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Chapter 7

Micro/Nanofluids in Sustainable Machining

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Additional information is available at the end of the chapter

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Abstract

Micro/nanofluids are the recent alternative solutions for cooling lubrication that can be defined as the fluids containing microparticles or nanoparticles, which own superior lubrication and cooling characteristics. For these reasons, they have gained significant attention in industrial applications, such as automotive, machining, and biomedical industries. In this chapter, the authors mainly present the recent progress and applications of nanofluids in machining processes, as well as some initial researches about microfluids. Nanofluids provide an excellent media in cutting zone for enhancing the thermal conductivity and tribological characteristics. Therefore, they help to enhance the cutting performance by reducing the coefficient of friction, cutting temperature tool wear, and improving the surface quality. Moreover, the application of nanoparticles in vegetable oils, which are inherently nontoxic as well as biodegradable, gives them superior lubrication properties suitable for MQL application, especially for difficult-to-cut materials. The novel green technology definitely brings out many new solutions in machining practice.

Keywords: micro/nanofluids, nanofluid, sustainable machining, MQL, hard machining, vegetable oil, cutting

1. Introduction

Nanofluids are suspensions of nanoparticles in fluids that show significant enhancement of their thermophysical properties with proper volumetric fraction of nanoparticles. Much of the research on nanofluids are about understanding their behavior, so that they can be utilized effectively as an alternative solutions in many industrial applications, nuclear reactors, transportation, electronics, machining, as well as biomedicine and food [1].

Environmental friendliness has become one of the biggest issues in modern industry worldwide, especially in machining industry. In addition, recent regulations on environmental problems,

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such as ISO 14000 and Green Round, have become much stricter for promoting green manufacturing approaches. The necessity of reducing environmental loads should be increasingly considered, and many green manufacturing processes have been developed and studied.

According to the statistics of cost distribution in manufacturing shown in **Figure 1**, the coolant expense for usage and disposal represents about 15% of total production costs, depending on the workpart and the types of cooling system, as well as machining location [3]. In contrast, tooling cost contributes only a small value of 4%. On the other hand, health and environmental issues associated with the airborne cutting fluid particles on factory shop floors motivate manufacturing enterprises to drastically reduce coolant consumption and, if possible, eliminate it altogether.

As a result, the conception of dry cutting has been first considered to achieve environmental friendliness. Eliminating the cutting fluids in machining processes means that there is no cooling lubricating media, which has three essential functions (i.e., reduction of friction, absorption of the generated heat, and chip evacuation). Hence, these following problems must be considered:

- Workpart: deteriorate surface texture and need additional works (cleaning or deburring)
- Cutting tool: difficulty in chip formation, reduction of tool life or change to expensive ones
- Machine tool: high rigidity, equipment specialized in pushing chips away from the cutting zone as well as controlling temperature

Especially in cases of machining difficult-to-machine materials like high-strength and high-hardness steels, solving the mentioned problems has strong influence on leading industrial branches as automotive, roller bearing, hydraulic, and die and mold sectors. The term "hard machining" is a recent technology that can be defined as the machining operation of a workpiece that has a hardness value typically in the 45–70 HRC range, using directly tools with geometrically defined cutting edges [5]. Hard-cutting operations are capable of replacing, in some cases, grinding operations and produce comparable surface finish. Various machining operations in hard machining include milling, boring, broaching, hobbling, and others. Together

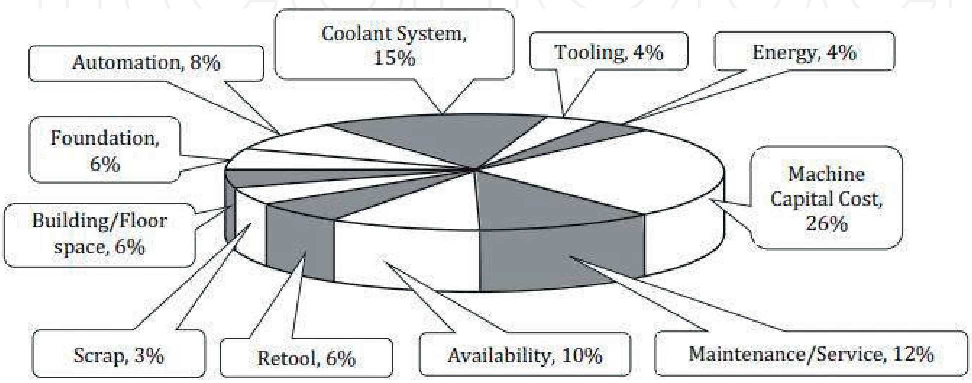

Figure 1. Distribution of manufacturing costs for wet machining [2].

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with the developments of suitable rigid machine tools, superhard cutting-tool materials and special tool (toolholders) designs, and complete set-ups, the machining of hardened parts has become more easily accessible and widely applied for the modern machining industry. However, the challenge of selecting a cutting-tool insert to ensure tool life and high-precision machining of the component is the main problem, which slows down the development and application of hard machining. Since its broader introduction in the mid-1980s in the form of hard turning, people have seen that the cutting inserts, such as coated carbides (PVD (Ti, Al) N–TiN and CVD Ti(C, N)–Al_2O_3-coated tools, etc.), ceramics, and (P)CBN, are widely utilized in various dry hard cutting processes.

Without cooling lubricating media, the enormous amount of heat generated from cutting zone remains a big question, which limits the cutting condition, reduces the tool life, and deteriorates the surface finish (i.e., the so-called "white layer" formation in hard machining). This problem has promoted the development of minimum quantity lubrication (MQL) using a special nozzle to form oil mist directly supplied to the machining interface with a tiny amount of fluid consumption (5–500 ml/hr). Because the cutting fluid mostly vaporizes and leaves dry chips, it brings out cost effective and green machining [4]. The very small amount of cutting fluids is utilized and delivered effectively to cutting zone, and the formation of oil films in contact faces plays an important role in lubrication [7]. Numerous publications have been reported on the effectiveness of the MQL technique for enhancing cutting performance [2, 4, 6, 7]. However, the main drawback of MQL technology is low cooling effect, and so it does not work so well in cutting difficult-to-machine materials with high strengths and hardness. To improve the MQL technology, nanofluids containing nanoparticles (Al_2O_3, MoS_2, SiO_2, CuO, diamond, and so forth) with at least one of their principal dimensions smaller than 100 nm [3] used in MQL technique recently reach a significant attention of worldwide researchers and are up-to-date topics to increase the cutting performance and productivity.

2. The effects of nanofluids on machining processes

The applications of nanofluids for MQL machining have been proven to improve the interaction of friction in cutting zone due to the occurrence of nanoparticles. However, the direct evaluation of cutting performance faces many difficulties, and so numerous publications are focused on the indirect evaluation through machining outputs such as cutting forces, cutting temperature, tool wear, tool life, and surface integrity. In this section, the recent studies related to the effects of nanofluids on machining performance will be discussed.

2.1. Thermal properties of nanofluids

From previous investigations, nanofluids have been found to possess enhanced thermophysical properties such as thermal conductivity, thermal diffusivity, viscosity, and convective heat transfer coefficients. The thermal conductivity of more than 50 various nanofluids based on water, ethylene glycol, and engine oil containing particles of SiO_2, Al_2O_3, TiO_2, ZrO_2, CuO, and diamond was experimentally measured [8]. The obtained results had shown that the thermal conductivity coefficient of nanofluids enhances with increasing particle sizes. It has been confirmed that the lower the thermal conductivity of the base fluid, the higher the relative thermal conductivity coefficient of the nanofluids. The different researches have made to investigate convective heat transfer of nanofluids [10]. Based on the results, augmenting nanofluid volume fraction, Rayleigh and Magnetic numbers lead to improve of the temperature gradient, while it reduces with augment of Lorentz forces. Heat transfer improvement augments with increase in Kelvin forces, while it reduces with augment of Lorentz forces at high Rayleigh number, but different manners are detected for low Rayleigh number. The active method for nanofluid heat transfer enhancement by means of EHD was also studied [10]. The obtained results suggest that influence of electric field on forced convection improvement is more sensible for lower *Re* number. Temperature gradient enhances with rise of voltage supply. Moreover, throughout the experimental results, the convective heat transfer increases with the presence of nanoparticles in the base fluids [11, 12, 21, 27]. Based on the newest publications, the deeper understanding about thermal properties of NFs is studied. The shapes of NPs are proven to influence on the rate of heat transfer, and the effect of thermal radiation on CuO nanofluid behavior is successfully modeled via Control Volume–based Finite Element Method (CVFEM). Platelet shape nanoparticles reveal the highest heat transfer rate [22, 25, 28, 29]. Nanofluid motion, as well as flow circulation and thermal energy transport, enhances by increasing the volume fraction of NPs [23, 24, 26]. A novel research of melting temperature of CuO-water NF heat transfer enhancement is simulated by CVFEM. The highlighted results include (1) flow velocity of NF increases due to the presence of CuO nanoparticles; (2) heat transfer enhancement of NF improves at higher nanoconcentrations; (3) melting temperature rises with the increment of nanovolume fraction [30, 31, 33]. The same observations were obtained from the study of Fe_3O_4-water nanofluid [32, 34]. They contribute a very good understanding of nanofluid behavior as cutting fluid in various cutting processes.

2.2. The effects on cutting temperature

The cutting fluid can be useless if not delivered efficiently to contact zone, and so the methods of supplying the coolant in machining are the critical parameter. However, the effectiveness of supplying cutting fluids in wet cutting can help to dissipate relatively small amount of the generated heat. It is well known that only very small amount of cutting fluid can penetrate to contact zone although large amount is delivered. On the other hand, costs, as well as health and environmental issues, motivate manufacturing enterprises to drastically reduce consumption of cooling fluids.

Dry machining processes face the serious difficulties in heat dissipation and chip transportation though eliminating the use of cutting fluids. From **Figure 2**, nongeometrically defined machining processes, such as grinding, honing, etc., are considered cooling function the most important factor. When some of these processes can be replaced by geometrically defined hard machining methods (for instance hard turning, hard milling), successful machining with minimization or without fluids can be achieved [13].

Stainless steel, for instance, belongs to the difficult machining material, which is easy to stick tool leading to increasing the cutting temperature and intensifying the abrasion of the tool

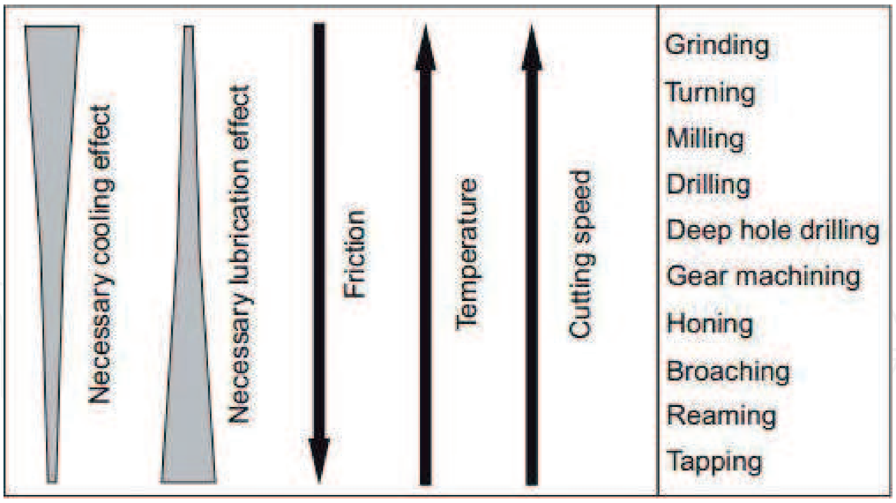

Figure 2. Machining operations and their needs for cooling and lubricating functions [3].

nose. Dry turning of AISI 304 stainless steel (85 HRB) at v = 75÷265 m/min; f = 0.1÷0.3 mm/rev; a_p = 0.8÷1.6 mm with two different groups of inserts: uncoated and TiN coated carbide inserts (rake angle $\gamma_o = 15°$, relief angle $\alpha_o = 8°$, inclination angle $\lambda_s = -4°$, and side cutting-edge angle $k_r = 75°$) [14].

From **Figure 3**, the cutting temperatures of two kinds of cutting tools increase with increasing cutting speed. The reason was that frictional heat generated from the contact zone of the bottom of chip and tool rake face was too late to transfer and was accumulated at the bottom of chip. Therefore, the cutting temperature increased. The comparison of cutting temperature is made among dry, wet, and MQL turnings of AISI 4140 steel (340 HV) at v = 50.2÷141.4 m/min; f = 0.09÷0.22 mm/rev; and a_p = 0.5÷1.5 mm with HSS tools [15]. The tool-chip interface temperature in which MQL fluid is supplied from both nozzles to the rake and flank faces is approximately

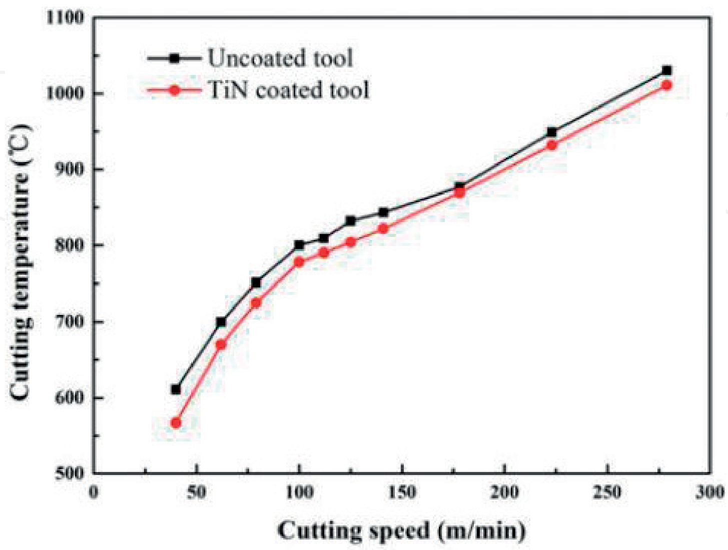

Figure 3. Evolution of cutting temperature with cutting speed in dry turning of AISI 304 stainless steel [14].

350°C lower than that in dry turning, and if supplied only to rake face, the tool temperature is about 200°C lower than that in dry turning. Additionally, the tool-chip interface temperature in wet turning is about 300°C lower than that in dry turning. The difference in cutting temperatures under dry, wet, and MQL conditions is closely related to the difference in cutting forces. The greater the cutting forces, the more heat and higher cutting temperatures are generated. Accordingly, the application of dry cutting processes is limited. It can also be observed that MQL techniques effectively provide oil mist directly to cutting zone to improve lubricant characteristics, but the main drawback of this technique is cooling character. It has a significant meaning for machining hard materials with the hardness range of 45 ÷ 70 HRC. Therefore, the application of nanofluids in MQL machining, an up to date research topic, brings out a novel substitution for dry and wet cutting, as well as the development of semi-dry machining (MQL technique).

The thermal conductivity of nanofluids has been found to be higher than that of the base fluid by using KD2 Pro Thermal analyzer to measure at room temperature (25°C) to note down the increased conductivity value (seen in **Figure 4**) [16]. It is also observed that the thermal conductivity of nanofluids enhances when increasing the nanoparticle concentration.

The comparison of six types of nanoparticles, namely molybdenum disulfide (MoS_2), zirconium dioxide (ZrO_2), carbon nanotube (CNT), polycrystalline diamond, aluminum oxide (Al_2O_3), and silica dioxide (SiO_2), mixed with palm oil to formulate nanofluids is made and used for MQL grinding of Ni-based alloys [17]. The grinding temperatures of six nanofluids are shown in **Figure 5**.

It can be clearly observed from **Figure 5** that the grinding temperatures sharply increase at the initiation of grinding process but decrease gradually to reach a stable temperature when six different nanofluids are supplied to contact zone.

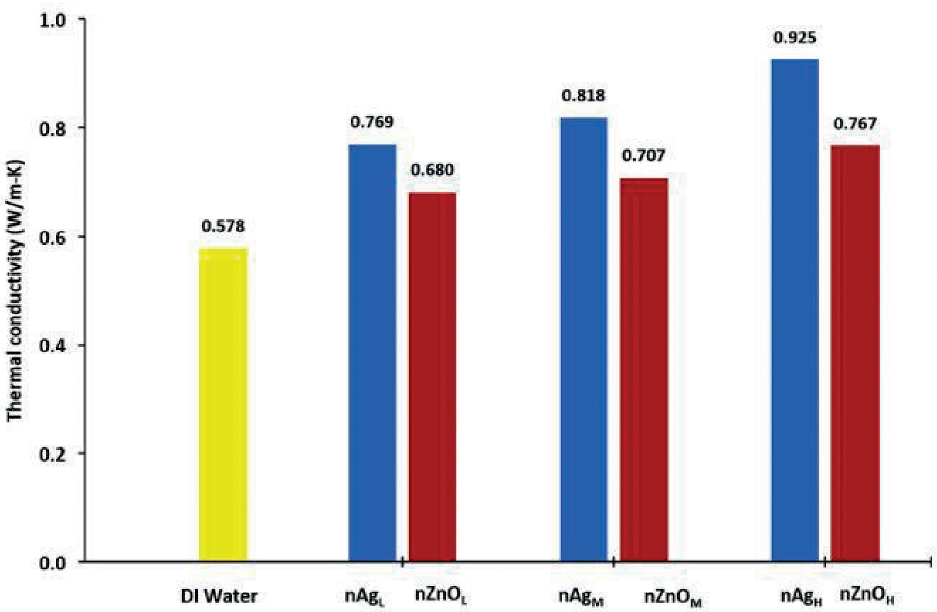

Figure 4. Thermal conductivity variation for silver and zinc oxide nanofluids with different volume fractions [16].

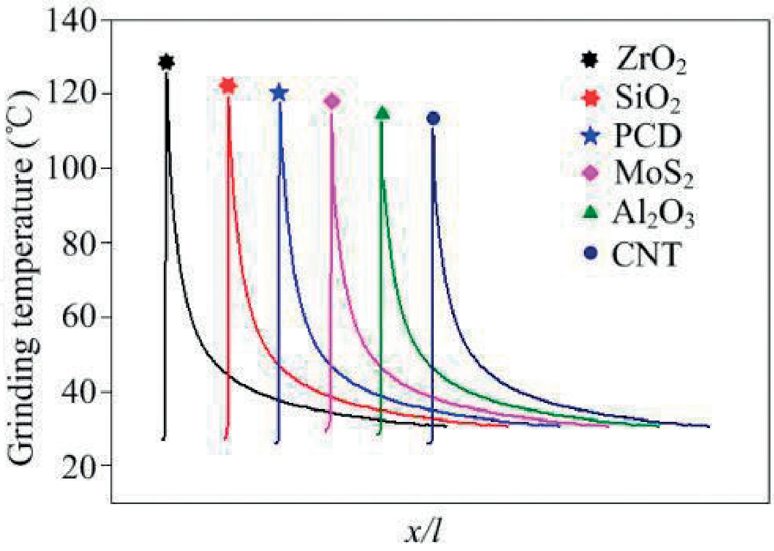

Figure 5. Grinding temperature of six nanofluids with respect to a dimensionless grinding distance *x/l* [17].

From **Figure 6**, it can be clearly seen that six different nanofluids help to effectively reduce MQL grinding temperature compared to the base fluid due to the presence of nanoparticles with hard property, as well as good heat transfer. The use of nanoparticles has a significant meaning in improving cooling and lubricating characteristics. CNT nanofluid shows the best cooling performance, presumably it has good heat transfer properties. On the other hand, the viscosity of cutting fluids is an important influencing factor of lubrication performance. **Figure 7** shows the relationship between six different nanofluids' viscosity and temperature.

The viscosity of all nanofluids decreases with the rise of temperature, especially before 70°C. SiO_2, Al_2O_3, and CNT nanofluids have higher viscosity than other ones. High viscosity allows the cutting fluids to stay in the cutting area for a longer time. This phenomenon improves the cooling

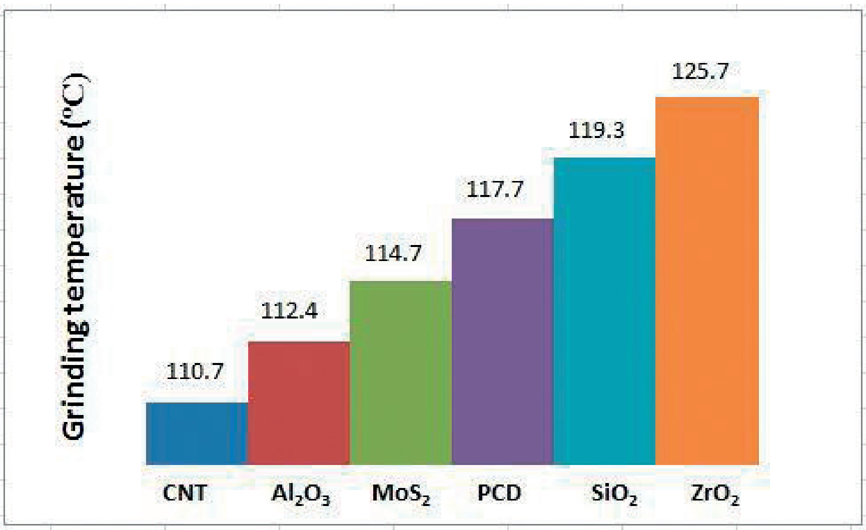

Figure 6. Grinding temperatures of six different nanofluids [17].

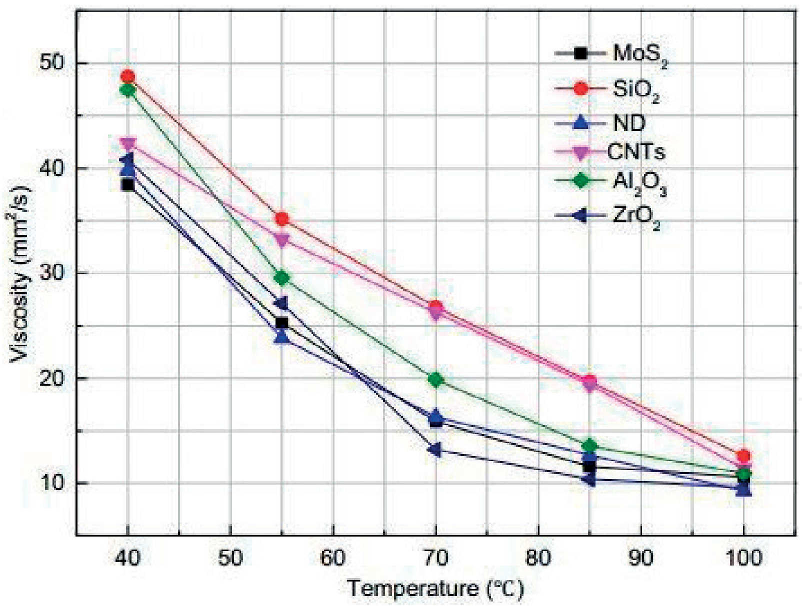

Figure 7. Relationship between nanofluids' viscosity and temperature [18].

lubrication of the contact area. In addition, the use of vegetable oils as the base nanofluids not only improves their cooling, lubricating, and viscous characteristics but also is the step toward sustainable manufacturing.

2.3. The effects on cutting forces

The tribological characteristic of cutting fluids has a significant meaning for investigating cutting forces. The nanofluids' tribological characteristics are improved by using Al_2O_3 and TiO_2 nanomaterials. The kinematic viscosity of Al_2O_3 and TiO_2 nanolubricants decreased slightly due to the presence of nanoparticles between the lubricant layers leading to an ease of relative movement with the nanoparticles acting as "rollers." On the other hand, the viscosity index increased with the use of nanolubricants [9]. Accordingly, nanoparticles in MQL fluid play an important role in converting sliding into rolling contact. That is the reason why the friction coefficient in cutting zone is much reduced, and the cutting temperature, cutting forces, and tool wear decrease. MQL hard milling of $60Si_2Mn$ steel (50÷52HRC) was done by using Al_2O_3 nanofluid (0.5 wt%) with carbide inserts at v = 110 m/min; f = 0.12 mm/tooth; a_p = 0.2 mm [19]. The cutting forces were directly measured during cutting process by Kistler quartz, three-component dynamometer (9257BA). **Figures 8–10** show the cutting force components F_x, F_y, and F_z of MQL hard milling process with/without Al_2O_3 nanoparticles. It is clearly observed that, compared to the case of MQL fluids without nanoparticles, all the cutting force components are much reduced when cutting with nanofluids. Interestingly, it is revealed that during the first 20 min, all the cutting forces F_x, F_y, and F_z in both cases are low; therefore, in this time, the performance of Al_2O_3 nanoparticles in MQL hard milling is not really clear. After the first period, the rapid tool wear occurs, and wear land reaches some extent, which allows nanoparticles to penetrate to cutting zone. The formulation of oil film with nanoparticles in contact zone plays an important role in creating "roller effect." Rolling friction instead of sliding one occurs between flank face and machined surface, rake face and chip surface, and so forth. Hence, the cutting forces significantly reduce and the tool life extends much.

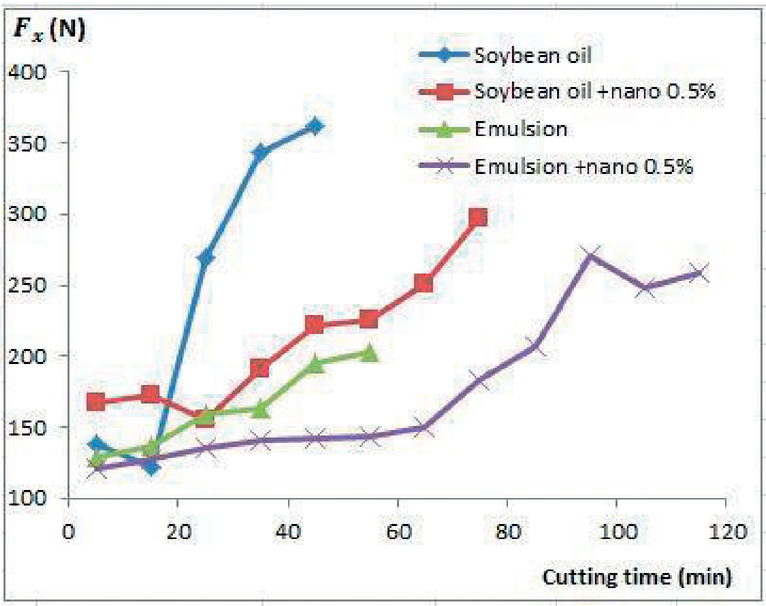

Figure 8. Cutting force component F_x under MQL conditions with/without nanofluids [19].

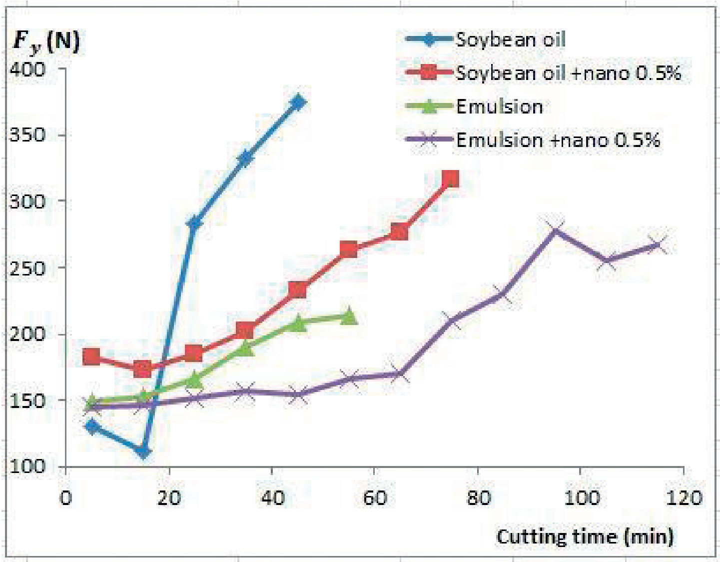

Figure 9. Cutting force component F_y under MQL conditions with/without nanofluids [19].

The use of soybean oil–based nanofluids in MQL hard milling was less effective than that of emulsion. However, both of them allow the normal APMT 1604 PDTR LT30 carbide inserts to use effectively for hard milling, and the economic and technological characteristics of cutting performance are achieved. Another promising research investigated lubrication properties of the wheel/workpiece interface in MQL nanofluids grinding compared with flood and MQL grinding without nanoparticles. The experiments were conducted at wheel speed v_s = 30 m/s, feed speed v_w = 3000 mm/min, and cutting depth a_p = 10 μm for machining the high-temperature nickel base alloy GH4169 [18]. **Figures 11** and **12** show the grinding forces obtained.

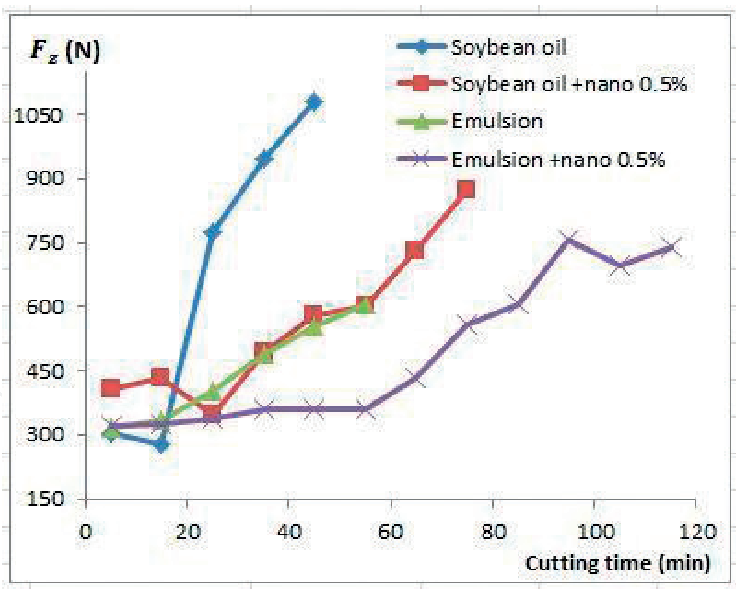

Figure 10. Cutting force component F_z under MQL conditions with/without nanofluids [19].

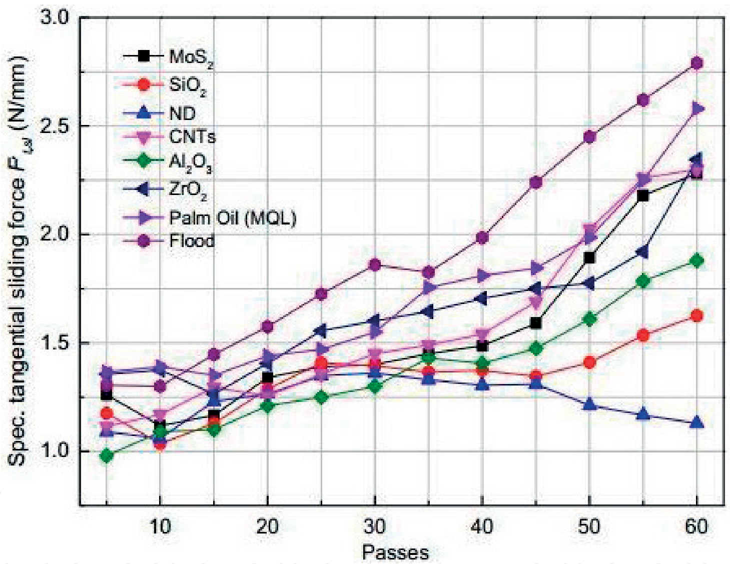

Figure 11. Specific tangential sliding grinding forces in the cases of flood, pure MQL, and nanofluids.

Both normal and tangential grinding forces increased with an increased number of passes. The flood grinding process shows the largest sliding grinding force. MQL grinding with pure palm oil achieves smaller sliding force because it effectively increases the lubrication effect of the grinding area due to oil-mist formation. Nanofluids are superior to pure palm oil in lubrication improvement. When making the comparison among six different nanofluids, the sliding grinding forces under MQL nanofluid (Al_2O_3, MoS_2, SiO_2, and ND) are lowest due to hard characteristic and small sliding friction coefficient. The effectiveness of nanofluids on reduction of cutting forces becomes a novel observation and has an important influence on tool wear and tool life, which directly affect the surface quality and manufacturing cost.

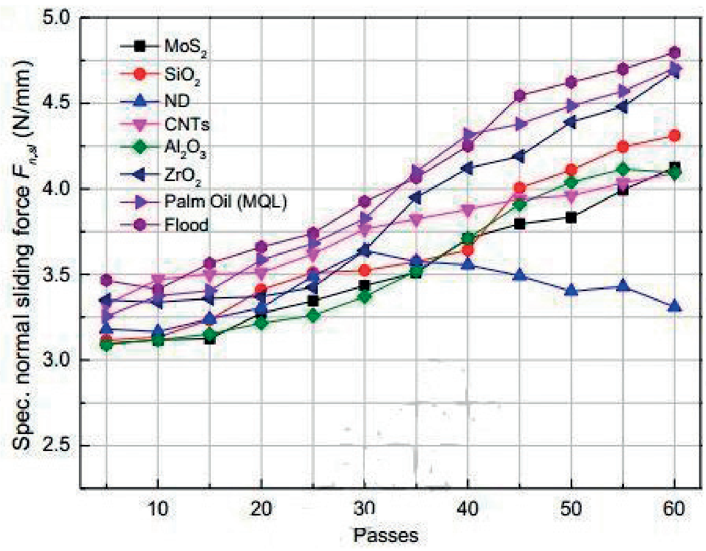

Figure 12. Specific normal sliding grinding forces in the cases of flood, pure MQL, and nanofluids.

2.4. The effects on tool wear and tool life

With the presence of nanoparticles between rake face and fresh chip, as well as flank face and machined surface, the mechanism of the tribological effect takes many forms, such as “roller effect,” third body effect, chemical mechanical protective film effect, mending effect, and polishing effect [2, 3]. For instance, during gear hobbing process of AISI 4118 steel (spindle speed = 200 rev/min, depth of cut =4.375 mm, feed rate = 1.27 mm/rev), using nanofluid (Al_2O_3 with the size 80 nm suspended in ISO VG46 lubricant oil with volume fraction of 0.1÷ 0.2%) shows many promising results. Nanoparticles in the base oil effectively improve the heat transfer capability and reduce the friction by “roller effect” in cutting zone, leading to the reduction of tool wear, the much extension of tool life, and the enhancement of gear profile accuracy and gear surface roughness [20]. **Figures 13** and **14** show the flank wear of hob tools at different time of machining the 50th, 300th gears. It is clearly seen that during the period of machining first 50 gears, gear hobbing under nanolubrication exhibits the reduction of tool wear, but at the period of machining the 300th gear, the significant reduction of hob wear is observed. Moreover, the wear land at the time of machining the 300th gear with nanolubrication (39.93 μm) is nearly equivalent to that of the tool at the period of machining the 50th gear under flood lubrication (36.29 μm). Accordingly, it is clarified that there is a significant increment in tool life when machining under nanolubrication.

On the other hand, the tool wear is much reduced under nanolubrication, which leads to achieve higher gear profile accuracy (shown in **Figure 15**). It could be said that nanolubrication is the main factor contributed to preserve the tool profile accuracy. In addition, the spherical morphology of Al_2O_3 nanoparticles takes part in the decrease of friction force and cutting temperature.

Hard milling process of $60Si_2Mn$ steel (50÷52HRC) was done by using Al_2O_3 nanofluid (0.5 wt %) with carbide inserts at v = 110 m/min; f_t = 0.12 mm/tooth; and a_p = 0.2 mm. **Figures 16** and **17** illustrate the difference of tool wear between MQL hard milling with nanofluids and pure MQL. In **Figure 16**, the wear on cutting edge including rake and flank faces is dominant.

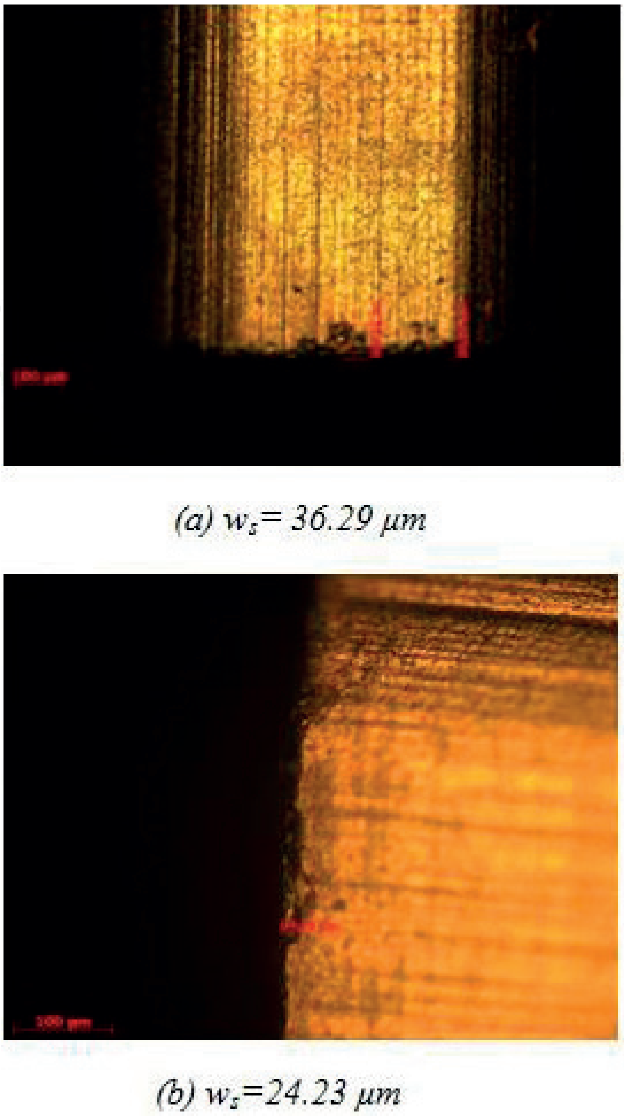

Figure 13. Flank wear after machining the 50th gear using: (a) flood lubrication; (b) nanolubrication [20].

In **Figure 17**, the friction between rake face and chip reduces due to "roller effect" of Al_2O_3 nanoparticles. Wear abrasion is not concentrated in cutting edge, and the abrasive area is formed on rake face (marked area shown in **Figure 17a**). On flank face, the formation of small wear land helps to form oil mist and contains nanoparticles to create "roller effect". The pressure on cutting edge decreases due to the reduction of friction. Therefore, the uniform wear occurs on cutting edge, which is different from the case without nanoparticles (**Figure 17b**). Moreover, the tool wear is reduced (about 26.4–33%) with the use of Al_2O_3 nanofluids.

From **Figure 18**, in case of soybean oil with Al_2O_3 nanoparticles, tool life is about 80 minutes (increase almost 177% compared to pure soybean oil). In case of emulsion 5% coolant with Al_2O_3 nanoparticles, tool life is about 115 minutes (increase almost 230% compared to pure emulsion 5% coolant). The promising results are supported to prove the explanation of "roller effect" of nanofluids.

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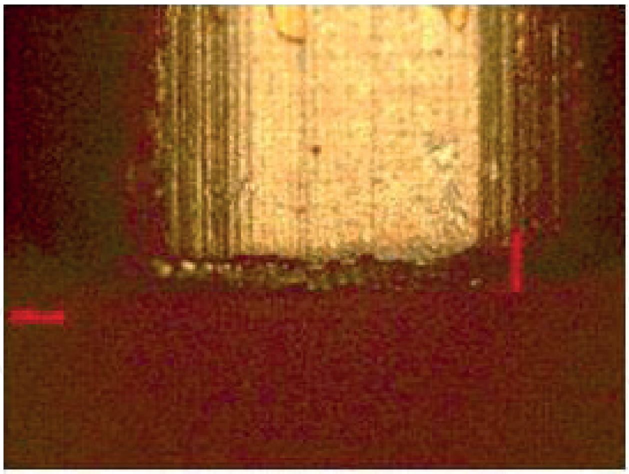
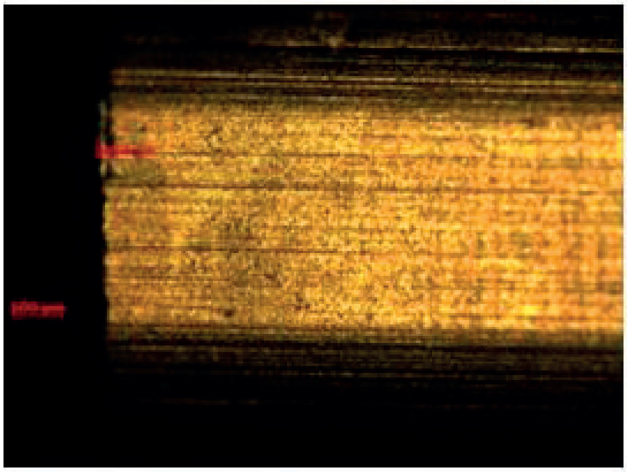


(a) w_s=89.3 μm



(b) w_s=39.93 μm

Figure 14. Flank wear after machining the 300th gear using: (a) flood lubrication; (b) nanolubrication [20].

The nanoparticles suspended in cutting fluids bring out the new trend in machining industries, which not only suggests many alternative solutions for conventional problems in metal cutting but also suits with green manufacturing industries, especially used as the base fluids of MQL techniques. Many publications have shown that the vegetable oils as the base fluids with MQL method, inherently nontoxic as well as biodegradable, can be effectively applied for machining processes, but their cooling characteristics is the main problem when cutting hard materials. During hard machining, the enormous amount of heat generated from cutting zone and strong adhesive wear between the tool and the work material will cause the reduction of hardness of cutting tool, increase the wear rate, and decrease the tool life. The occurrence of nanomaterials in MQL fluids has a strong meaning to overcome this problem. The difficulty of heat dissipation from cutting zone has been solved by the reduction of friction coefficient caused by "roller effect" of nanoparticles. Besides, MQL nanofluids also broaden the applicability of carbide tools in hard cutting with economic characteristic.

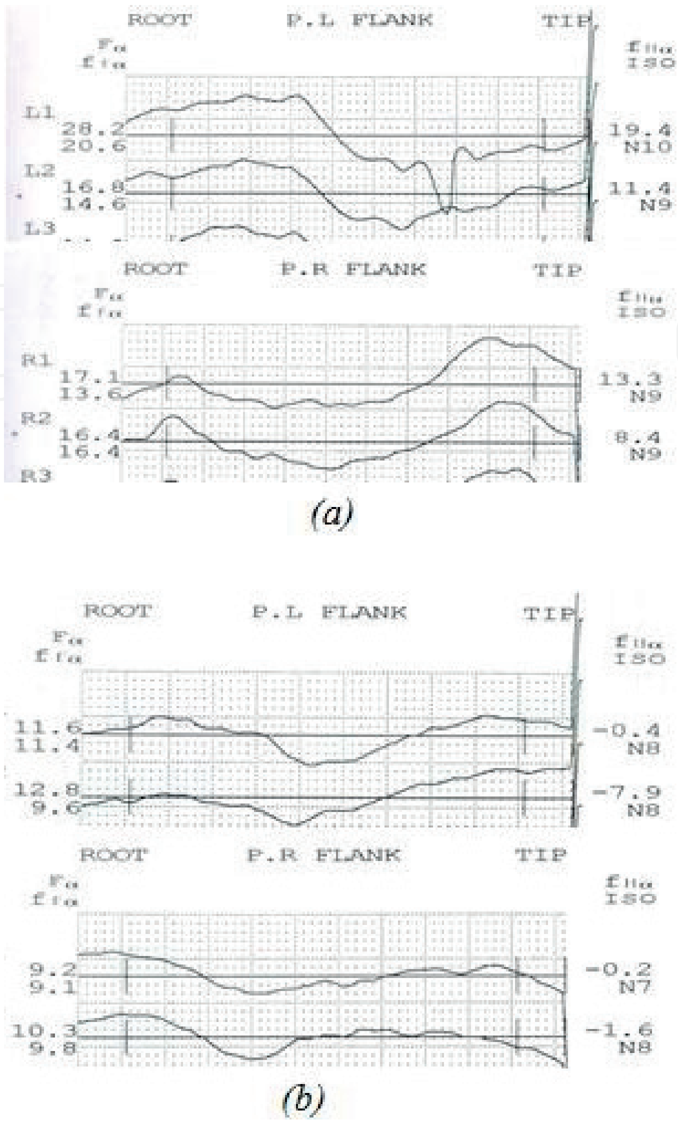


Figure 15. Measuring the gear profile error of the 300th machined gear by OSAKA SEIKI KIKAI gear measuring machine: (a) flood lubrication; (b) nanolubrication [20].

2.5. The effects on surface integrity

The surface integrity has become unquestionably a crucial parameter of any product in the past, present, and future. Quality characteristics must be tested during and after the manufacturing processes. With regard to components, the distinction is often made between macrogeometrical parameters and the surface quality. Macro-geometrical parameters refer to deviations of dimension, form and position. The surface quality is defined by roughness parameters. **Figures 19** and **20** show the surface roughness values of hard milling of $60Si_2Mn$ steel (50÷52HRC) under different MQL conditions. The values of surface roughness obtained from MQL nanofluids are better than those of MQL pure fluids. Furthermore, the good surface quality of hard milling under MQL nanofluid condition achieves and remains stable during longer cutting time. The best performance of nanoparticles is obtained when the flank wear land reaches to some extent called “appropriate wear land.” This can be explained that the profile of machined surface of hardened steel reflects that of flank face of cutting tool with

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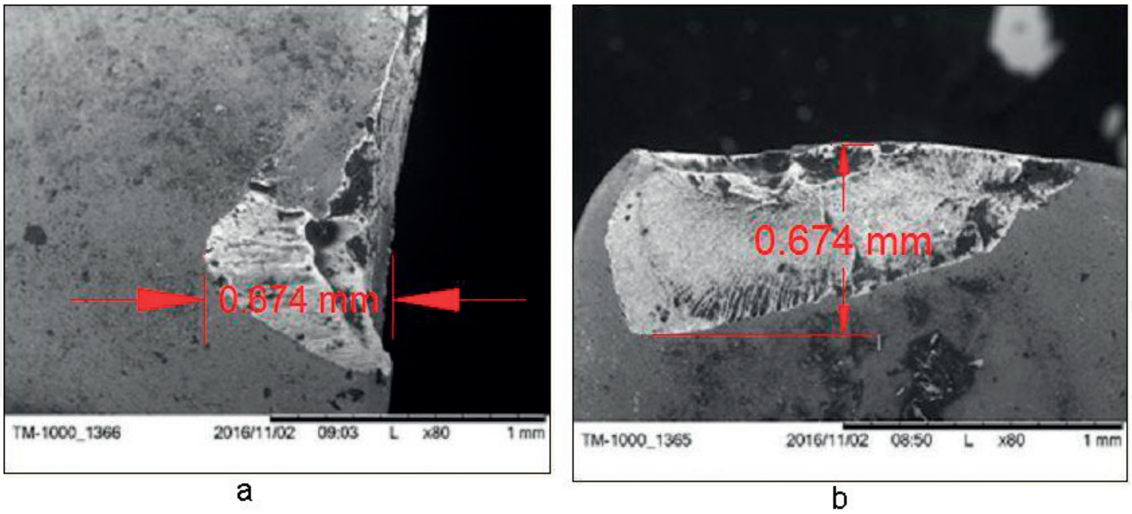

Figure 16. Tool wear under pure MQL cutting fluid with soybean oil (cutting time at 45 minutes): (a) rake face wear; (b) flank face wear [19].

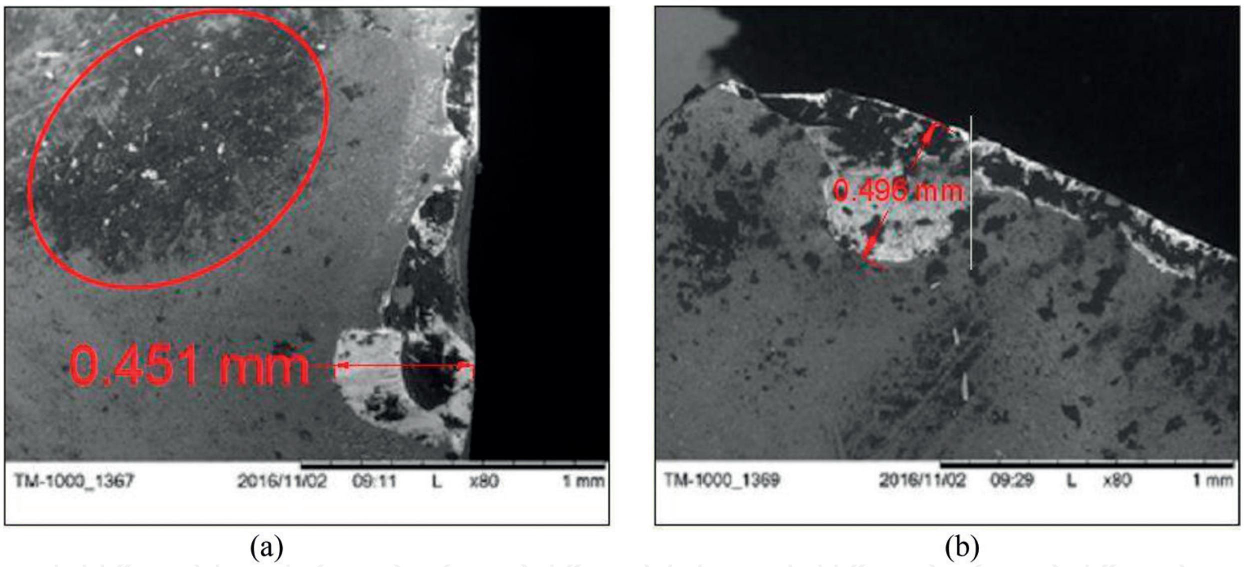

Figure 17. Tool wear under MQL nanofluid with soybean oil (cutting time at 80 minutes): (a) rake face wear; (b) flank face wear [19].

reasonable accuracy. As long as the flank wear profile is remained smooth, the flank wear to some extent not only deteriorates the surface finish but also somehow keeps or increases the surface quality [19]. This feature makes MQL hard machining utilizing nanofluids very different from other types of machining processes.

The surface roughness of grinding the high-temperature nickel base alloy GH4169 is shown in **Figure 21**. The comparison of different lubricating conditions reveals that the amount of surface quality improvement in the nanofluid MQL grinding is much higher. It is attributed to the more effective lubrication of nanofluids. The Al_2O_3 nanofluid MQL grinding achieved the best surface roughness.

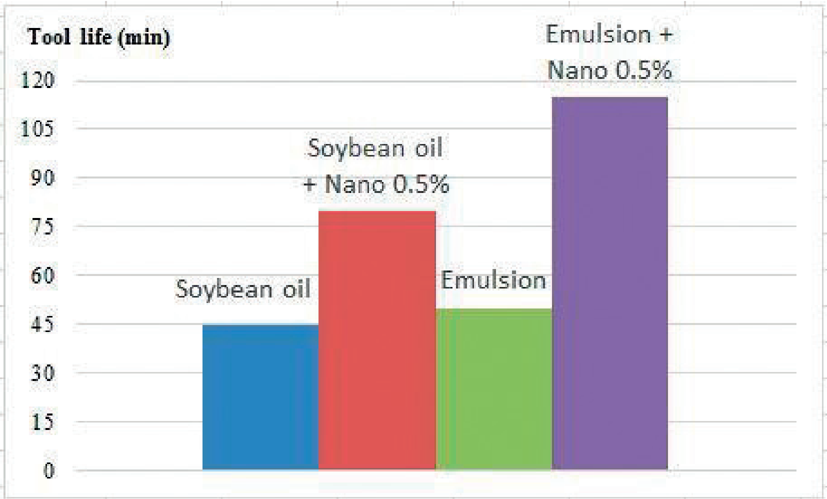

Figure 18. Tool life under MQL conditions with or without nanofluids [19].

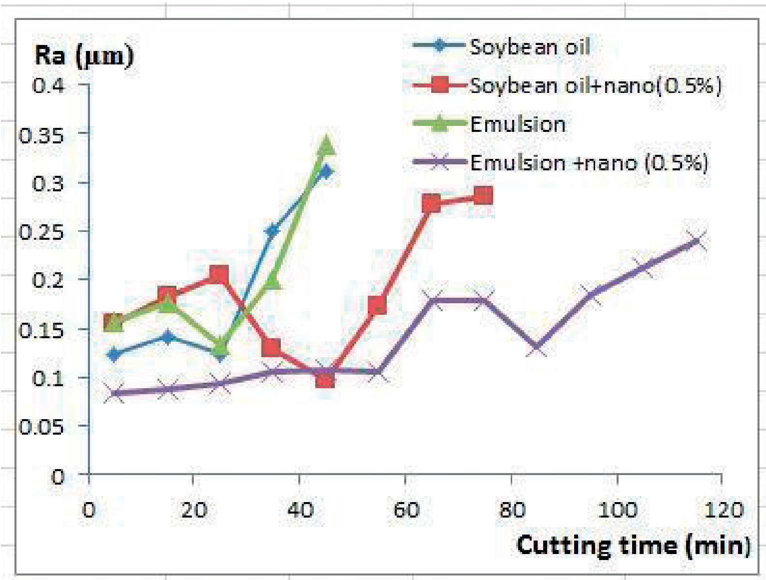

Figure 19. Surface roughness R_a under MQL conditions with or without nanofluids [19].

The nanofluid MQL grinding leads to a smoother surface and is better than either pure palm oil MQL or flood lubrication (seen in **Figure 22**). Interestingly, MQL grinding with Al_2O_3 nanofluid offers significant reduction in the sliding friction coefficient, specific sliding grinding energy, and best surface quality [18]. In addition, the SiO_2 and diamond nanofluids show relatively good lubrication effect.

The application of nanolubrication led to the formation of a tribo-film (seen in **Figure 23**) as a solid lubricant [9]. This observation can be made in machining field due to extremely high contact pressure and temperature in cutting zone, and so many nanoparticles are deformed and remained in the machined surface. The occurrence of tribo-film on the machined surface may lead to many new research topics needed to study. The deposition of a tribo-film on the surfaces could help to improve the operating function of the machined part. The very thin

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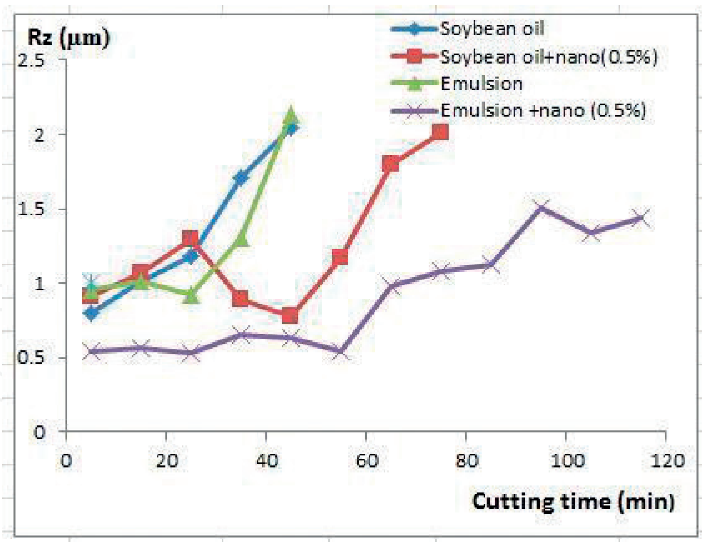

Figure 20. Surface roughness R_z under MQL conditions with or without nanofluids [19].

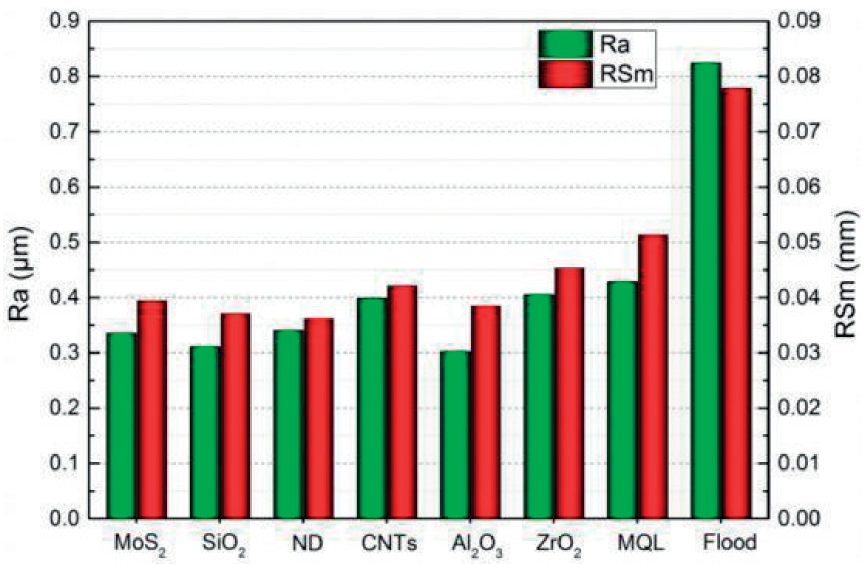

Figure 21. Surface roughness of grinding process at different lubrication conditions [18].

layer formed by nanoparticles has the same characteristics as nanopowder, and so through cutting processes by nanofluids, we can make further improvement for tribological effect on part surfaces by using proper nanofluids and cutting condition. These topics will be discussed and confirmed in many further researches.

2.6. Conclusion

An inclusive review on the application of nanofluids in various machining processes has been made. The nanofluid has achieved significant attention due to its capability to enhance the heat transfer and lubrication performance in cutting zone. The effects of nanofluids were proven to reduce the coefficient of friction and wear effect to enhance the cutting performance,

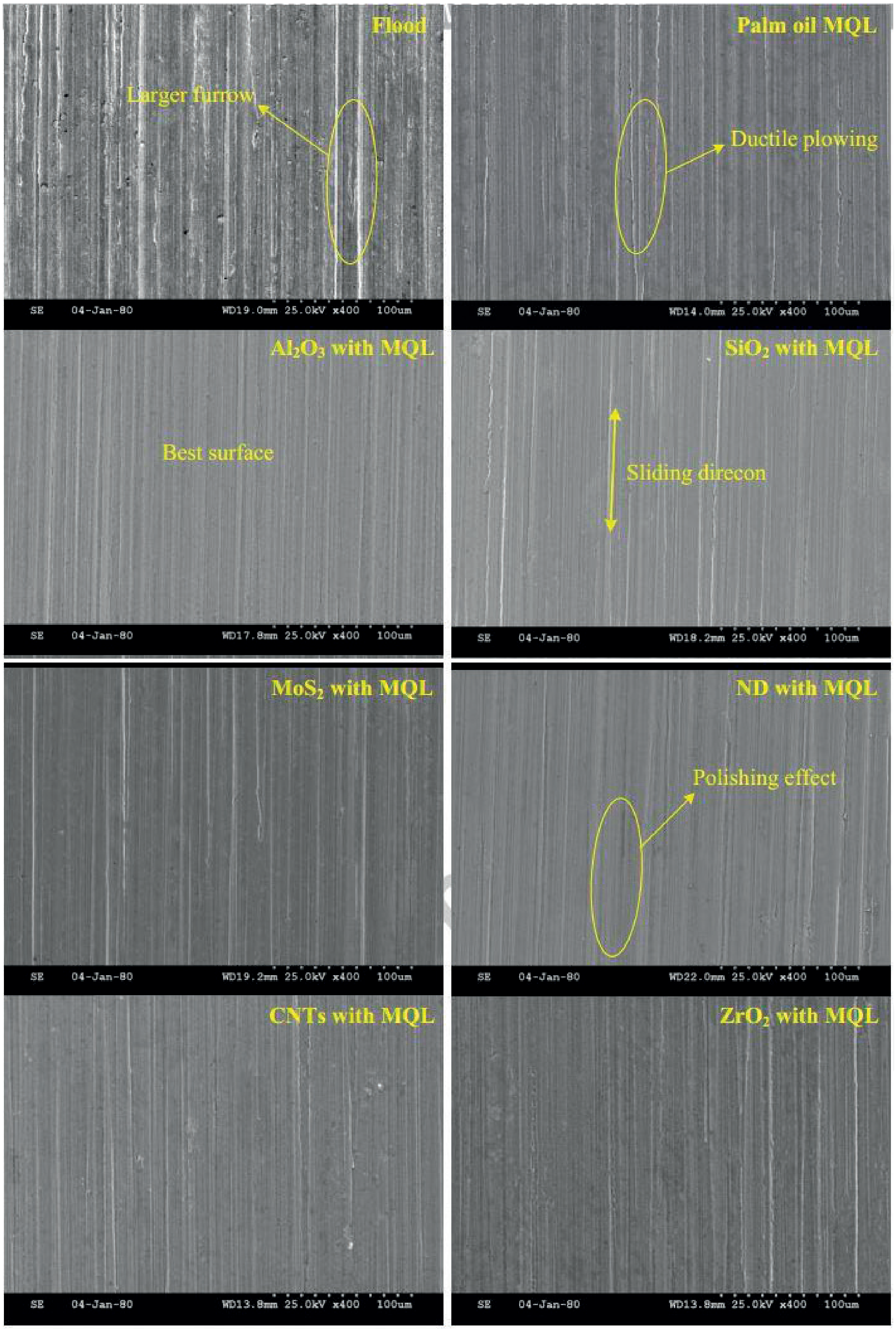

Figure 22. SEM micrographs of workpiece surface of nickel base alloy GH4169 at different lubricating conditions [18].

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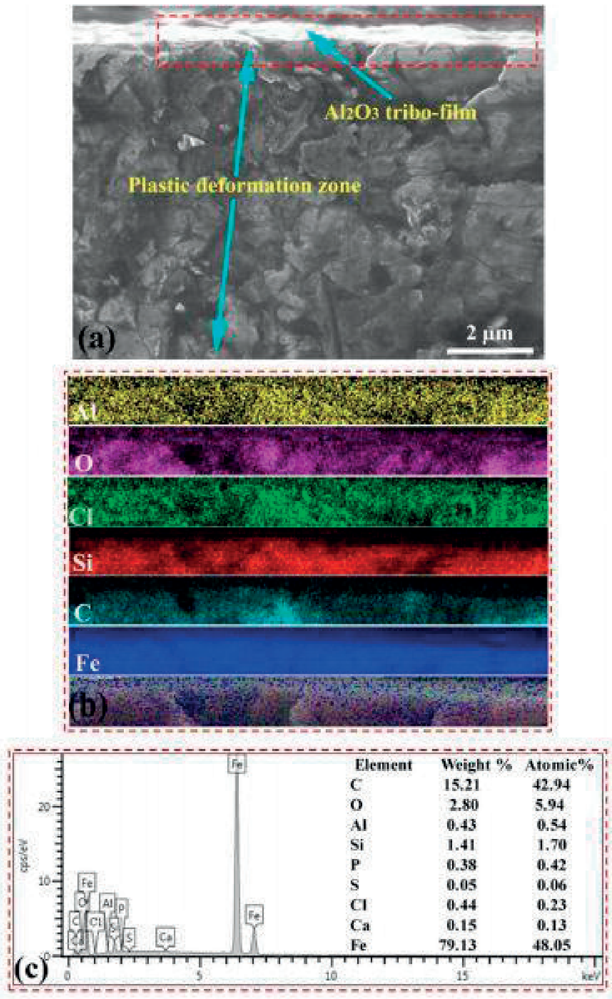

Figure 23. Formation Al_2O_3 tribo-boundary film on worn surface of the piston ring surface. (a) FE-SEM imaging on the cross-section, (b) EDS element mapping on tribo-boundary film, (c) EDS spectrum on tribo-boundary film [9].

tool life, and surface quality. Moreover, MQL technique with NFs makes a big improvement for some hard machining processes like hard turning, hard milling in term of surface quality, which is equivalent to that of finish grinding. Together with MQL using nontoxic fluids like water and vegetable oils, nanofluids have opened the new trend in machining and exhibited a wide range of application in different cutting processes. The promising results obtained definitely ensure the success of MQL machining with nanofluids. However, the performance and behavior of nanofluids may be affected by many parameters, such as the base fluid, nanoparticle type, nanoparticle size, nanoconcentration, and so on. Further research is necessarily made to optimize these parameters.

3. The effects of parameters of nanofluids

Each type of nanoparticles has with different structures, shapes, and sizes, which will vary in physical and morphological features, demonstrating diverse tribological performances [35].

From **Table 1**, it can be seen that the technical properties of each type of nanoparticles are different, and so the effectiveness of various nanofluids on MQL cutting performance will be an important investigated factor.

In this section, the authors will present the effects of six different types of nanoparticles on nanofluids mainly used in MQL machining in term of MQL base fluid, types of nanoparticles, size and morphology of nanoparticles, and nanoparticle concentration.

3.1. The base fluid of nanofluid

Nanofluids are formulated by suspending nanoparticles in various types of fluid, which can be the water, vegetable oil, industrial oil and so on. The properties of the medium are considered an important parameter, which directly influences on the activity of nanoparticles. Along with the trend of sustainable machining all over the world, the cutting fluids used in nanofluids should not be contained different toxic ingredients, and therefore water and vegetable oils are motivated to use as the alternative solution. There are some types of vegetable oils, which are commonly utilized in MQL machining: soybean, peanut (groundnut), maize, rapeseed, palm, castor, and sunflower oils. The ingredients, molecular structure, viscosity, and friction coefficient of the base fluids are the key parameters for vegetable oils [37]. **Figure 24** shows the relationship between vegetable oils and their coefficient of friction, which strongly influences in the contact area during machining. Vegetable oil is mainly composed of fatty acid and triglyceride -COOH in the fatty acid molecules and -COOR in triglyceride both belong to polar groups, which gives them excellent lubrication property [38]. **Figure 25** illustrates the typical polar molecule of vegetable oil.

Table 2 lists the basic ingredients of fatty acids of seven vegetable oils. The lubrication properties of saturated fatty acids are better than those of unsaturated fatty acids [41]. Saturated fatty acids have a strong effect on decreasing friction and wear, especially stearic acid, which

Types of nanoparticles technical properties	Al_2O_3	SiO_2	MoS_2	ZrO_2	CNT	ND
Morphology	Nearly spherical	Porous & nearly spherical	Ellipsoidal	Mainly spherical	Coaxial circular tubes	Spherical & flaky
Purity (%)	> 99	~99.5	> 99	99.9	> 95	93-95
Color	White	White	Black	White	Black	Gray
True density (g/cm^3)	3.97	2.4	4.8	5.89	~2.1	3.05–3.30
Thermal conductivity (W/m.K)	40	7.6	138	< 2	3000	2000
Friction coefficient	—	—	0.03 ~0.05	—	—	—
Melting temperature (°C)	2200	1600	1185	2715	3127	3727

Table 1. Technical properties of different types of nanoparticles.

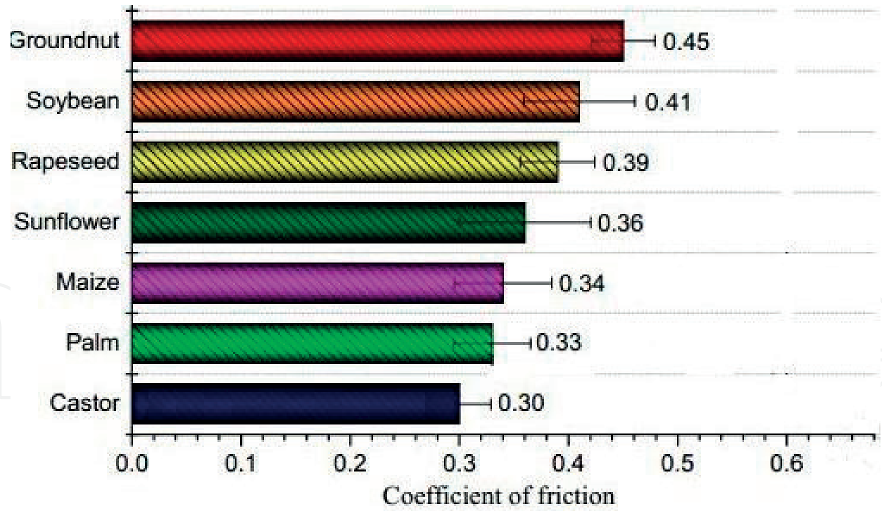

Figure 24. Friction coefficient of different vegetable oils [36].

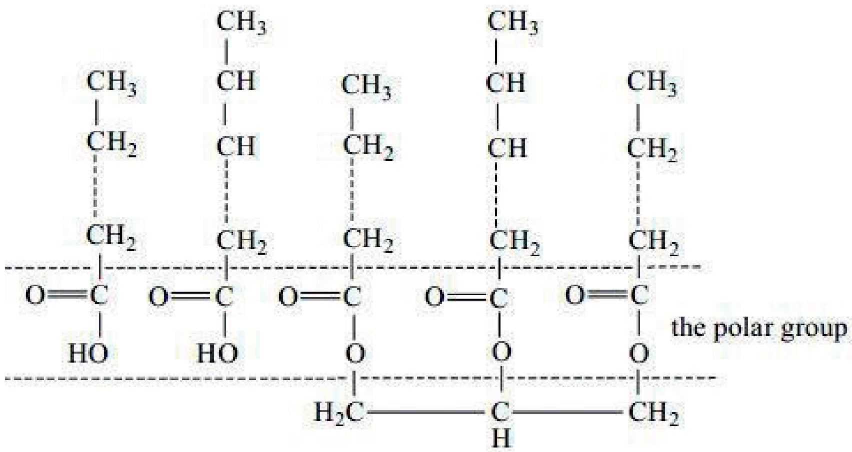

Figure 25. Polar molecule of the typical vegetable oil [36].

Oil types	Ingredient				
	Palmic acid	Stearic acid	Oleic acid	Linoleic acid	Linolenic acid
Peanut oil	6–9	3–6	55–71	13–25	0.5
Soybean oil	7–10	3–5	22–31	49–55	6–11
Maize	9–19	1–3	26–40	44–55	< 1
Castor oil	—	—	3–9	3–5	Trace
Palm	35–48	4–6	38–41	8–12	Trace
Rapeseed oil	2–4	1–2	40–60	19–20	7–8
Sunflower oil	4–19	3–6	14–35	50–75	0.1

Table 2. Ingredient of various vegetable oil (%) [36].

provides a more stable oil film in contact zone. Besides, they tightly contaminate to the molecular film and remain on metal surfaces, such as tiny magnets, to form lubricating film for anti-friction and anti-wear [39]. Hence, this characteristic gives vegetable oils good lubrication property and shows the excellent lubrication effects in the application of MQL fluids. The double bonds in unsaturated fatty acids are relatively unstable and easily generate chemical reactions, such as oxidization. Moreover, they can also weaken the acting force between molecules, which leads to poor lubrication properties [36]. Lubrication property of unsaturated fatty acids with a higher carbon atom number is stronger than those with a lower carbon atom number, and so the friction coefficient decreases as the chain length increases [42].

On the other hand, the selection of proper vegetable oil depends on the climate and soil texture of each country, but it contributes very little to total manufacturing cost because of very small amount of fluids used in MQL techniques. The small quantity lubrication (SQL) grinding process of Inconel 718 using silver and zinc oxide NPs mixed with DI water at cutting velocity (V) =18 m/s, table speed (V_w) = 6 m/min, depth of cut (a_p) = 10 mm. The flow rates of MQL nanofluids are 50, 100, 150, 200, 250 ml/h [40]. Minimum tangential forces have been obtained in the case of SQL grinding with nanofluids (seen in **Figure 26**), which is essentially due to better cooling, and lubrication that helps in preserving the cutting ability of the grits over a longer period. Additionally, hard NPs under grinding pressure might convert sliding to rolling friction.

Vegetable oil evidently has better lubrication property than water-soluble fluid, but the lubrication properties of seven typical vegetable oils also differ. Among these vegetable nanofluids, castor oil has the best lubrication property, followed by palm oil. In addition, peanut, sunflower, soybean, and rapeseed oils also exhibit excellent lubrication properties.

The viscosity of vegetable oils also has a strong influence on the machining performance and strongly affects its cooling and lubricating properties. They have a high natural viscosity as the machining temperature increases and drops more slowly than that of mineral oils [36]. These statements have significant meanings in machining difficult-to-cut materials such as hardened steel, tool steel, and so on. The formulation of oil film containing nanoparticles in cutting zone plays a key role in reducing the friction, which leads to decrease cutting temperature and tool wear. This film forms and loses continually, and so the higher the viscosity of cutting fluids, the more stable the film on contact faces.

3.2. The types and morphology of nanoparticles

Recently, nanomaterials have attained much attention because of their unique properties and tremendous application potentials in a wide range of industries. Currently, more and more researchers have been devoted to enhance the lubricant properties by using nanoparticles as lubricant additives (also called as nanolubrication or nanofluids). There are numerous types of nanoparticles in markets, and they are used in a wide range of industries. For machining processes, some types of nanoparticles are mainly used as Al_2O_3, MoS_2, ZrO_2, SiO_2, CNT, and ND. From **Table 1**, it is clearly seen that the morphology of six different NPs is different, and so it causes the various effects on cutting performance. Owing to the high cost of nanoparticles, the appropriate selection of nanoparticle type to suspend in MQL fluid is so important.

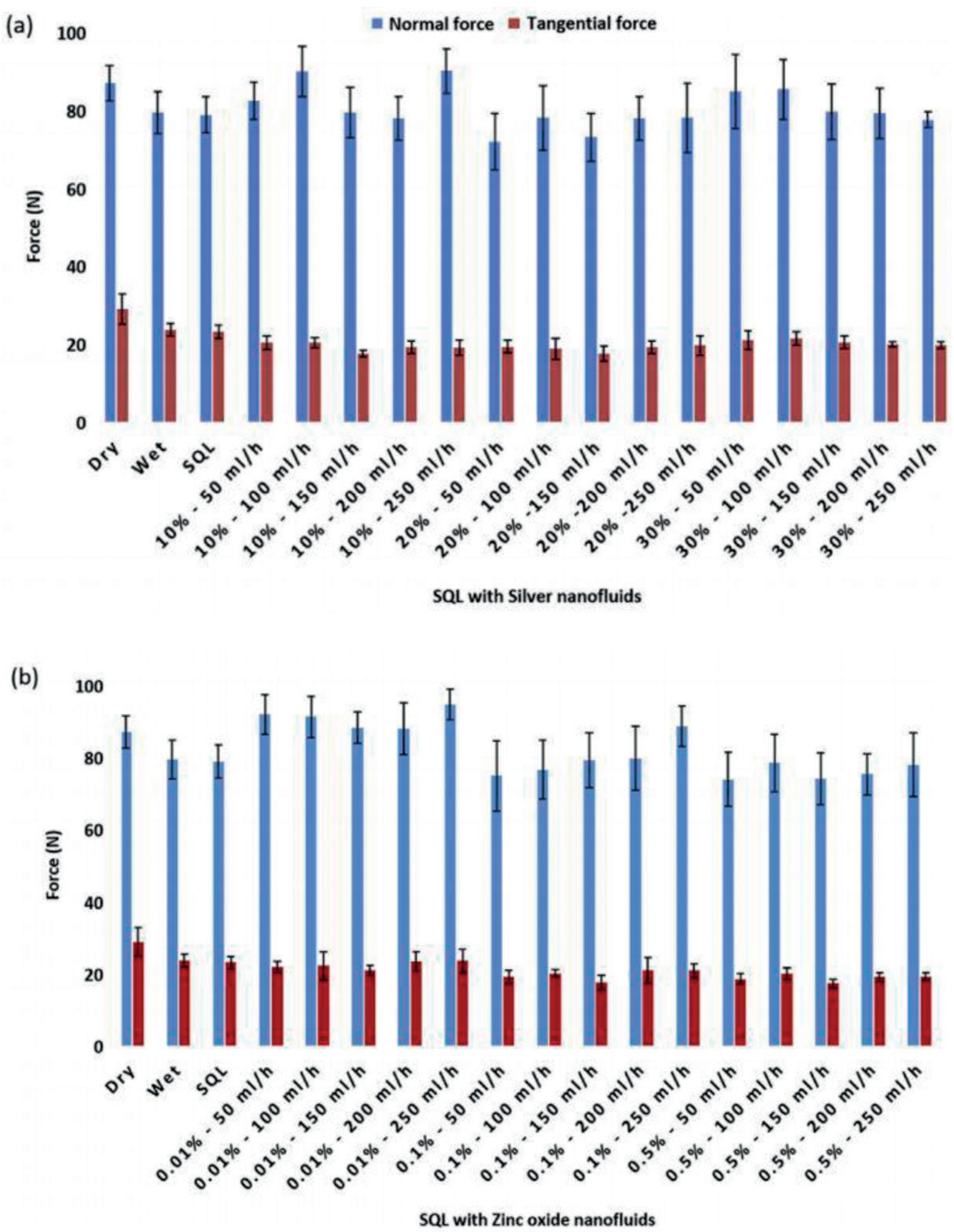

Figure 26. Grinding forces under different SQL nanofluids [36].

Al_2O_3 nanoparticles, one of hexagonal close-packed crystal materials, exhibit the good lubrication performance, which is related to its structures and characteristics. Al_2O_3 nanoparticles are spherical (shown in **Figure 27**) with characteristics of high strength, hardness, and heat resistance. The Al_2O_3 NPs are hard phase (HR = 2700-3000), showing good abrasive resistance during the friction process, and can carry some support to friction surface load between the area [43]. When Al_2O_3 nanoparticles are added into cutting fluid, they can easily move into the worn area under the compressive stress of nanocutting fluid, and then a self-laminating film can be formed, which results in micropolish and can self-mend the friction surface [44, 45]. Furthermore, the Al_2O_3 nanoparticles demonstrate good resistance to high temperature. The melting point of oil film can reach 2200°C. The morphology of Al_2O_3 nanoparticles are mostly

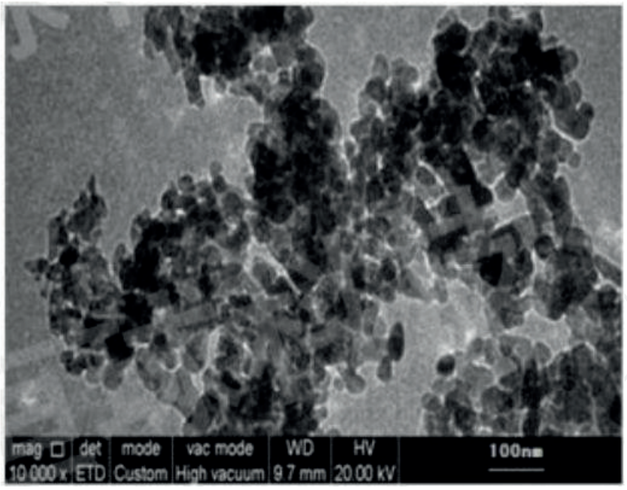

Figure 27. The SEM image of Al_2O_3 nanoparticles (30 nm) [57].

spherical; therefore, they can play the role of ball bearings that prevent the direct contact of friction pairs, and the sliding friction is changed to rolling friction in contact zone, which improves the cutting performance and the carrying capacity of lubricant [46].

The SiO_2 nanoparticles are spherical (shown in **Figure 28**), and the surface molecules exhibit a 3D network structure. Given the abundant unsaturated vacant bonds on the surface, SiO_2 nanoparticles exert high surface energy and activity, making them easy to sediment onto the workpiece friction surface [47]. For such machining processes having the intensive friction as grinding, hard turning, hard milling, and so on, the melting point of SiO_2 nanoparticles in contact faces decreases under local extremely high temperature and pressure. Therefore, they may be melted, semi-melted, or sintered to form the lubrication film. Furthermore, a ceramic-like

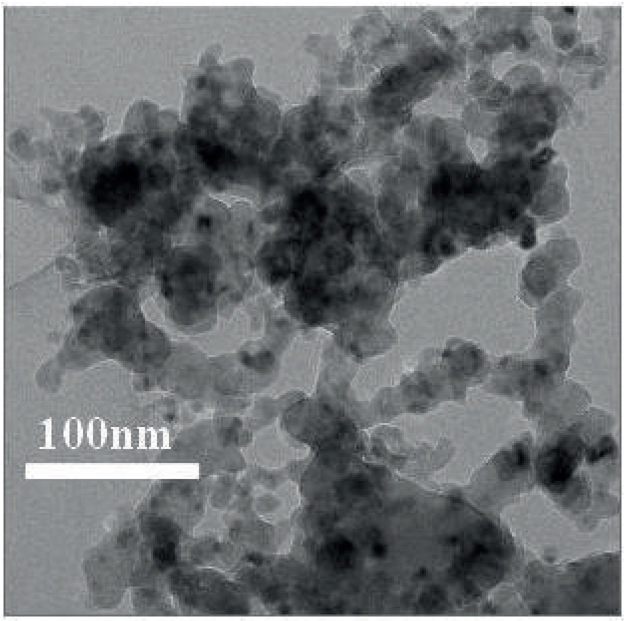

Figure 28. The SEM image of SiO_2 nanoparticles (8 nm) (www.us-nano.com).

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nanofilm can be formed by diffusing and penetrating into machined surface or sub-surface of the elements in some SiO_2 NPs [48]. This phenomenon prevents direct contact between cutting tools and the workpiece, thus reducing the friction and achieving better surface quality.

Molybdenum disulfide or MoS_2 has been utilized in machining processes as solid lubricant for many years. MoS_2 has been considered to be the best solid lubricant material, because it can provide low coefficient of friction up to 0.03–0.05 or even lower. The MoS_2 nanoparticles are ellipsoidal (shown in **Figure 29**). The layer structure of MoS_2 is a hexagonal crystal system combining Mo and S through a covalent bond, and the bond between them is short, but the spacing between sulfur atoms is large. Accordingly, the bond between two adjacent sulfur atom layers is weak. That is the best explanation why a plane, so called "an easy-to-slide plane," will be generated from weak binding of sulfur atoms between molecular layers by shearing force caused by cutting processes. The numerous easy-to-slide planes make the contact faces sliding relatively to each other and they do not contact directly [43]. This unique characteristic makes MoS_2 good friction-reducing effect. Moreover, exposure sulfur atoms of the crystal surface on the metal surface have a very strong adhesion to form a very solid film, therefore lubrication is superior to other general-lubricating materials. When MoS_2 particle size becomes smaller, it is attached to the surface of the friction material and the coverage has increased significantly, and anti-wear friction properties have been significantly improved.

Carbon nanotubes or CNTs are coaxial circular tubes (shown in **Figure 30**) composed by layers and dozens of layers of carbon atoms in hexagonal arrangement. CNTs present a high modulus and strength because carbon atoms in CNTs adopt the sp^2 hybridization, which follows a higher proportion of S pathways than sp^3 hybridization [49]. During machining processes, CNTs will not be ground into hard film under high loads and pressure because of its high strength and hardness. As such, CNTs can reduce the friction force of the cutting area and improve the lubrication effect of nanofluids. Tool-workpiece interface thus provides efficient lubrication. Two types of CNTs include the single-walled carbon nanotubes (SWCNT) and multi-walled carbon nanotubes (MWCNT). The performance between CNTs found by them revealed better performances of MWCNT over the SWCNT in terms of cutting temperature

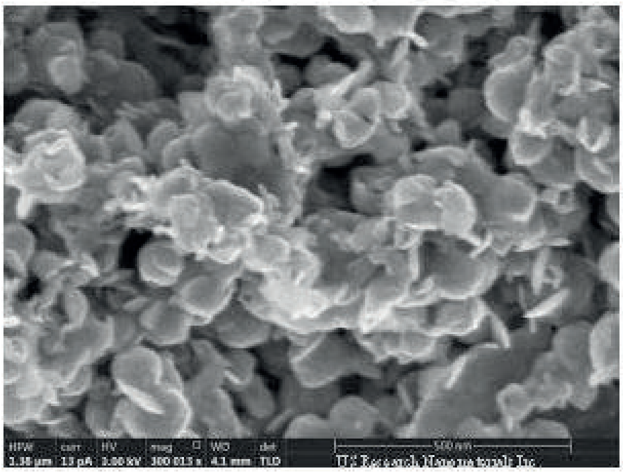

Figure 29. The SEM image of MoS_2 nanoparticles (135 nm) (www.us-nano.com).

Figure 30. The SEM image of single-walled carbon nanotube (outside diameter: 1-2 nm; inside diameter: 0.8-1.6 nm) (www.us-nano.com).

and cutting force due to higher wettability although MWCNT had lower thermal conductivity than SWCNT [50]. However, they cannot produce effective rolling like other spherical nanoparticles due to their cylinder structures. Therefore, CNTs can only produce limited anti-friction effect [43]. Furthermore, CNTs possess the highest coefficient of thermal conductivity among nanoparticles (**Table 1**), and so their application can be broadened by additionally dispersing other appropriate types of nanoparticles to form hybrid nanofluids [51, 52].

The ZrO_2 nanoparticles are mainly spherical (shown in **Figure 31**). They appear oblique crystal at low temperature and show tetragonal crystal formation at high temperature. ZrO_2 is soluble in sulfuric acid and hydrofluoric acid and has good thermal-chemical stability due to very high melting temperature. When at high temperature, they have good strength and toughness. ZrO_2 nanoparticles have the lowest coefficient of thermal conductivity among nanoparticles (**Table 1**), but their high surface energy and surface activity tend to be adsorbed onto the machined surface establishing a layer of self-healing lubrication film on the friction pair surface and achieving good lubrication effect [43].

The nanodiamond or ND exhibits cubic structure, and the morphology of nanoparticles is spherical or flaky (shown in **Figure 32**). ND presents very high hardness (HV = 98 GPa) which is superior to that of workpiece materials. Moreover, the ND exhibits extremely large elasticity modulus (980 GPa) with a compressive strength of about 13 GPa. With a size less than 1 μm, ND has attracted remarkable scientific attention due to their excellent mechanical and optical properties, high surface areas, and tunable surface structures. Due to unique properties, the excellent performances will certainly influence the lubrication performance in term of reducing

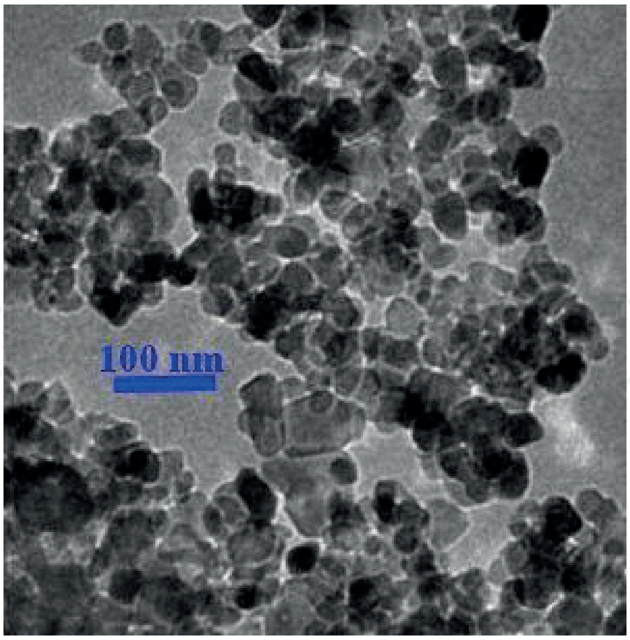

Figure 31. The SEM image of ZrO_2 nanoparticles (40 nm) (www.us-nano.com).

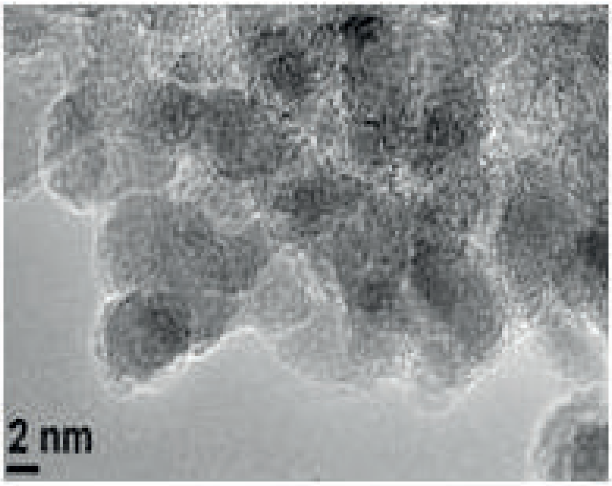

Figure 32. The SEM image of ND nanoparticles (50 nm) (ndp.diamonds).

friction coefficient, cutting forces, cutting temperature [53–56]. Interestingly, NDs can serve as abrasive grains and take part in cutting processes under high pressure like grinding process [43]; therefore, if the size of NDs becomes larger, they may deteriorate the surface quality.

3.3. The size of nanoparticles

The size of nanoparticles should not be avoided because it not only influences on the performance of nanofluids and cutting processes but also contributes significant amount of nanofluid cost. In markets, the smaller the grain size of nanoparticles, the higher their cost will be. **Figure 33** shows the relationship between the NP size and its cost, and it can be seen that the

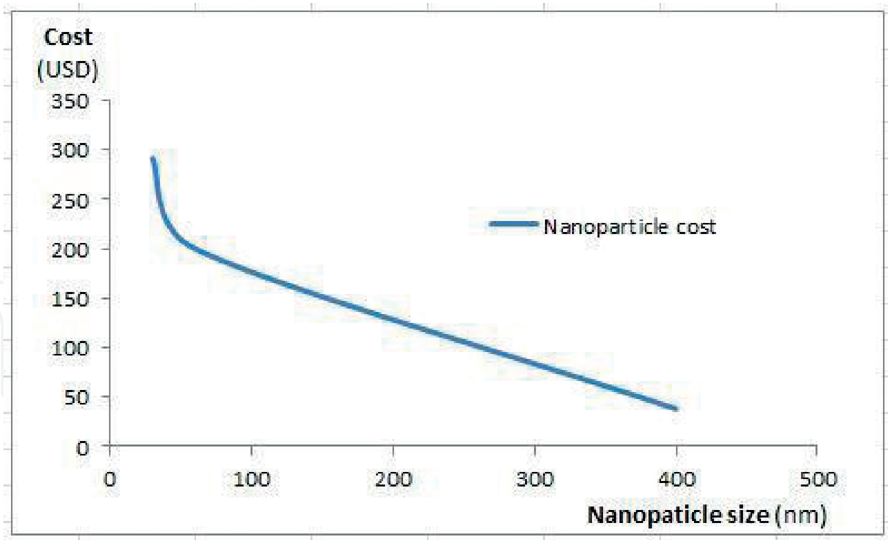

Figure 33. The relationship between 500 g of MoS_2 nanoparticle size and its cost.

grain size of nanoparticles strongly influences the cost of NPs. Hence, the NP size is definitely needed to optimize while remaining the good performance of nanofluids and the reasonable manufacturing cost [58, 59]. The experimental study on nanolubricant of nanographite (0.1 vol%) was carried out with diffrent particle sizes 5 μm, 450 nm, and 55 nm [60].

From **Figure 34**, the friction coefficient of nanolubricant of the disc specimen as a function of the applied normal force exhibits the much lower values compared to microlubricant and raw mineral lubricant. In this test, the fluid with the smallest NP size 55 nm shows the lowest friction coefficient and reaches stable state when increasing the applied normal force. Moreover, the microfluid of the microparticle size 5 μm shows the highest friction coefficient, which is also higher than that of pure mineral lubricant.

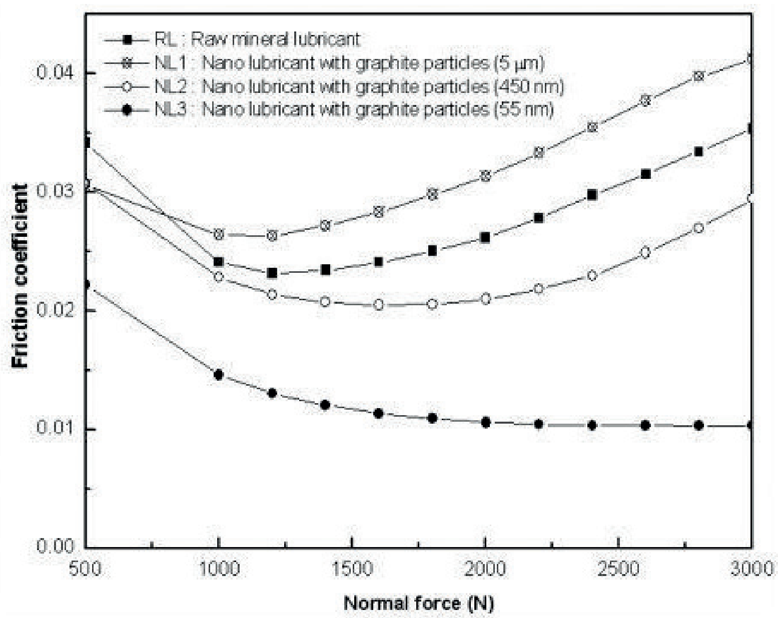

Figure 34. Friction coefficients of the disc specimen as a function of the applied normal force at different particle sizes [60].

The MQL grinding process of hardened AISI 52100 steel with Al_2O_3 nanofluids was done to investigate the effect of size of nanoparticles at grinding wheel speed =0.05 m/s and the grinding depth = 10 μm [61]. The grinding temperature was reduced with the nanofluid of smaller NP size (**Figure 35**). When comparing the surface roughness of Al_2O_3 nanofluids with NP size of 40 nm and 80 nm, it is clearly seen that the better surface roughness can be achieved by using NFs with NP size of 40 nm, even in different nanoconcentration (shown in **Figure 36**).

Another MQL grinding process with Al_2O_3 nanofluids and nanodiamond was done to investigate the effect of size of nanoparticles [62]. From **Figures 37** and **38**, MQL grinding process with nanofluids exhibits better surface roughness and reduces grinding forces when compared to those of dry and pure MQL grinding. Considered the NP size among nanofluids, the ND with smaller size 30 nm gives the best grinding performance in term of surface roughness and grinding forces.

Overall, the nano/microparticle sizes have the strong effects on cutting performance. Nanofluids exhibit better machining performance than microfluids. The smaller the NP size is, the better surface quality will be. However, the cost of NPs rises with smaller size, and so the appropriate nanoconcentration in fluid will be the key parameter affecting the application of nanofluids in machining practice.

3.4. The nanoparticle concentration

The nanoparticle concentration has attained a significant attention of many researchers because it influences on the performance of nanofluids and directly contributes a large fraction of the NF cost. The experimental study on nanolubricant of nanographite with different concentration 0.1% and 0.5% reveals that the lower friction coefficients and average temperature of lubricated surfaces of the specimens can be achieved in case of nanolubricant with larger volume of fraction 0.5% (shown in **Figures 39** and **40**) [60]. The similar observation can be made from **Figure 36** by the comparison of Al_2O_3 nanofluids with three concentrations 1, 3, and 5%. The value of surface roughness decreases as the nanoconcentration rises from 1 to

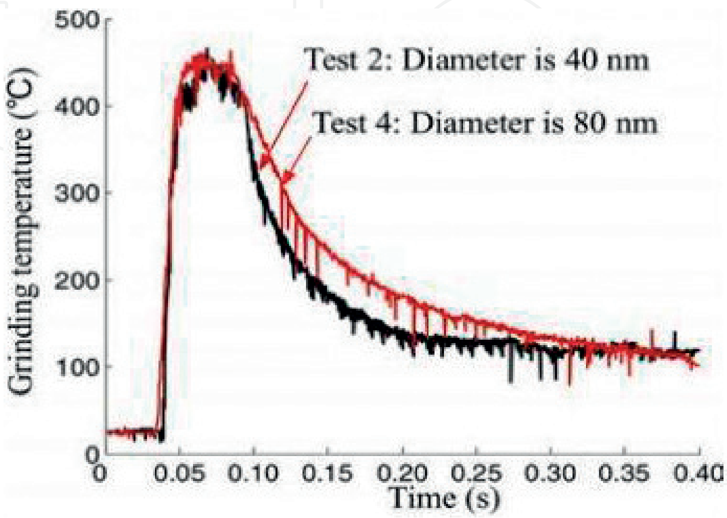

Figure 35. MQL grinding temperature of hardened AISI 52100 steel with Al_2O_3 nanofluids (grinding wheel speed =0.05 m/s; the grinding depth 10 μm) [61].

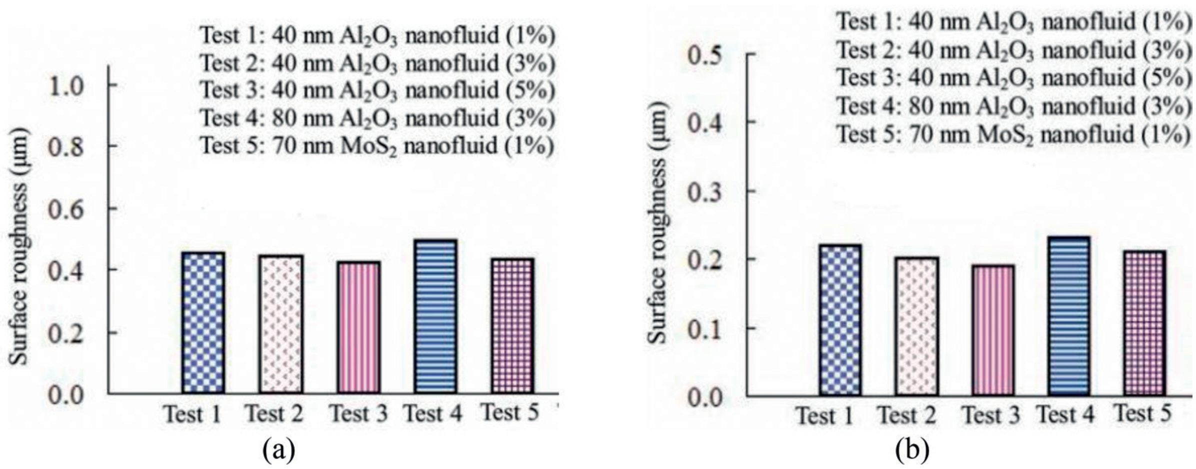

Figure 36. Surface roughness of MQL grinding: (a) across the grinding direction; (b) along the grinding direction [61].

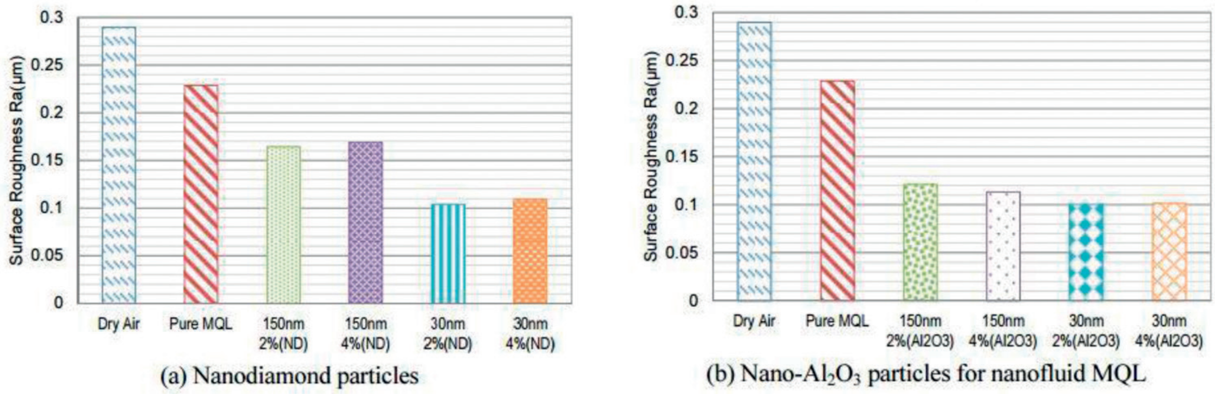

Figure 37. Surface roughness of MQL grinding with different nanofluids [62].

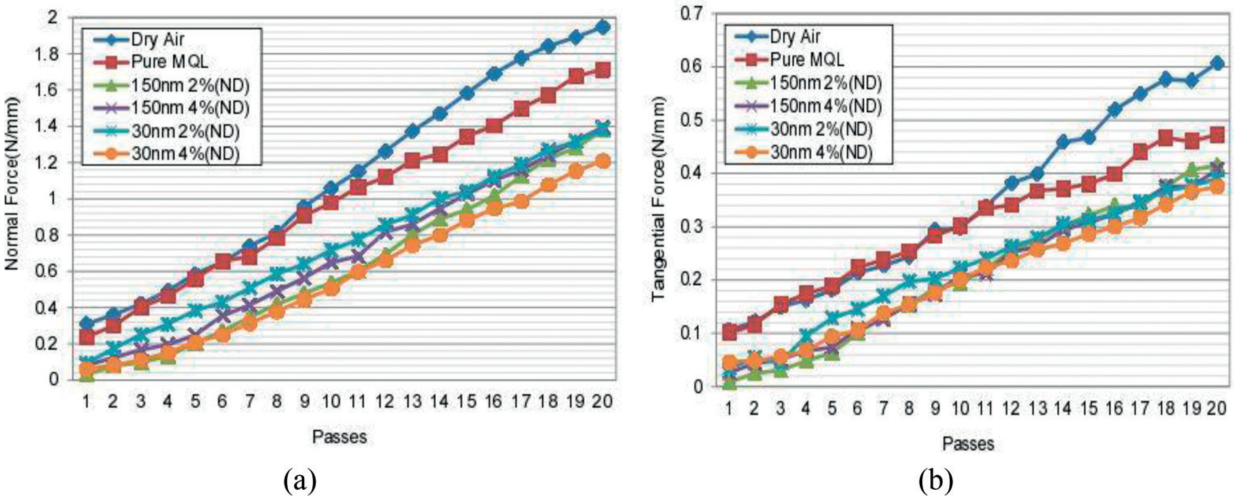

Figure 38. Measured grinding forces; (a) normal direction and (b) tangential direction in the cases of dry, pure MQL and MQL nanofluid with nanodiamond [62].

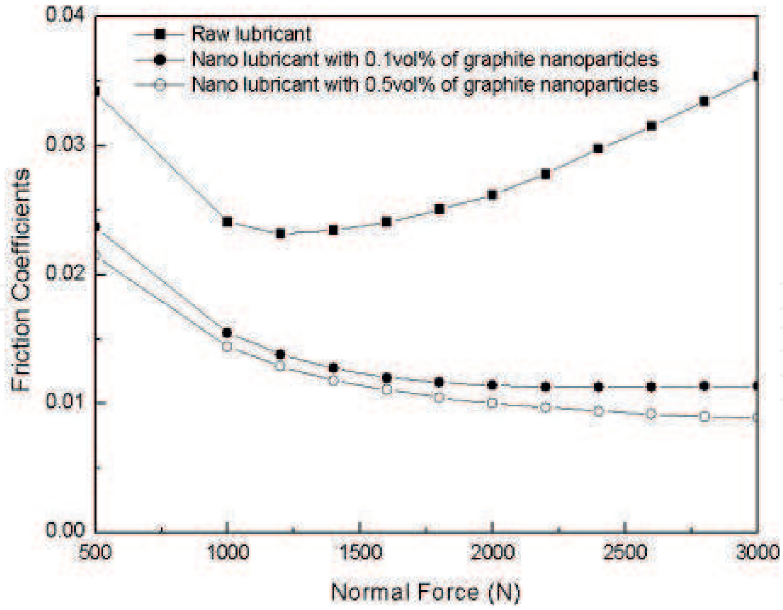

Figure 39. Friction coefficients of the disc specimen as a function of the applied normal force at different nanoconcentration [60].

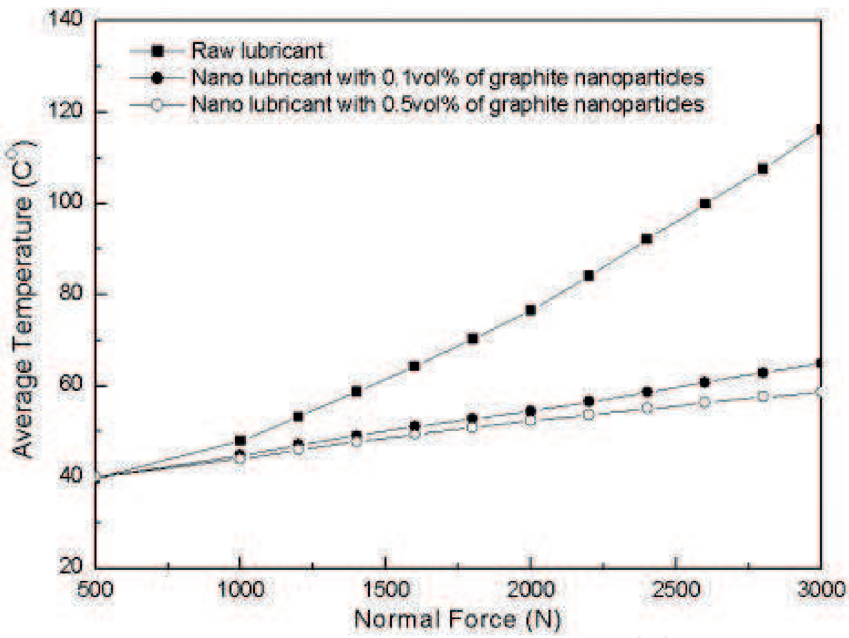

Figure 40. Temperature of lubricated surfaces of the specimens as a function of normal force with different nanoconcentration [60].

5%. In contrast, when rising the volume fraction of nanodiamond in MQL grinding, the little effectiveness on cutting performance can be achieved. From **Figure 37a**, the value of surface roughness increases along with the rise of the concentration of ND.

In summary, the nanoconcentration is necessarily investigated by further research to optimize this key parameter, by which the application of nanofluids together with MQL technique cannot be limited by the cost of nanoparticles. Although the volume fraction of nanoparticles in MQL fluid is relatively small in each experimental research, it will be large when applied to production line in practice.

3.5. Conclusion

The cost-effective and sustainable manufacturing techniques are being given considerable importance these days to ensure economic, societal, and environmental sustainability globally. The basic parameters of nanofluids are discussed in detail, and they give strong effects on their tribological and lubricating characteristics, as well as the cost of NFs. The selection of appropriate nanofluids with suitable parameters is the crucial factor for machining processes. Especially for hard machining materials using geometrically defined cutting edges (hard turning, hard milling, hard drilling, and so on), the effectiveness of nanofluids is evaluated in terms of reducing the friction coefficient, enhancing the cutting performance, ensuring the tool life, and achieving good surface quality. However, very few records can be seen in the literature indicating that more experimental research is needed to find the optimal parameters in order to ensure maximum performance of using nanofluids in machining.

4. The development trend of nanofluids

The successful application of nanofluids in MQL technique using vegetable oils becomes a big step toward sustainable manufacturing. This new trend is well suited to encounter the issue of environmental change. MQL machining under nanofluid condition significantly develops the cutting processes, which generate large amount of heat such as hard turning, hard milling, grinding, and so on. The machining capability and achieved surface integrity of hard cutting operations are much improved and equivalent to those of grinding, but the productivity is higher. They can replace or supplement to some of grinding processes. The progression of hard machining will reach further achievements.

Like the idea coming from composite materials, the use of hybrid nanofluids (two or more different types of nanoparticles suspended in fluids) recently gains much attention due to better performance when compared to nanofluids [63–65], but the ratio of mixing and the types of nanoparticles will be continually studied and proven. On the one hand, the MQCL technique, the novel development of the MQL technique will be the future of modern machining processes. MQCL technique has overcome the cooling effect, the main drawback of MQL method [66, 67]. MQCL technique with nanofluids or hybrid nanofluids definitely brings out novel solutions and develops hard machining and grinding to the new level in the near future. On the other hand, the development of ice jet machining is one of the greatest achievements in the field of modern/advanced machining. It is a nondestructive, nonabrasive, residue-free, and environmentally friendly way of machining [68].

Symbols and Abbreviations

a_p	depth of cut (mm)
v	cutting speed (m/min)

v_w	table speed (m/min)
f	feed rate (mm/rev)
f_t	feed rate (mm/tooth)
γ_o	rake angle (°)
α_o	relief angle (°)
λ_s	inclination angle (°)
k_r	side cutting-edge angle (°)
F_x, F_y, F_z	cutting forces (N)
CNT	carbon nanotube
CNTs	carbon nanotubes
SWCNT	single-walled carbon nanotube
MWCNT	multi-walled carbon nanotube
MQL	minimum quantity lubrication
MQCL	minimum quantity cooling lubrication
SQL	small quantity lubrication
ND	nanodiamond
NF	nanofluid
NFs	nanofluids
NP	nanoparticle
NPs	nanoparticles

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