance contributes to increase surface quality. Furthermore, hybrid MoS_2-CNT nanofluids provided the superior cooling lubrication compared to that of the fluid with a single type of nanoparticles. Luo et al. [22] studied Al_2O_3 nanoparticles enriched in MQL based fluid and concluded that Al_2O_3 nanofluid exhibited good resistant ability for high temperature. Then, the cutting temperature is not high to cause the reduction of wear rate, which is much smaller than that of dry condition. Yıldırım et al. [23] had done the study of MQL turning process of the difficult-to-cut steel Inconel 625 using hBN nano additives. The better lubricating performance and surface roughness are reported from the obtained results, which led to reduce friction coefficient and wear rate. The authors also concluded that the optimal hBN nanoparticle concentration was 0.5 wt%. The experimental study on Al_2O_3 nanoparticle concentration used as MQL based fluid in hard milling had been done by using ANOVA analysis and response surface methodology (RSM), from which the research direction was made for optimizing the concentration variable [24]. F**igures 10–11** show the response surface plots of the relation of surface roughness and cutting force versus nano concentration (*np*), cutting speed V_c, and feed rate *F*. It can be clearly observed from **Figure 10** that, for better surface roughness, the low value of nanoparticle concentration about 0.5 wt% is more preferable than the larger ones (1.0 and 1.5 wt%). In contrast, the larger concentration (about 1.0 and 1.5 wt%) contributes to reduce the cutting forces and cutting temperature significantly when compared to the lower one (0.5 wt%.). From those, the wear rate much reduces by increasing the concentration of Al_2O_3 nanoparticles to 1.0–1.5 wt%, so the tool life prolongs (F**igures 12–15**). Accordingly, the nanoparticle concentration must be chosen not only to ensure the good tool life but also to maintain the high surface quality.

From **Figure 13**, the chip colors are well matched with the reduction of cutting temperature. The dark purple and blue colors in the case of using *np* = 0.5 wt% change to brown and dark straw one in the case of using *np* = 1.0–1.5 wt%, which indicates that cutting temperature decreases [25]. It can be concluded that the decrease of coefficient of friction and generated heat is reported by increasing



(a) (b)

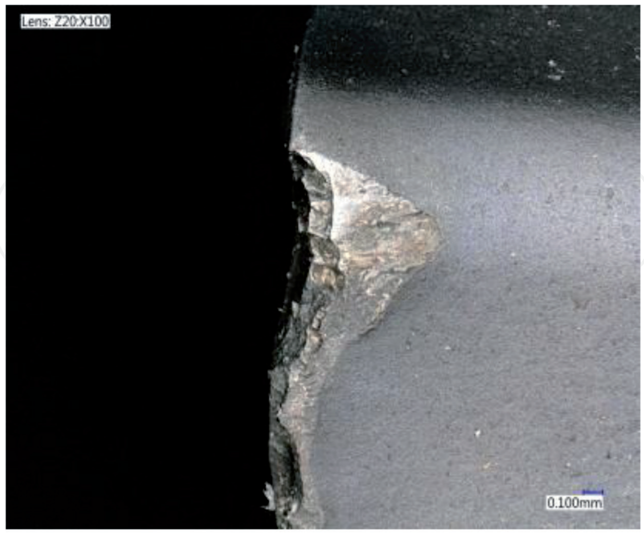
Figure 10.
Response surface plots of surface roughness versus nano concentration and cutting speed (a), and nano concentration and feed rate (b) [24].



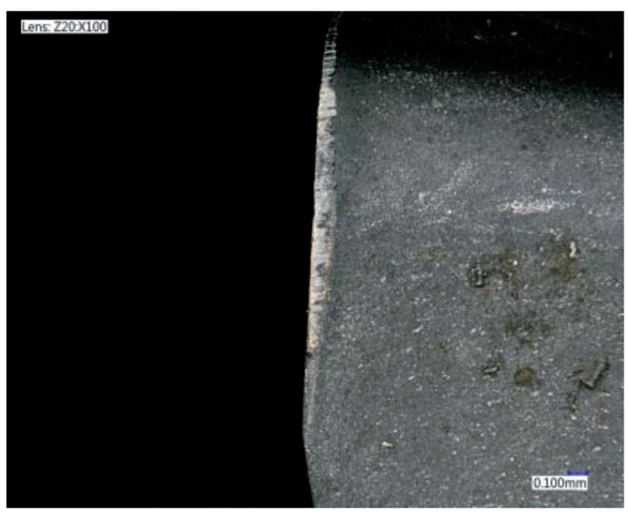
(a) (b)

Figure 11.
Response surface plots of cutting force F_z versus nano concentration and cutting speed (a), and nano concentration and feed rate (b) [24].

the concentration parameter of Al_2O_3 nanofluid, leading to reduce cutting forces and wear rate and prolong the tool life (**Figure 14**). From **Figure 15**, it clearly reveals that during the first 40 min, the values of surface roughness are higher when utilizing the high nanoparticle concentration (1.0–1.5 wt%). After that, the



(a)



(b)

(c)

Figure 12.
Wear on flank face under MQL using soybean-based nanofluid at 80 min using different nano concentrations: (a) 0.5 wt%, (b) 1.0 wt%, and (c) 1.5 wt% [24].

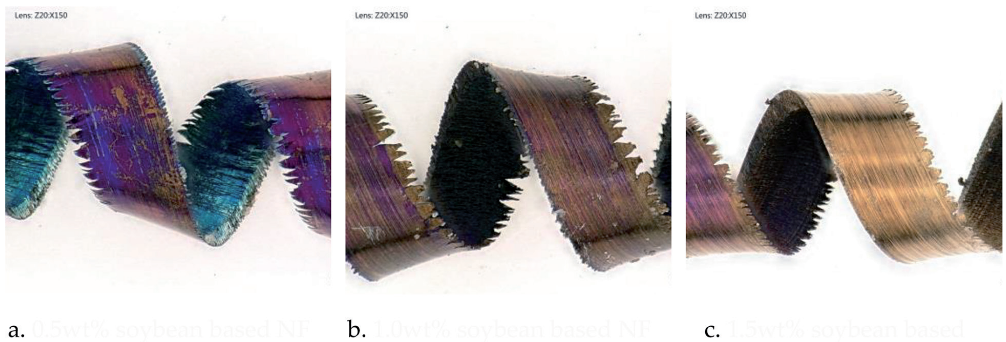


Figure 13.
Chip colors and micrographs with different Al_2O_3 nanoparticle concentrations (at 80 min): (a) 0.5 wt%, (b) 1.0 wt%, and (c) 1.5 wt% [24].

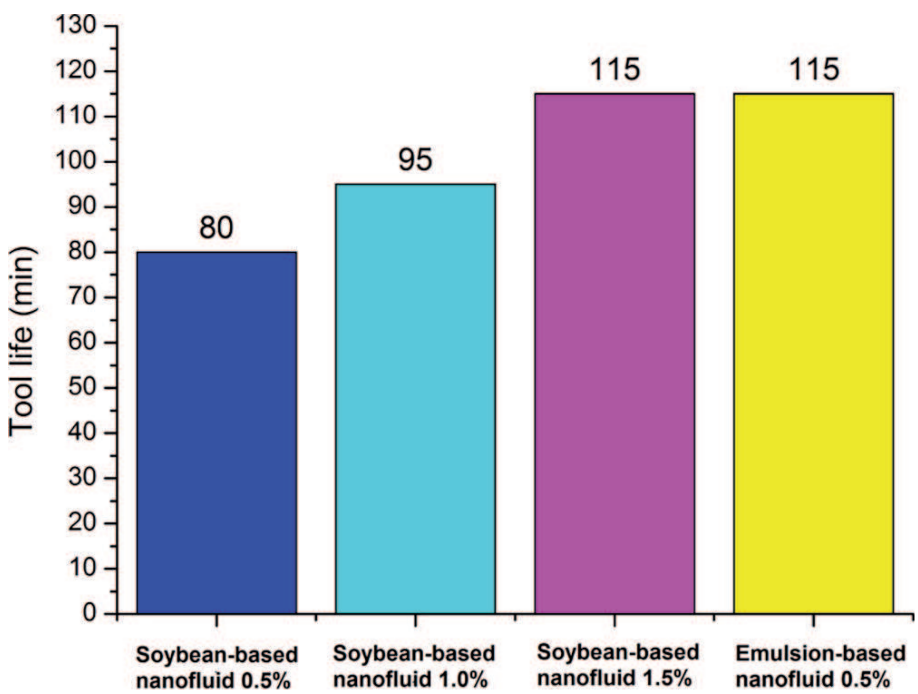


Figure 14.
Tool life with different Al_2O_3 nanoparticle concentrations [24].

rate of reduction of surface roughness values rapidly increases, which is contrary to the case of using 0.5 wt%. It is the novel observation obtained from the validation experiments, which is conducted until the tool life ends to see the actual phenomena after receiving the ANOVA and RSM results. Interestingly, the tool life in the case of soybean-based nanofluid 1.5 wt% is equal to that of emulsion-based nanofluid 0.5 wt%. It provides an important technical guide to enlarge the applicability of vegetable oil-based nanofluid in hard cutting processes as well as maintains its environmental-friendly characteristics.

However, each type of nanoparticles has its own specific morphology and property, so the appropriate or optimal concentration parameters are different [26]. This is the up-to-date research topic. Accordingly, more investigations are needed to make and build up the technical guides for manufacturers in machining practice, even though many studies have been done to optimize these variables. In order to develop MQL method, minimum quantity cooling lubrication (MQCL) has been considered as another promising approach to solve the low cooling performance, the main MQL drawback. It is also the newest research topic, which is discussed in Sections 3 and 4.

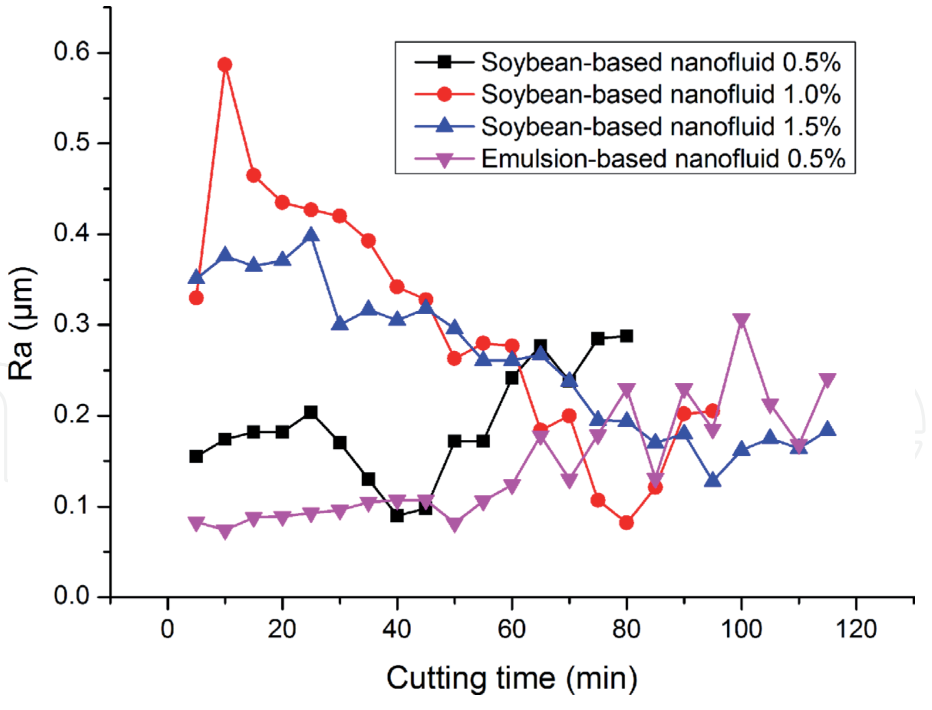


Figure 15.
Surface roughness Ra *with different Al_2O_3 nanoparticle concentrations [24].*

3. Hard machining under MQCL condition

The large amount of heat generated from hard cutting is always the big challenge for selecting cutting tools and cutting condition while ensuring the technical requirements, productivity, and proper manufacturing cost. Hence, providing appropriate cooling and lubricating effects to cutting zone plays a vital role in the development of hard machining processes. The applicability of those can be enlarged to some or all of the traditional grinding processes. MQCL technique has been proposed and developed to fulfill the cooling and lubricating requirements and is also a solution for improving MQL method. Up to now, MQCL has drawn much attention and has been studied in recent years. Maruda et al. [27, 28] made the study on MQCL parameters using emulsion-based fluid in hard turning process. The obtained results indicated that emulsion oil mist formed under MQCL condition plays an important role for improving the cooling lubricating performance in the cutting zone and increasing the cutting condition. The formation of tribo-films tends to occur easily with the droplets with smaller size, which help to decrease the coefficient of friction, cutting forces, and wear rate [29, 30]. The better cooling and lubricating effects of MQCL technique also reflect through the chip shape and the reduction of chip thickening coefficient [31]. Pervaiz and his co-authors [32] studied MQCL performance in the turning process of difficult-to-cut material Ti6Al4V. The author concluded that cutting forces and tool wear reduced and surface quality improved when compared to dry and flood conditions. It reveals the better cooling and lubricating effects of MQCL technique. Krolczyk together with his co-authors [33] investigated the parametric and nonparametric description of the surface topography under dry and MQCL conditions using emulsion-base fluid. The study results showed that the nozzle distance causes the strongest influence on droplet diameter. The most outstanding finding of this research is that parameters can be chosen for oil mist formation in a certain time, which is enough for creating cooling and lubricating effects and then evaporating due to generated heat from the cutting zone. Based on a brief review, it can be clearly seen that there is little information of MQCL technique and most of the studies relied on the based fluid having cooling effect like emulsion oil to form MQCL method. The use of a real cooling method assisted to MQL technique to form MQCL condition is a novel approach. In this section, the author presents the newest advances in using the principle of Ranque-Hilsch vortex tube for separating a compressed gas into hot and cold streams from ordinary air [34], in that the cold stream is used to create cooling effects combined with MQL method to form MQCL [35]. The deep study on hard milling of SKD 11 steel (52–60 HRC) in terms of surface quality under MQCL condition was done, and the results were compared to dry and MQL conditions. From **Figure 16**, hard milling under MQCL method brought out better surface roughness than those under dry and MQL conditions. The main reason is that MQCL technique provides sufficient cooling and lubricating effects, especially cooling effect, which helps to reduce the cutting temperature and tool wear.

KEYENCE VHX-6000 Digital Microscope (Keyence Corporation, Osaka, Japan) was utilized for studying surface microstructure and surface profile (**Figure 17**). The

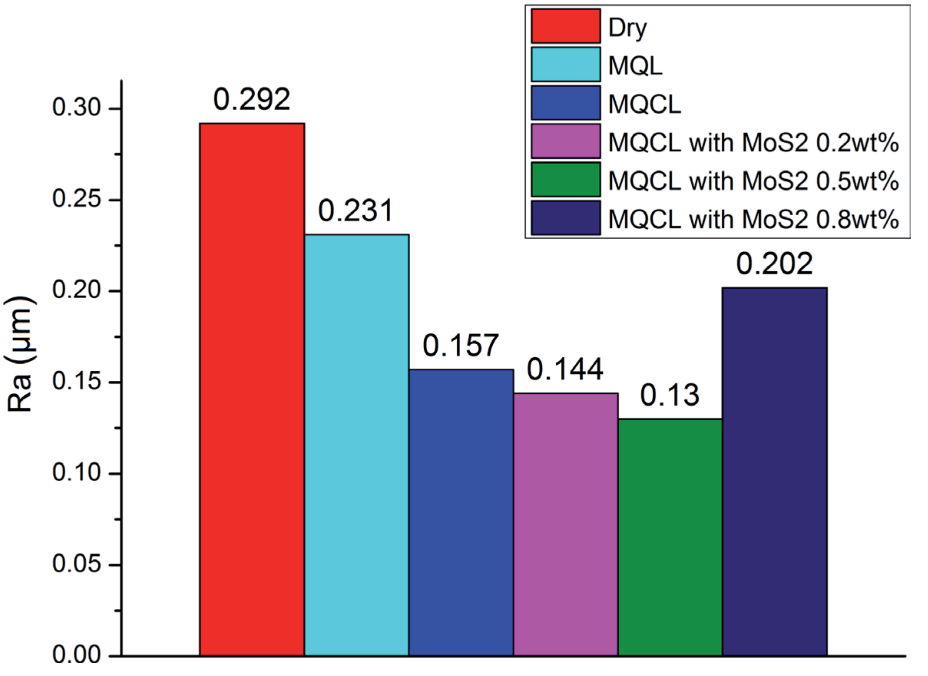
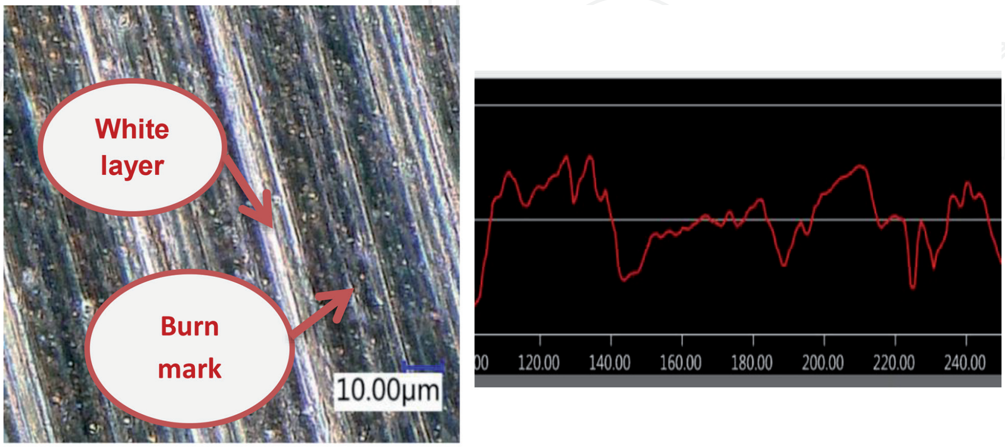


Figure 16.
The average values of surface roughness Ra under different cooling and lubricating conditions (cutting speed Vc = 110 m/min, feed rate F = 0.012 mm/tooth, depth of cut d = 0.12 mm, hardness of 56 HRC) [35].

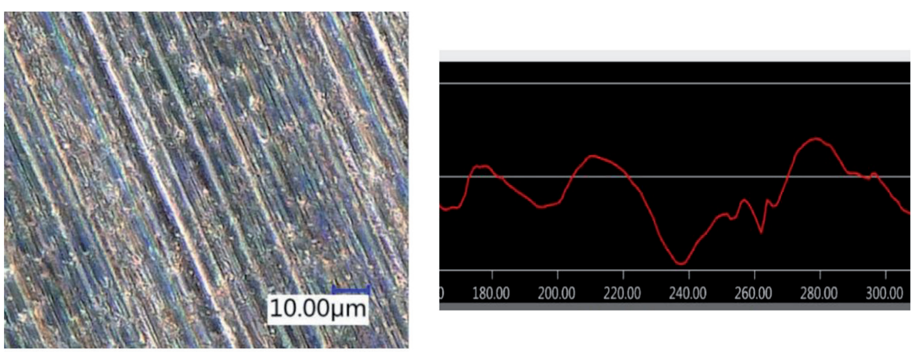
Figure 17.
KEYENCE VHX-6000 digital microscope for studying machined surface topography.

machined surfaces under different cooling and lubricating conditions are investigated (Figures **18–22**). The white layer and burn marks significantly reduced under MQL and MQCL conditions compared to dry cutting because of cooling and lubricating enhancement. The burn marks under MQCL condition are less than those under MQL method due to better cooling performance (**Figures 19(a), 20(a)**). In addition, compared to dry and MQL conditions, the compression of machined surface observed from the surface profile much reduces (**Figures 18(b), 19(b), 20(b)**).



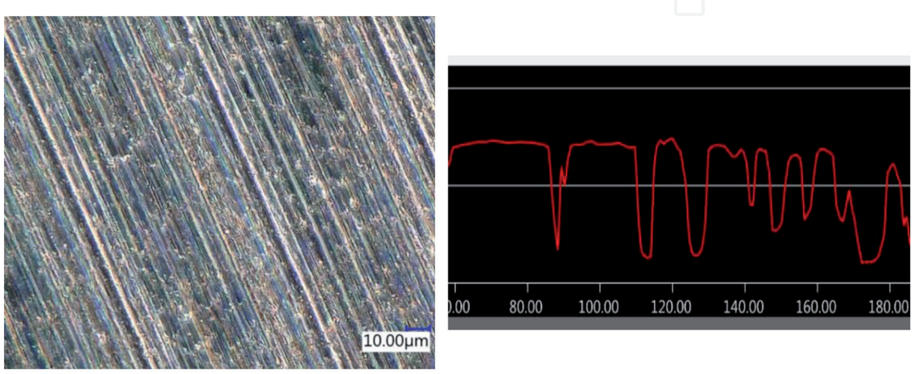
(a) (b)

Figure 18.
Surface microstructure (a) and profile (b) under dry condition [35].



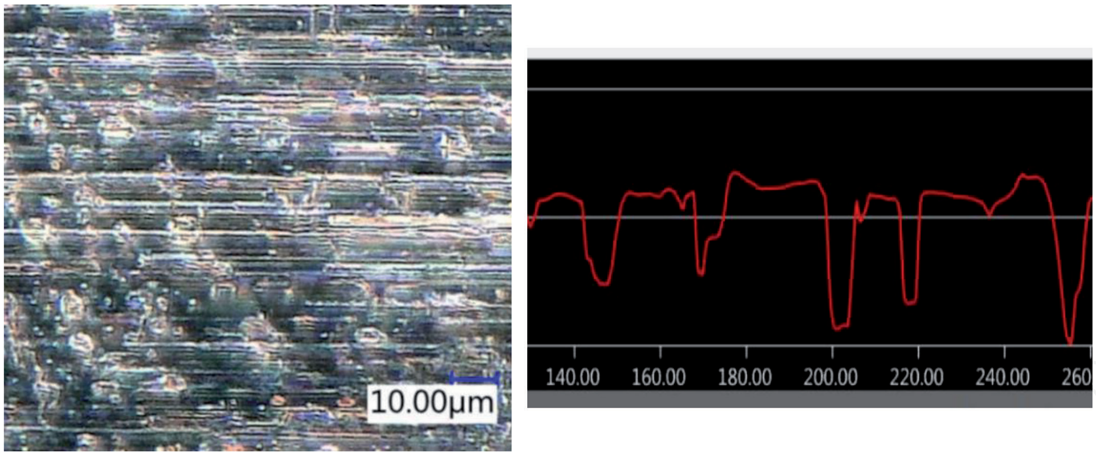
(a) (b)

Figure 19.
Surface microstructure (a) and profile (b) under MQL condition [35].



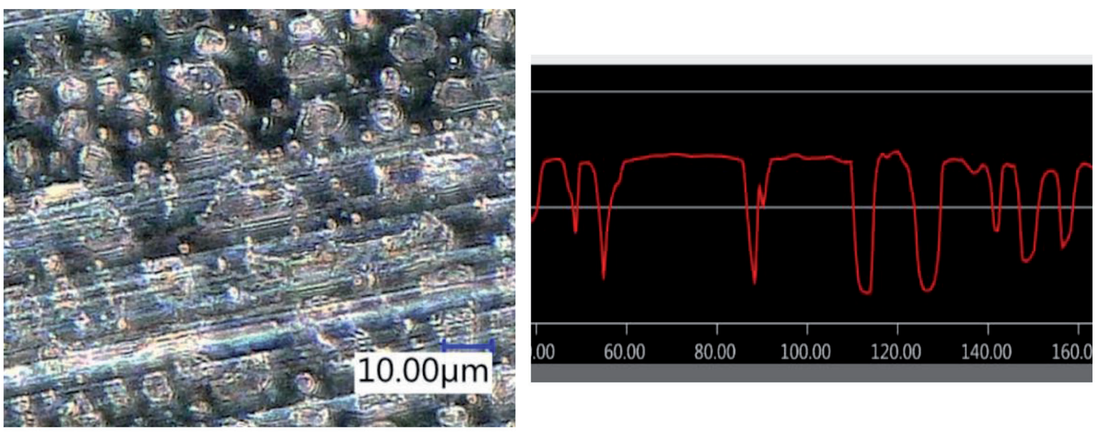
(a) (b)

Figure 20.
Surface microstructure (a) and profile (b) under MQCL condition using pure emulsion-based fluid [35].



(a) (b)

Figure 21.
Surface microstructure (a) and profile (b) under MQCL condition using emulsion-based nanofluid of MoS_2 0.2 wt% [35].



(a) (b)

Figure 22.
Surface microstructure (a) and profile (b) under MQCL condition using emulsion-based nanofluid of MoS_2 0.5 wt% [35].

4. MQCL hard machining using nanofluids

The nanofluids used for MQL are successfully proven to be an alternative solution for difficult-to-cut materials while maintaining its environmental friendly property. Based on this idea, the use of nano additives in MQCL method will bring out the promising solution to increase the hard machining performance. The study of surface quality under MQCL using MoS_2 nanofluid for hard milling is the first attempt to investigate the cooling and lubricating effects [35]. From the obtained results, the values of surface roughness R_a under MQCL using nanofluids are lower than those of dry and MQL conditions. By using MoS_2 nanoparticle concentration of 0.2 and 0.5 wt%, surface roughness is even slightly better than that of MQCL with pure fluid, but the R_a value rapidly increases when increasing the concentration to 0.8 wt%. It can be explained that the morphology of MoS_2 nanoparticles is ellipsoidal with the low friction coefficient up to 0.03–0.05 or even lower [36], by which the better lubricating effect contributes to improve the surface quality. On the other hand, nanoparticles possess the large surface area, which remain on the machined surface to form a thin protective film, which amplifies with the increase of MoS_2 nanoparticle concentration [37]. Furthermore, it also contributes to form MoS_2 tribo-film easily [29], which can be observed from the so-called microbubbles on the machined surface (F**igures 21–22**). The protective film reduces and disappears when increasing the concentration to 0.8%, which causes the negative effect on surface quality [37]. Moreover, the white layer and burn marks are much reduced due to superior cooling and lubricating performance under MQCL condition using nanofluid. From those, the hard machining ability of normal carbide tools improves significantly and is about 157% higher than manufacturer's recommendations [38, 39]. It is the most outstanding finding of this research, and also the proper MoS_2 nanoparticle concentration in emulsion-based fluid was reported about 0.2 and 0.5 wt%, which provides a very important technical guide for further researches and manufacturers. More investigations are necessary to be made for building up technical guidelines and optimizing nanofluid parameters.

5. Conclusion

The application of nanofluids continues to receive growing attention in basic science and machining technology. As shown, nano additives in based fluid of MQL and MQCL methods improve the cooling and lubricating effects as well as tribological property, thus increasing the cutting performance, especially for difficult-to-cut materials. It brings out the alternative solutions for improving productivity and reducing manufacturing cost. From those, the applicability MQL technique having environmental friendly characteristic has been enlarged in hard machining. Furthermore, the use of different types of vegetable oils can fulfill the cooling and lubricating performance by suspending nanoparticles, which is an interesting research topic and exhibits very promising results. On the other hand, MQCL has been considered as another approach for MQL development to overcome the low cooling effect. In this chapter, Ranque-Hilsch vortex tube, a real cooling method, used for creating cooling effect from ordinary compressed air rather than other gas sources to form MQCL method, is the first attempt applied to hard cutting processes. Also, nano additives enriched in MQCL-based fluids are the latest advances in the field of studying MQL and MQCL techniques. The parameters of nanofluid, such as types and size of nanoparticles, concentration, and based fluid, play a key role in successful applications in metal cutting practice, and more studies are needed to make further development and optimize those variables. Those superior cooling and lubricating methods presented in this chapter will contribute to the solutions to reduce/eliminate the cutting fluids and replace dry and wet conditions. It is suitable for protecting our environment and aims for a sustainable production. In the future work, more attention will be paid on other types of nanoparticles, concentration, and parameters of MQL and MQCL methods.

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Conflict of interest

The authors declare no conflict of interest.

Acronyms and abbreviations

d	depth of cut (mm)
V_c	cutting speed (m/min)
F	feed rate (mm/tooth)
F	cutting force (N)
HSS	high speed steel
hBN	hexagonal boron nitride
CNTs	carbon nanotubes
MQL	minimum quantity lubrication
MQCL	minimum quantity cooling lubrication
NFMQL	nanofluid minimum quantity lubrication
ND	nanodiamond
NF	nanofluid
NFs	nanofluids
NP	nanoparticle
NPs	nanoparticles
ANOVA	analysis of variance

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References

[1] Byrne G, Dornfeld D, Denkena B. Advancing cutting technology. CIRP Annals. 2003;**52**(2):483-507

[2] Zhang K, Deng J, Meng R, Gao P, Yue H. Effect of nano-scale textures on cutting performance of WC/Co-based Ti55Al45N coated tools in dry cutting. International Journal of Refractory Metals and Hard Materials. 2015;**51**:35-49

[3] Paulo DJ. Machining of Hard Materials. London: Springer-Verlag London Limited; 2011

[4] Kumar CS, Patel SK. Effect of WEDM surface texturing on Al2O3/TiCN composite ceramic tools in dry cutting of hardened steel. Ceramics International. 2018;**44**:2510-2523

[5] Su Y, Li Z, Li L, Wang J, Gao H, Wang G. Cutting performance of micro-textured polycrystalline diamond tool in dry cutting. Journal of Manufacturing Processes. 2017;**27**:1-7

[6] S N, G.L S. Drilling performance of micro textured tools under dry, wet and MQL condition. Journal of Manufacturing Processes. 2018;**32**:254-268. DOI: 10.1016/j.jmapro.2018.02.012

[7] Minh DT, The LT. Investigation of MQL-employed hard-milling process of S60C steel using coated-cemented carbide tools. Journal of Mechanics Engineering and Automation. 2016;**6**:128-132

[8] Rahim EA, Sasahara H. A study of the effect of palm oil as MQL lubricant on high speed drilling of titanium alloys. Tribology International. 2011;**44**:309-317

[9] Duc TM, Long TT, Ngoc TB. Performance of Al_2O_3 nanofluids in minimum quantity lubrication in hard milling of $60Si_2Mn$ steel using cemented carbide tools. Advances in Mechanical Engineering. 2017;**9**:1-9

[10] Long TT, Duc TM. Micro/Nanofluids in Sustainable Machining. In: Microfluidics and Nanofluidics. London, UK: IntechOpen; 2018

[11] Lee P-H, Nam JS, Li C, Lee SW. An experimental study on micro-grinding process with nanofluid minimum quantity lubrication (MQL). International Journal of Precision Engineering and Manufacturing. 2012;**13**:331-338

[12] Li B, Li C, Zhang Y, Wang Y, Jia D, Yang M, et al. Heat transfer performance of MQL grinding with different nanofluids for Ni-based alloys using vegetable oil. Journal of Cleaner Production. 2017;**154**:1-11

[13] Ali MKA, Hou X, Mai L, Cai Q, Turkson RF, Chen B. Improving the tribological characteristics of piston ring assembly in automotive engines using Al_2O_3 and TiO_2 nanomaterials as nano-lubricant additives. Tribology International. 2016;**103**:540-554

[14] Pashmforoush F, Bagherinia RD. Influence of water-based copper nanofluid on wheel loading and surface roughness during grinding of Inconel 738 superalloy. Journal of Cleaner Production. 2018;**178**:363-372

[15] Uysal A, Demiren F, Altan E. Applying minimum quantity lubrication (MQL) method on milling of martensitic stainless steel by using nano MoS_2 reinforced vegetable cutting fluid. Procedia - Social and Behavioral Sciences. 2015;**195**:2742-2747

[16] Duc TM, Long TT, Ngoc TB. Effectiveness of alumina nanofluid on slotting end milling performance of SKD 11 tool steel. Journal of Computational and Applied Research in Mechanical Engineering. 2019. DOI: 10.22061/JCARME.2019.4041.1484

[17] ISO 8688-2:1989 (en). Tool life testing in milling — Part 2: End milling; 1989. pp. 9-14

[18] Duc TM, Dong PQ. Influence of coolant fluid and method on tool wear, tool life and the surface roughness in slot machining using end mills. Journal of Science and Technology Technical Universities. 2008;**65**:55-58

[19] Garg A, Sarma S, Panda B, Zhang J, Gao L. Study of effect of nanofluid concentration on response characteristics of machining process for cleaner production. Journal of Cleaner Production. 2016;**135**:476-489

[20] Lee G-J, Park J-J, Lee M-K, Rhee CK. Stable dispersion of nanodiamonds in oil and their tribological properties as lubricant additives. Applied Surface Science. 2017;**415**:24-27

[21] Zhang Y, Li C, Jia D, Li B, Wang Y, Yang M, et al. Experimental study on the effect of nanoparticle concentration on the lubricating property of nanofluids for MQL grinding of Ni-based alloy. Journal of Materials Processing Technology. 2016;**232**:100-115

[22] Luo T, Wei X, Huang X, Huang L, Yang F. Tribological properties of Al_2O_3 nanoparticles as lubricating oil additives. Ceramics International. 2014;**40**:7143-7149

[23] Yıldırım ÇV, Sarıkaya M, Kıvak T, Şirin Ş. The effect of addition of hBN nanoparticles to nanofluid-MQL on tool wear patterns, tool life, roughness and temperature in turning of Ni-based Inconel 625. Tribology International. **2019**;***134***:443-456

[24] Duc TM, Long TT, Dong PQ. Effect of the alumina nanofluid concentration on minimum quantity lubrication hard machining for sustainable production. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. 2019;**233**(17):5977-5988. DOI: 10.1177/0954406219861992

[25] Oberg E, Jones F, Horton H, Ryffel H, McCauley C. Machinery's Handbook. 30th Edition, Toolbox ed. United States: Industrial Press; 2016. ISBN: 9780831130916

[26] Duc TM, Long TT, Chien TQ. Performance evaluation of MQL parameters using Al_2O_3 and MoS_2 nanofluids in hard turning 90CrSi steel. Lubricants. 2019;**7**(5):1-17. DOI: 10.3390/lubricants7050040

[27] Maruda RW, Krolczyk GM, Feldshtein E, Nieslony P, Tyliszczak B, Pusavec F. Tool wear characterizations in finish turning of AISI 1045 carbon steel for MQCL conditions. Wear. 2017;**372**:54-67

[28] Maruda RW, Krolczyk GM, Feldshtein E, Pusavec F, Szydlowski M, Legutko S, et al. A study on droplets sizes, their distribution and heat exchange for minimum quantity cooling lubrication (MQCL). International Journal of Machine Tools and Manufacture. 2016;**100**: 81-92

[29] Maruda RW, Krolczyk GM, Wojciechowski S, Zak K, Habrat W, Nieslony P. Effects of extreme pressure and anti-wear additives on surface topography and tool wear during MQCL turning of AISI 1045 steel. Journal of Mechanical Science and Technology. 2018;**32**:1585-1591

[30] Maruda RW, Feldshtein E, Legutko S, Krolczyk GM. Research on emulsion mist generation in the conditions of minimum quantity cooling lubrication (MQCL). Tehnicki Vjesnik. 2015;**22**:1213-1218

[31] Maruda R, Krolczyk G, Niesłony P, Krolczyk J, Legutko S, Krolczyk G. Chip

formation zone analysis during the turning of austenitic stainless steel 316L under MQCL cooling condition. Procedia Engineering. 2016;**149**:297-304

[32] Pervaiz S, Deiab I, Rashid A, Nicolescu M. Minimal quantity cooling lubrication in turning of Ti6Al4V: Influence on surface roughness, cutting force and tool wear. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture. 2017;**231**:1542-1558. DOI: 10.1177/0954405415599946

[33] Krolczyk G, Maruda R, Krolczyk J, Nieslony P, Wojciechowski S, Legutko S. Parametric and nonparametric description of the surface topography in the dry and MQCL cutting conditions. Measurement. 2018;**121**:225-239

[34] Hilsch R. The use of the expansion of gases in a centrifugal field as cooling process. The Review of Scientific Instruments. 1947;**18**(2):108-113

[35] Dong PQ, Duc TM, Long TT. Performance evaluation of MQCL hard milling of SKD 11 tool steel using MoS_2 nanofluid. Metals. 2019;**9**:658. DOI: 10. 3390/met9060658

[36] Wang Y, Li C, Zhang Y, Li B, Yang M, Zhang X, et al. Experimental evaluation of the lubrication properties of the wheel/workpiece interface in MQL grinding with different nanofluids. Tribology International. 2016;**99**:198-210

[37] Rahmati B, Sarhan AA, Sayuti M. Morphology of surface generated by end milling AL6061-T6 using molybdenum disulfide (MoS2) nanolubrication in end milling machining. Journal of Cleaner Production. 2014;**66**:685-691

[38] Available from: https://wix.laminatech.ch/img/catalog/1237.pdf

[39] Duc TM, Long TT, Dong PQ, Ngoc TB. Applied research of Nanofluids in MQL to improve hard milling performance of $60Si_2Mn$ steel using carbide tools. American Journal of Mechanical Engineering. 2017;**5**(5):228-233. DOI: 10.12691/ajme-5-5-6