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CRITICAL REVIEW

Recent progress on the application of nanofluids and hybrid nanofluids in machining: a comprehensive review

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Abstract
This paper summarises the recent progress of nanofluids and hybrid nanofluids in various machining processes including milling, turning, grinding and drilling. Thermophysical properties of nanofluid and hybrid nanofluid, such as viscosity, thermal conductivity, stability and wettability, are also discussed. Results showed that thermal conductivity and viscosity of nanofluid are strongly affected by temperature, mass volume fraction, types of nanoparticles and nanoparticle size. Thermophysical properties of hybrid nanofluids are greater than those of nanofluids and base fluids. Scientific findings also indicated that nanofluids and hybrid nanofluids outperform other cooling-lubrication techniques. The application of nanofluids and hybrid nanofluids enhances the surface finish and reduces the cutting temperature, cutting force and tool wear during machining. However, more research work is still needed to determine their applicability in practical industries, especially in the usage of hybrid nanofluid in milling and drilling processes.

Keywords Nanofluid · Hybrid nanofluid · Cutting fluid · Cooling technique · Machining

1 Introduction

A contact of the workpiece and cutting tool will generate heat at the contact zone during machining [1]. The rising temperature at the contact zone will exert a negative effect on the machining performance such as high tool wear, high cutting force, and result in poor finishing quality. Therefore, cooling and lubrication are extremely important in this area. Cutting fluid, which is normally used as a coolant or lubricant, is essential in machining processes [2]. According to Samanta et al. [3], cutting fluid (water-based fluid) is used to cool the cutting area during machining and eliminate the unwanted effect of heat on both the workpiece and tools. In addition, cutting fluid (oil-based fluid) also works as a lubricant by penetrating in the chip–tool interface to reduce friction and prevent build-up edge formation. The cutting fluid also helps in the chip removal from the cutting zone and protects the machine tool against corrosion to improve the accuracy and ease of use during machining.

Figure 1 shows the various types of cooling–lubrication techniques, such as dry machining, wet machining, minimum quantity lubricant (MQL), cryogenic cooling, nanofluid and hybrid nanofluid. According to Goindi and Sarkar [4], dry machining is conducted without the assistance of any cutting fluids. Tool wear is high in this technique because of the effects of several wear mechanisms, such as abrasion, adhesion and diffusion, which reduce the tool life [5]. Furthermore, without the use of cutting fluid, chips formed during machining processes that cannot be washed away result in flaws on the machined surface [2].

Wet machining/flood cooling is another type of cooling–lubrication technique that involves supplying a constant stream of fluid to the tool work or chip–tool interface during the machining operation [6].Wet machining requires more coolant fluid than MQL or any other cooling system. Gueli et al. [7] investigated the machining performance of slot milling of Inconel 718 under dry and flood cooling conditions by varying the depth of cut and feed rate. The results indicated that the average surface roughness of machined slots is slightly lower for flood coolant machining compared with that of dry machining

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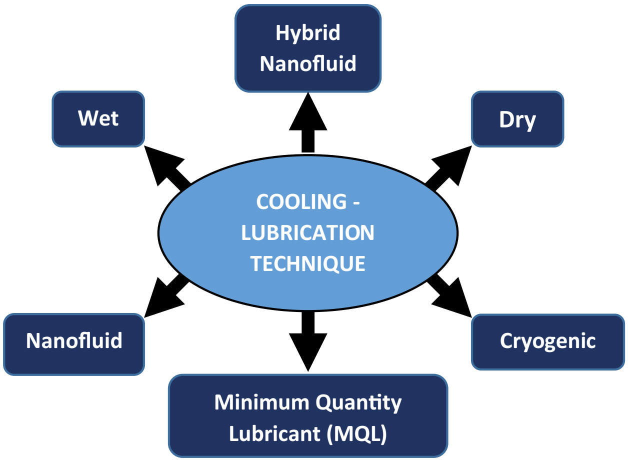


Fig. 1 Cooling–lubrication techniques in machining

at a lower depth of cut and feed rate settings. However, Razak et al. [8] analysed wet machining and revealed that nonuniform surface roughness is formed and the final surface presents an alternate shiny and dull area. Meanwhile, Najiha and Rahman [9] discovered that the cutting edge is completely damaged due to attrition and adhesion when wet machining is used with flooded conditions.

MQL is a lubricant sprayed in a fine mist over the workpiece surface and the cutting tool after being mixed with compressed air [10]. Jagatheesan et al. [11] investigated the impact of MQL in the turning process with AISI 4320 alloy steel and showed that MQL provides excellent tool and workpiece interplay, low temperature and minimal cutting force. These results are consistent with recent study of Sun et al. [12], whereby milling force and cutting temperature by using MQL decrease by 12.8% and 9.2%, respectively, compared to that of dry milling.

Cryogenic machining is an environmentally friendly cooling method that typically employs liquid nitrogen as the cooling medium [13]. An external spray cooling cryogenic machining setup was created to spray the cryogenic coolant at the machining zone [14]. Pusavec et al. [15] revealed that cryogenic machining produces lower surface roughness compared with other machining methods. Danish et al. [16] also showed that the cryogenic–LN_2 system can significantly reduce the cutting force by 32.1%, tool flank wear by 33.3%, and total energy consumption by 18% compared with dry machining conditions. Table 1 shows some of the previous research that conducted by using different cooling–lubrication techniques.

Nanofluids have shown higher efficiency at heat transfer than conventional fluids in recent studies. Nanofluid is a dispersion of nanometre-sized solid particles in base fluids, such as water and oils [17]. In 2019, Sirin and Kivak [18] reported that better surface roughness values, lower cutting force and better tool wear are observed when hBN nanofluid is used during cutting instead of MoS_2 and graphite nanofluids. Chakma et al. [19] discovered that machining aluminium metal matrix nanocomposite with carbon nanotube nanofluid significantly enhances surface quality compared with that in dry environment. Danish et al. [20] concluded that the interlayer slip behaviour of graphene in sunflower oil reduces the contact surface between the tool and workpiece and results in improved surface morphology and machining efficiency.

Hybrid nanofluid, another type of cutting fluid, is a combination of two or more nanoparticles mixed in a medium of base fluid. In 2016, Sidik et al. [21] reported that hybrid nanofluids present higher heat transfer performance and thermophysical properties compared to nanofluids with a single type of nanoparticle. Similarly, Sarkar et al. [22] demonstrated that hybrid nanofluids present higher thermal conductivity than individual nanofluids because of the synergistic effect. The hybrid nanofluid can be produced by suspending (i) various types of nanoparticles (two or more) and (ii) composite nanoparticles in the base fluid.

By using different cooling–lubrication techniques in machining, the machining performance has been extensively investigated with various optimisation methods. For example, Aslantas et al. [23] explored the multi-objective optimisation of micro-turning process parameters, such as cutting speed, feed rate and depth of cut, using response surface method (RSM). The researchers revealed that optimised values for surface roughness of Sa and Sz are 0.50 and 4.16 µm, respectively, and the material removal rate is 239.03 mm^3/min. Jamil et al. [24] also used the RSM to design experiments for bone drilling with micro cooling spray technique. The researchers reported that parameters of cutting speed and feed rate highly influence temperature and thrust force, respectively. Danish et al. [25] utilised the RSM to develop an arithmetic model for predicting the maximum temperature of the surface during cryogenic and dry machining of AZ31 magnesium alloy. The investigation revealed that the cutting speed, feed rate and depth of cut present a significant impact on the maximum temperature. Sada and Ikpeseni [26] applied artificial neural network (ANN) and adaptive neuro-fuzzy inference system (ANFIS) models to predict the metal removal rate and tool wear in the turning process of AISI 1050 steel. The researchers indicated that ANN outperforms ANFIS techniques in terms of the accuracy of results. Apart from these methods, genetic algorithm (GA) technique has also been widely used in optimisation studies. Kabil and Kaynak [27] reported that optimisation via GA can effectively increase the machining performance (material removal rate, tool wear and power consumption) of Titanium Ti-5553 alloy.

In the literatures, although many experimental and modelling studies have been conducted on machining performance using various cooling–lubrication techniques, a comprehensive review on the use of nanofluid and hybrid

Table 1 Previous researches that conducted by using different cooling-lubrication techniques

Cooling-lubrication technique	Machining process	Workpiece material	Cutting tool/insert	Important findings	Researcher
Dry	Turning	Titanium alloy and Ti-55531	Cemented tungsten carbide tools (WC–Co)	High cutting temperature and high stress generation caused the tool wear when using Ti-5531 and Ti-6Al-4 V alloy as a workpiece	Nouari and Makich [28]
	Turning	Inconel 718 alloy	Coated insert (CVD TiCN–Al_2O_3–TiN)	At the optimum cutting speed, dry machining with the coated carbide tool led to acceptable surface finish	Devillez et al. [29]
	Turning	Titanium alloy	Carbide insert PVD TiAlN coated	The important mechanism that led to tool wear was abrasion with built-up edge, abrasion and cutting edge plastic deformation	Joshi et al. [30]
	Drilling	Aluminium alloy	Carbide K10F	By using Al–7Si–4Zn–3Cu alloy, surface roughness and thrust force were minimum compared with other type of aluminium	Bayraktar and Afyon [31]
	Turning	LM 25 aluminium alloy	Polycrystalline diamond insert	Better machining performances were obtained by using wet machining rather than dry machining	Dhanalakshmi and Rameshbabu [32]
	Turning	Aluminium alloy 2024	TiN, TiAIN, PCD coated on cemented carbide insert and uncoated cemented carbide	Lowest tool wear was observed when using TiAIN coated insert compared with TiN, PCD and uncoated cemented carbide by 36%, 58% and 21%, respectively	Uddin et al. [33]
	Drilling	CFRP/Ti6Al4V composites	PVD TiAIN coated drill bit	Dry machining caused poor surface roughness and higher drilling torque compared with MQL condition	Ji et al. [34]
	Micro drilling	Inconel 718	TiAIN coated carbide micro drill bit	At dry condition, low speed (1000 rpm) with low feed rate (3 µm/rev) produced longer tool life	Khadtare et al. [35]
	Drilling	Aluminium alloy	Coated tool	Burr formation can be seen at the exit hole of workpiece when dry machining was used compared to the used of lubricant	Sandeep reddy et al. [36]
	Turning	Al-12Si-0.6 Mg	CVD-TiCN + TiN and PVD-TiAlN + TiN coated insert	The cutting force was reduced with T6 heat treatment at all cutting speed and feed rate values	Bayraktar and Demir [37]
	Milling	Aluminium alloy 6061	TiAIN coated carbide PVD insert	Tool wear in dry condition was higher than using MQL and flood technique. Best surface finish can be seen by using MQL technique compared with dry condition	Shukla et al. [38]
	Milling	Inconel 718	β-SiAlON ceramic tool	The highest material removal volume was obtained at $v_c = 800$ m/min, $a_p = 1$ mm, and $f_z = 0.05$ mm/z, which was 5 times more than that of commercial coated tool	Yin et al. [39]
Wet	Turning	17–4 PH Stainless steel	Coro Turn DCMX 11 T3 04-WM 1115 insert	Cutting force in dry condition was higher than using wet and MQL condition	Leksycki et al. [40]
	Turning	AISI-1055, AISI-4340	Coated cemented carbide	Wet machining in AISI 4340 was better than AISI 1055 steel, in terms of Ra and MRR obtained	Rahman et al. [41]
	Drilling	Aluminium alloy	Tungsten carbide textured tool	Hole accuracy and surface roughness were improved with the assistance of lubricant	Dheeraj et al. [42]

Table 1 (continued)

Cooling-lubrication technique	Machining process	Workpiece material	Cutting tool/insert	Important findings	Researcher
Cryogenic	Turning	NiTi alloys	DCGT11T308HP-grade KC5410 cutting tool insert with TiB_2 coating	Under cryogenic machining, surface quality was improved and the carbide inclusion helped to increase tool life	Kaynak et al. [43]
	Turning	Hardened AISI 420	M grade CVD Ti (C, N) + Al_2O_3 + TiN coated carbide insert	Surface roughness and surface topography were better by using nanofluid cooling system but cryogenic condition was better for chip morphology, tool-chip interface temperature, and longer tool life	Yildirim [44]
	Milling	Inconel 718	S10 carbide end mills	Tool life was improved 57% by using cryogenic-MQL compared with emulsion coolant	Pereira et al. [45]
	Drilling	CFRP composites	Solid carbide	Holes surface finish for cryogenic drilling was improved by 14–38% compared to dry drilling	Khanna et al. [46]
	Drilling	Inconel 718 Superalloy	TiAIN coated carbide twist drill	Compared to dry machining, cryogenic caused improvement of tool life by 87.50% and better hole quality can be obtained	Khanna et al. [47]
	Drilling	AZ31 magnesium alloy	Two flute helical PVD (TiAIN) coated drills	Cryogenic condition resulted less tool wear, reduced adhesion and produced smaller size of chip than dry condition	Koklu and Coban [48]
Minimum Quantity Lubricant	Turning	Inconel 718 nickel alloy	TiAIN coated CNMG 12 04 04-SM 1105 insert	Compared with flood condition, MQL produced higher surface quality and lower cutting speed	Gong et al. [49]
	Turning	Aluminium alloy 6026-T9	Tungsten carbide insert	The most significant parameter for surface roughness was feed rate. Progression of flank wear was slower at MQL condition than dry condition	Abas et al. [50]
	Turning	Alloy Haynes 25	Uncoated carbide (H13-A)	MQL parameters like cutting speed, cutting fluid and flow are the significant factors affecting tool wear and surface roughness	Sarikaya and Güllü [51]
	Milling	Aluminium alloy 7075-T6	Uncoated carbide	When compared to dry milling and nanofluid MQL milling, the MQL method produced a better surface finish	Kulkarni et al. [52]
	Milling	Ti40 burn-resistant titanium alloy	Carbide inserts coated with Ti (C, N)-Al_2O_3 multilayer	Tool wear and cutting temperature were dramatically lowered when pneumatic mist jet impinging cooling technology was used instead of traditional flood cooling	Lv et al. [53]
	End Milling	Titanium alloy	Carbide inserts coated with titanium carbonitride (TiCN) by PVD process	MQL technique can improve tool life, decrease surface roughness and improve productivity	Garcia and Ribeiro [54]
	Drilling	CFRP/ Ti6Al4V stacks	TiAIN and diamond coated drill	MQL condition failed to improve the machining performance for composite surface	Xu et al. [55]
	Drilling	Aluminium 2024-T351 alloy	Uncoated tungsten carbide drills	Temperature reduction can be obtained by using MQL condition compared with dry and air cooling condition	Zhu et al. [56]
	Grinding	AISI H13 tool steel	White alumina wheel	Under MQL mist, surface quality has been improved	Awale et al. [57]
	Grinding	Inconel 718	Alumina AA80 K5 V8	Lower grinding energy and good surface quality can be obtained using MQL condition	Lal Virdi et al. [58]

nanofluid in the machining area is still scarce. Therefore, this paper aims to provide a critical and comprehensive review of the current advancements in the application of nanofluids and hybrid nanofluids in machining, particularly in turning, grinding, milling and drilling processes. The multi-response optimisation studies and the mechanism of nanofluid and hybrid nanofluid techniques for improving the machining performance also have been explained. This paper also discusses the thermophysical properties of nanofluids and hybrid nanofluids, such as viscosity, thermal conductivity, stability and wettability.

2 Nanofluid and hybrid nanofluid

The term nanofluid was first coined by Choi and Eastman [17] at Agronne National Laboratory in the USA. Raja et al. [59] stated that nanofluid is created from the dispersion of nanomaterials in base fluids, such as oil and water. This new type of heat transfer fluids has attracted considerable research attention in the last few decades. Nanofluid is more efficient at heat transfer than conventional cutting fluids. As for nanoparticles, the size is 1–100 nm and the widely used nanoparticles are metal and metal oxide nanoparticles.

Yu and Xie [60] demonstrated that nanofluid can be prepared using a one- or two-step method. Base fluids are very important in the stage of nanofluid preparation because of special requirements of nanofluids, such as stable and even suspension, low particle agglomeration, adequate durability, absence of chemical change of particles or fluid, good fluidity, low viscosity and high thermal conductivity [60, 61]. According to Heris et al. [62], base fluids, such as ethylene glycol, oil and water, show poor heat transfer. Therefore, properties should be enhanced to improve their suitability for cutting fluids in practical metal cutting operations. Nanofluids have been widely used in many industry sectors as coolant, lubricant and heat transfer agent due to their advantages of high safety margin, reduced cost, reduced size of the system and improved efficiency of heat conversion [63].

Hybrid nanofluids are considered an extension of nanofluids and formed by suspending two or more different nanoparticles in a base fluid in either composite or mixture form [22]. The benefit of hybrid nanofluid in heat transfer enhancement is due to its synergistic effect. Hybrid nanofluids may present better thermal properties compared with base fluids and nanofluids containing a single nanoparticle [64].

Figure 2 depicts the lubrication mechanism and tribochemical reaction effect of the base fluid with nanoparticles. There are few mechanisms have been observed, such as rolling, interlayer sliding, polishing, mending and protective film. The rolling mechanism refers to nanoparticles that roll like bearings between friction surfaces. If the shear force applied to nanoparticles is sufficiently large to overcome van der Waals force, then sliding between nanoparticles layers will occur and result in an interlayer sliding effect. In terms of the polishing mechanism, nanoparticles will grind the peaks under high pressure and speed to smoothen the surface, reduce friction and improve surface quality. As for mending mechanism, the occurrence of fine nanoparticles subsides and they become adsorbed in the furrows whilst lowering the surface roughness. In addition, nanoparticles also adhere to the contact surface and form a physical tribofilm, which reduces friction and wear [65].

3 Thermophysical properties of nanofluid and hybrid nanofluid

3.1 Viscosity

Investigation of the viscosity rate is important to reveal the fluidic behaviour of the liquid [67]. According to the previous studies, temperature significantly affects the viscosity of nanofluid and hybrid nanofluid. Dardan et al. [68] revealed that with the increment of temperature at a range of 25–30 °C, the viscosity reduces due to the enhancement of nanofluid movement. However, when the temperature further increases, the movement of nanotube becomes perpendicular to the flow direction, thereby increasing the viscosity. Esfe et al. [69] investigated the viscosity of ZnO–MWCNT/10w40 hybrid nanofluid at a temperature from 5 to 55 °C with a solid volume fraction of 0.05–1%

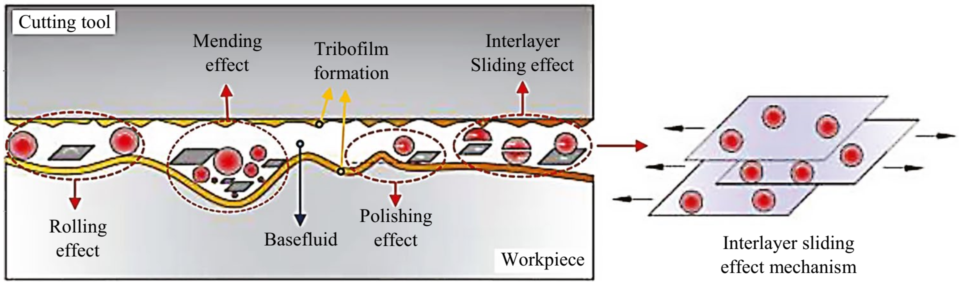


Fig. 2 Nanofluid mechanisms formed in the cutting zone. Reprinted from [66] with permission from Elsevier

and showed that the viscosity decreases as the temperature increases.

Other than temperature, mass volume fraction is another factor that influences the nanofluid and hybrid nanofluid viscosity. Figure 3 illustrates the variations of dynamic viscosity with nanoparticles volume fraction at different temperatures [70]. The viscosity clearly increases with the increase of the nanoparticle volume fraction. This result is consistent with the findings of Ghasemi and Karimipour [71], wherein the viscosity of CuO–paraffin nanofluid significantly changes when the particle mass fraction is higher than 1.5 wt%. According to Hemmat et al. [72], collisions between nanoparticles and the base fluid caused by van der Waals forces will increase and result in the increase of viscosity when the amount of nanoparticles in a constant volume of a liquid increases.

Notably, the effect of particle size on the viscosity of nanofluids achieves contradictory results. According to Hu et al. [73], the relative viscosity of the nanofluid increases with the increase of the particle size, particularly at a high volume fraction. However, Nithiyanantham et al. [74] indicated that the nanofluid with smaller particles (SiO_2: 27 nm) present higher viscosity than those with larger particles (SiO_2: 450 and 800 nm) due to the availability of larger surface area. Hu et al. [73] concluded that interparticle spacing and extent of particle aggregation, which are highly influenced by nanoparticle size, are extremely important factors in determining the viscosity of nanofluids.

The viscosity of different types of nanofluids has been extensively investigated. For example, Kazemi et al. [75] investigated the effect of adding silica (SiO_2) and graphene (G) nanoparticles as well as their hybrid (G [30%] + SiO_2 [70%]) on the viscosity of water. The researchers discovered that the SiO_2/water mono-nanofluid indicates the least rise in viscosity amongst the three types of nanofluids at high concentrations. Furthermore, Shahsavar et al. [76] demonstrated that the viscosity of CNT–Fe_3O_4 hybrid nanofluid is nearly 28.60% higher than that of Fe_3O_4 nanofluid. The presence of CNT significantly affects the increase of viscosity value on hybrid nanofluids. Ahammed et al. [77] revealed that the viscosity of graphene–alumina hybrid nanofluid is greater than that of the alumina nanofluid but lower than that of the graphene nanofluid. However, Yang et al. [78] indicated that describing the effect of particle type on viscosity is impossible because viscosity values for different nanofluids vary substantially and appear erratic.

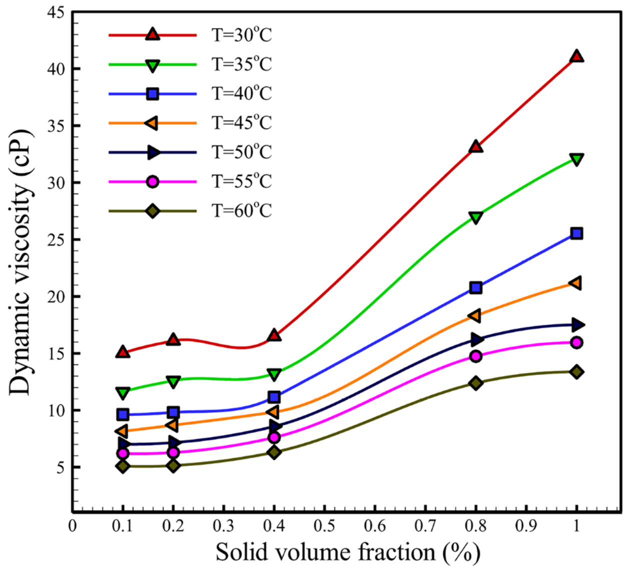


Fig. 3 Variation of dynamic viscosity to solid volume fraction at different temperature. Reprinted from [70] with permission from Elsevier

3.2 Thermal conductivity

Thermal conductivity refers to the fluid's ability to absorb and disperse heat to its surrounding. Temperature significantly affects the thermal conductivity of nanofluid and hybrid nanofluid. According to Baby and Sundara [79] and Madhesh et al. [80], the nanofluid's thermal conductivity increases as the temperature increases. Besides that, many studies have explored the influence of nanoparticle concentration on thermal conductivity. For example, Thakur et al. [81] discovered that the thermal conductivity of SiC nanofluids improves when the nanoparticle concentration increases, as shown in Fig. 4. Hamid et al. [82] also showed that the thermal conductivity of TiO_2–SiO_2 hybrid nanofluids is higher than that of the base fluid at all concentrations and the maximum thermal conductivity occurs at a concentration of 3.0%. This finding is consistent with data obtained by Sajid and Ali [83], whereby the concentration of nanoparticles is directly proportional to thermal conductivity due to the high thermal conductivity of nanoparticles. However, other reports also claimed that there is no improvement of

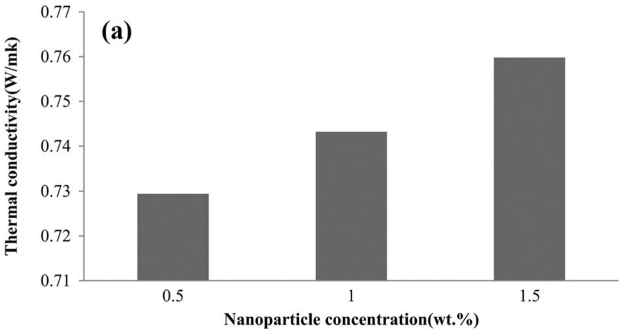


Fig. 4 Variation of thermal conductivity with concentration of SiC. Reprinted from [81], Copyright 2020, with permission from Springer

thermal conductivity, especially at high concentrations [84, 85]. Nfawa et al. [85] reported that the decline of thermal conductivity above a volume concentration of 1% is attributed to the decrease of the specific area-to-volume ratio of nanomaterials and the formation of nanoparticle clusters.

Particle size is another crucial factor that influences the thermal conductivity of nanofluid and hybrid nanofluid. For example, Nithiyanantham et al. [74] compared the effect of SiO_2 nanoparticle size (27, 450 and 800 nm) on the thermal conductivity of nanofluid and revealed that larger spherical-shaped SiO_2 nanoparticles have lower thermal conductivity than smaller nanoparticles. This observation is consistent with the findings of Loong et al. [86]. Yang et al. [78] stated that the increase of thermal conductivity with small particles is due to enhanced Brownian velocity and surface effect that small particles can achieve.

Apart from the aforementioned factors, particle type also affects the thermal conductivity of nanofluids and hybrid nanofluid. According to Yang et al. [78], carbon nanomaterials (CNTs and graphene), metals (Au, Ag, Cu and Fe) and metal oxides (CuO, Al_2O_3, TiO_2, ZnO, SiC and SiO_2) are commonly used nanomaterials. High thermal conductivity in nanoparticles can remarkably enhance the thermal conductivity of nanofluids in general. For example, Loong et al. [86] investigated various types of metal oxide (Al_2O_3, CuO, MgO, TiO_2, SiO, ZnO and ZrO_2) water-based nanofluids and discovered that the MgO nanofluid presents the best heat transfer performance amongst these metal oxides due to its high thermal conductivity. In addition, CNTs and graphene nanomaterials are also widely known for their capability to enhance the thermal conductivity of nanofluids due to their exceptional thermal conductivity [64]. Nasiri et al. [87] found that single-walled CNT nanofluid demonstrated the maximum improvement in thermal conductivity over the base fluid. Furthermore, Das et al. [88] showed that 0.1 wt% of graphene nanoparticles can enhance the thermal conductivity of graphene nanofluid by 29% compared with that of deionised water.

3.3 Stability

Nanofluid stability can be affected by many factors, such as dielectric constant of base fluid, pH value, particle size, shape and concentration of nanofluid. Zhu et al. [89] and Kim et al. [90] used zeta potential to examine the stability of copper and Au–water nanofluids, respectively. According to Hwang et al. [91], suspended nanoparticle characteristics (particle morphology and chemical structure) and the base fluid significantly impacted the nanofluid stability. Similarly, Suresh et al. [92] showed that the nanofluid stability reduces with the increase of volume concentration. The stability of the nanofluid seriously influences the machining performance. This view is also supported by Kim et al. [93], who found that the stability of the water-based bohemite alumina nanofluid significantly depends on the particle shape. The researchers concluded that the sedimentation of blade-shaped particles is faster than that of platelet- and brick-shaped particles. Poor stability was also observed with the increase of particle concentration because the van der Waals attractive potential dominated over the electrostatic repulsive potential and caused the agglomeration of nanoparticles that led to sedimentation [94]. According to Sharmin et al. [95], 0.3 vol% of carbon nanotube nanofluid can be used as an efficient coolant to improve the surface roughness, cutting force and tool wear because of its high stability.

3.4 Wettability

Contact angle values in the surface wettability test represent the ability of lubricants to wet metal surfaces, and a low contact angle value (high wettability) increases the chances of tribo-film formation [96]. Kumar et al. [97] revealed that the alumina–MoS_2 hybrid nanofluid recorded the smallest contact angle compared with the alumina nanofluid and base fluid. This result is consistent with those of Xie et al. [96]. The lower contact angle of SiO_2:graphene combination nanofluids than that of pure water and graphene nanofluids indicated that the workpiece surface is more wettable with SiO_2:graphene combination nanofluids than that with pure water and graphene nanofluids.

According to Kumar et al. [98], physical and morphological features of nanoparticles significantly affect wettability characteristics. Figure 5 shows that the contact angle of hard nanoparticles, such as B_4C, ZnO and Al_2O_3, remarkably decreases compared with that of soft nanoparticles (WS_2, MoS_2 and h-BN) when added to the base fluid (DI water).

4 Nanofluid and hybrid nanofluid in the machining process

4.1 Turning

Turning or lathe is a type of machining operation that removes unwanted materials from the workpiece using a single-point cutting tool to obtain the final product. A pre-shaped material was attached to the fixture on the turning machine and then rotated at a high-speed motion during the lathe operation [99]. Due to the regular contact of workpiece and cutting tool, the cutting zone generated a considerable amount of heat and deteriorated the surface finish of the product. Lubricants and coolants are normally supplied to the workpiece–tool intersection to solve this issue. Various types of nanofluids have been applied to the turning operation due to their great advantages. For example, Amrita et al. [100] revealed that the addition of nanographite increases

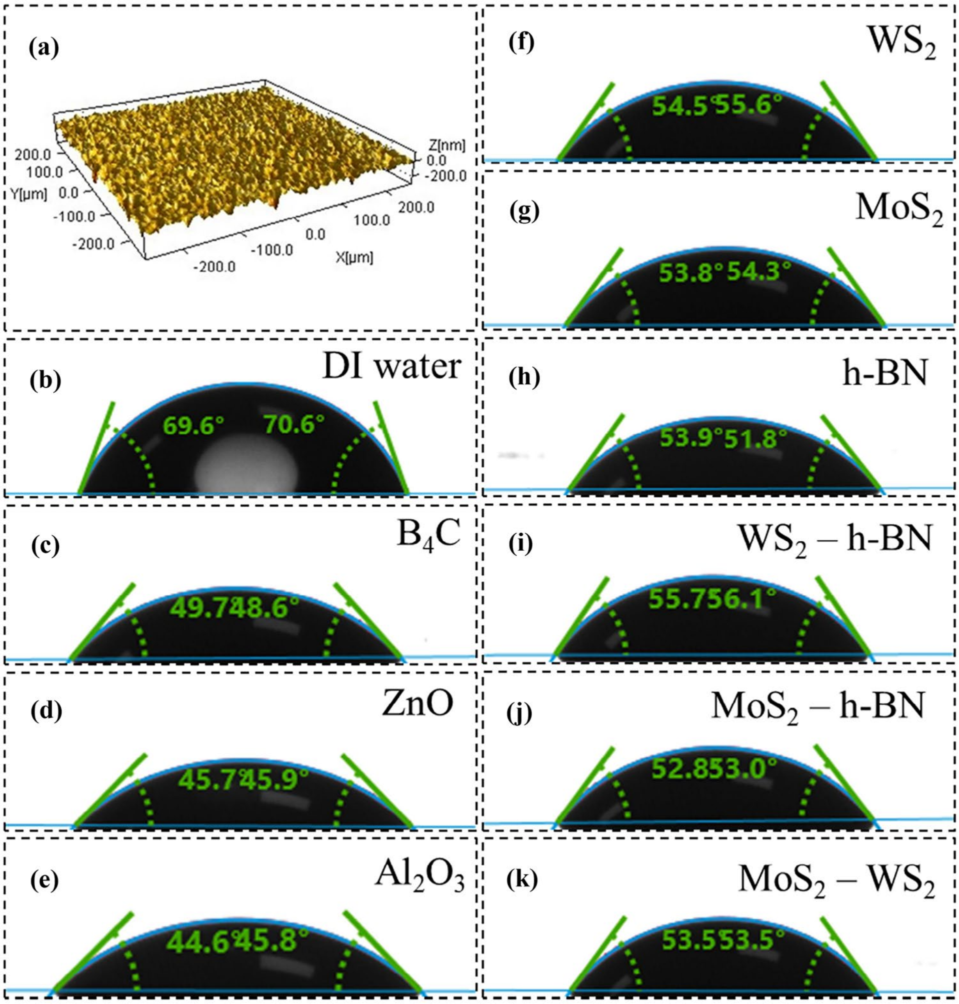


Fig. 5 **a** 3D profile of refined silicon nitride surface and **b**–**k** contact angle between the surface and various nanofluids. Reprinted from [98] with permission from Elsevier

the heat carrying capacity of soluble oil, thereby improving tool wear, surface roughness and cutting force compared with dry and wet conditions. Saravanakumar et al. [101] investigated the turning process with and without silver nanoparticles under different machining conditions. The researchers claimed that tool tip temperature can reduce with the inclusion of 0.5 vol% of silver nanoparticles, mainly due to the increase of thermal conductivity of the silver nanofluid caused by the interfacial layer between nanoparticles and the liquid interface as well as the Brownian motion of nanoparticles.

Su et al. [102] turned the AISI 1045 using vegetable-based oil mixed with graphite nanoparticles through the MQL method. The results indicated that the temperature and cutting force remarkably reduce when the nanofluid MQL is used. Li et al. [103] revealed that the efficiency of cooling and lubrication enhances as the frictional force and cutting temperature significantly reduces with the addition of graphene oxide nanosheets into the coolant. As illustrated in Fig. 6, under nanofluid minimum quantity lubrication (NMQL), tool wear evidently decreased by 18.17% and 4.54% and surface quality improved by 55.58% and 5.48% compared with those under dry and flood machining, respectively [104].

Duc et al. [105] compared the turning performance of MoS_2 and Al_2O_3 nanofluids on 90CrSi steel and demonstrated that the Al_2O_3 nanofluid achieves better surface finish compared with the MoS_2 nanofluid. Khan et al. [106] compared the machining performance of Ag and Cu nanofluids and showed that Cu-based nanolubricant produces a lower coefficient of friction, cutting force and cutting temperature than Ag-based nanolubricants. Yi et al. [107] indicated that the respective tool flank wear reduces by about 44.1%, 53.9% and 71.3% when 0.1, 0.3 and 0.5 wt% of graphene oxide (GO) nanofluids are used instead of conventional coolants (Fig. 7). MQL turning of SiC–based nanofluids exhibited better performance than MQL turning in terms of temperature, cutting force and surface roughness height [81]. Other important studies that utilise nanofluids in the turning process are summarised in Table 2.

Hybrid nanofluids have been widely used as coolant in the machining process in recent years. For example, Kumar

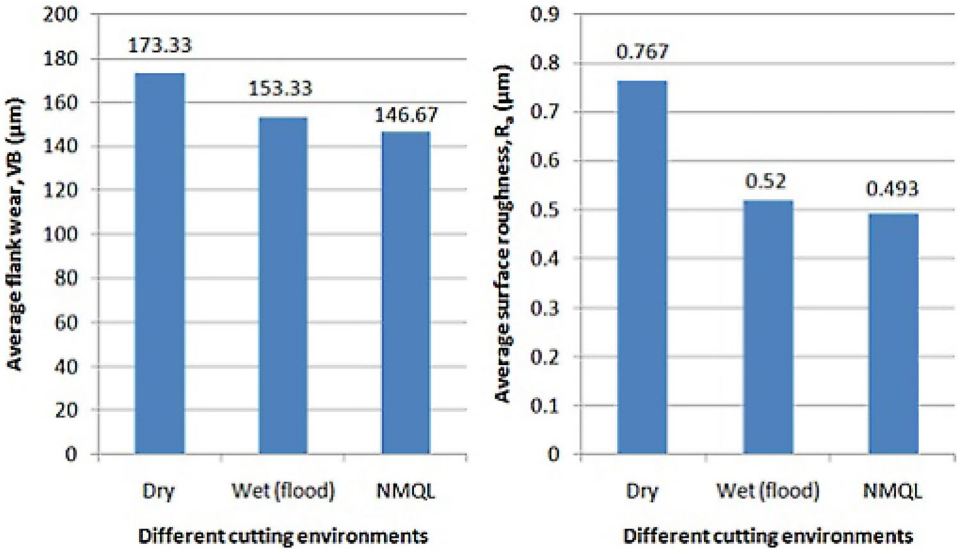


Fig. 6 Tool wear and surface roughness under dry, wet and NMQL. Reprinted from [104], Copyright 2018, with permission from Springer

et al. [97] demonstrated that the Al–MoS_2 hybrid nanofluid shows a significant reduction of 7.35% in cutting force (Fz), 18.08% in feed force (Fx), 5.73% in thrust force (Fy) and 2.38% in surface roughness compared with the Al_2O_3 mixed nanofluid. The results showed that the reduction in cutting force and surface roughness can be attributed to the entrapment of nanoparticles in porous abrasives and tribo-film layers consisting of the Mo–S–P (molybdenum, sulphur and phosphorus) chemical complex at the machining zone that generates lubrication due to the continuous shearing and alignment. Gugulothu and Pasam [108] also presented that minimum surface roughness can be obtained using the CNT/MoS_2 hybrid nanofluid compared with that of dry machining and conventional cutting fluids. Jamil et al. [109] reported that Al_2O_3–MWCNT hybrid nanofluid can reduce 8.72% of surface roughness and 11.8% of cutting force whilst increasing the tool life by 23% compared with cryogenic cooling. Kumar and Krishna [110] examined the efficiency of CuO and Al_2O_3 hybrid nanofluids at various weight percentages during the turning process of AISI 1018 steel. The findings indicated that the combination of CuO and Al_2O_3 (50:50) can reduce the surface roughness value to a maximum of

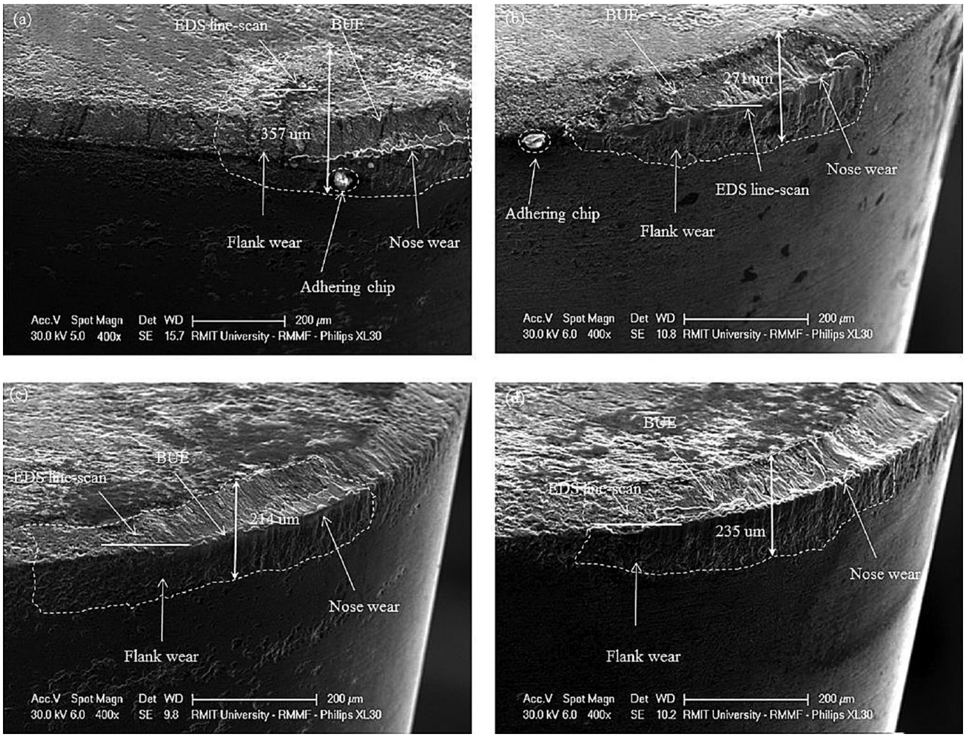


Fig. 7 SEM image of tool flank wear using various types of coolant: **a** conventional coolant **b** 0.1 wt.% GO coolant **c** 0.3 wt.% GO coolant **d** 0.5 wt.% GO coolant. Reprinted from [107] with permission from Elsevier

Table 2 Application of nanofluid in turning

References	Type of nanoparticles	Base Fluid	Size (nm)	Concentration	Workpiece material	Cutting tool/insert	Important findings
Amrita et al. [113]	Graphite	Water-based soluble oil	80	0.3 wt%	AISI1040 steel	Cemented carbide tool insert	In comparison to conventional cutting fluid, nanographite nanofluid reduced the cutting force by 54%, surface roughness 30%, tool wear 71%, cutting temperature 25% and improved chip morphology
Amrita et al. [114]	Functionalised Nanographite, Nano molybdenum disulphide (nMoS_2), nano boric acid (NBA)	Soluble oil	80 100 100	0.3 wt%	AISI1040 steel rod	Uncoated cemented carbide tool	By using MoS_2 nanoparticles, surface roughness was improved; cutting force and tool wear were reduced. However, NBA showed lower cutting temperatures
Sayuti et al. [115]	SiO_2	Mineral oil	5–10	0.0, 0.2, 0.5 and 1.0 wt%	hardened steel AISI4140	Coated carbide inserts	With 0.5 wt% of nanoparticle concentration, tool wear was reduced and surface roughness also can be enhanced
Gupta et al. [116]	Al_2O_3, MoS_2, Graphite	Vegetable oil	40	3 wt%	Titanium (grade 2) alloy	CCGW 09T304 2 Cubic boron nitride inserts	Under graphite nanofluid–based MQL conditions, cutting force and temperature were reduced; surface finish and tool life were improved
Raju et al. [117]	MWCNT	Distilled water	10–20	0.2 vol%	EN 31	Carbide inserts (TNMG 160408CQ) with CVD coating	Surface roughness was improved 9–22% and cutting force was reduced 5–8% when MWCNT nanofluid was used for turning EN 31 bars. The MWCNT-based nanofluid outperformed the conventional and oil-based cutting fluids
Behera et al. [118]	Al_2O_3	Deionised water	40	0.1 vol%	Inconel 718	Uncoated W-6CO carbide insert and Ti–Al-N coated W-6CO carbide insert	In comparison to dry machining, nanofluid reduced the coefficient of friction, chip curling radius, and increased tool life when machining Inconel 718
Mahboob et al. [119]	Al_2O_3	Soluable cutting oil (SolCut)	< 50	0.2, 0.4 and 0.6 wt%	Ti-6Al-4 V grade 5	Carbide-PVD coated	High-concentration nanoparticles can transfer more kinetic energy to the workpiece's surface and dissipate more heat. As a result, cutting force and tool wear can be decreased
Anamalai et al. [120]	Crystalline Nanocellulose (CNC)	Ethylene glycol–distilled water	9–14	0.1, 0.5, 0.9 and 1.3 vol%	SUS 304 stainless steel	Tungsten–cobalt (cemented WC–Co) CVD coated with Ti (C,N) + Al_2O_3	Superior thermal conductivity can be obtained using 0.5 vol% of CNC-based nanofluid compared to metal working fluid

Table 2 (continued)

References	Type of nanoparticles	Base Fluid	Size (nm)	Concentration	Workpiece material	Cutting tool/insert	Important findings
Shuang et al. [121]	Graphene Oxide (GO)	Rocol Ultracut Clear	50	0.1, 0.3 and 0.5 wt%	Ti-6Al-4 V alloy	Polycrystalline cubic boron nitride	Increasing the concentration of GO nanofluid resulted lower chip thickness and chip compression ratio. GO nanofluid also resulted lower cutting temperature and surface roughness when compared to conventional coolant
Yi et al. [122]	Graphene Oxide (GO)	Rocol Ultracut Clear	50	0.1, 0.3 and 0.5 wt%	Titanium alloy	PCBN010	Friction force was reduced about 5.36% when 0.3 wt% GO nanofluids was used. But, as the concentration of GO nanofluids increased, cutting temperature and cutting force decreased

13.72%. Moreover, the combination of CuO and ZnO with coconut oil can lead to a better surface finish than other syntheses [111]. Khan et al. [112] compared the turning performance of AISI52100 steel using base fluid, Al_2O_3 nanofluid and Al–GnP hybrid nanofluid. The results revealed that the hybrid nanofluid MQL achieves the best surface quality, cutting power, MRR and tool life compared with other cutting fluids.

4.2 Drilling

Drilling is a simple machining process that uses a spiral fluted tool to remove the material in a circular motion to create a hole [123]. High temperature at the cutting zone will affect the surface quality during machining because the tip of the drill bit begins to burn and wear [124].

Nanofluids have recently been utilised to improve the drilling performance. For example, Chatha et al. [125] revealed that the use of nanofluids with MQL enhances the number of drilled holes whilst decreasing thrust forces and drilling torques compared with the use of pure MQL, wet and dry drilling conditions. These findings are consistent with those of Huang et al. [126]. The researchers stated that the use of 2 wt% of nanodiamond in micro drilling with MQL can reduce the force, torque and burr formation around the holes and thus increase the cutting tool life with the reduction of force. Liew et al. [127] performed the drilling process on titanium alloy using carbon nanofibre nanofluid. When compared the results with those utilising pure deionised water, the carbon nanofibre nanofluid produces better surface finish and lower cutting temperature. Compared with the coconut oil–based fluid, Muthuvel et al. [128] stated that copper nanofluid can reduce the surface roughness and flank wear by 71% and 53%, respectively, with the optimum setting predicted via ASN-RSM.

Babu and Muthukrishnan [129] investigated the effect of copper nanofluid under MQL condition in the drilling of AA 5052 alloy. The results indicated that the use of copper nanofluid significantly decreases the cutting temperature, tool wear and surface roughness compared with the application of oil lubrication and dry machining. Moreover, nanofluids under MQL generated a thin protective cover on the machined zone and thus lowered the machining temperature and friction at the tool–workpiece interface whilst reducing the adhesion wear and chipping on the inserts. This view is further supported by Khanafer et al. [130]. When using MQL nanofluid, the tribo-film that formed between the cutting tool and the inner drilled hole (Fig. 8) can reduce the rubbing action caused by the rolling effect, thus reducing the cutting heat and burrs cut around the circumference of the drilled hole (Fig. 9). Other important studies that use nanofluids in the drilling process are listed in Table 3.

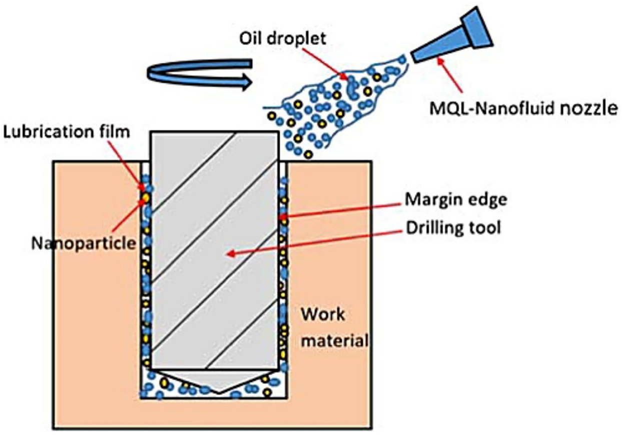


Fig. 8 Schematic of nanofluid mist mechanisms in the drilling zone. Reprinted from [130], Copyright 2020, with permission from Springer

4.3 Grinding

Grinding is an abrasive machining process that is commonly used in the finishing process for component that requires accurate dimensional tolerances and smooth surface textures [123]. Surface texture and precision obtained through grinding are 10 times greater than those via turning or milling. Abrasive grains come into controlled contact with the rotating wheel in a binder during the grinding process. According to Sanchez et al. [138], the heat generated during the grinding operation may negatively affect the surface integrity in the form of metallurgical transformations and oxidation. Coolants and lubricants were used to reduce the resistance within the wheel and workpiece to protect them from unfavourable conditions, such as heat distortion, burning, undesirable waste, tensile stress and phase transformation. Moreover, coolants and lubricants can also wash out chips, free the wheel surface from contaminations and thus reduce heat generation and grinding force [139]. Tu et al. [140] concluded that the use of cutting fluid in the grinding process is an important factor to ensure that the fluid can penetrate the contact zone and maintain its lubricating effectiveness.

Wang et al. [141] explored the temperature distribution of 45 steel during the grinding process under four cooling and lubrication conditions, namely, dry, MQL, nanofluid and flood conditions. The researchers discovered that the grinding zone temperature is significantly reduced because of the excellent heat transfer property of nanofluids. Setti et al. [142] demonstrated that the tangential force and grinding zone temperature decrease when nanofluids are utilised. In 2017, Li et al. [143] carried out the grinding process on Ni-based alloy using nanofluid MQL with six different types of nanoparticles. The CNT nanofluid presented the lowest grinding temperature amongst the investigated nanofluids due to its highest heat transfer coefficient. Dambatta et al. [144] showed that forces and surface roughness decrease significantly when SiO_2 nanofluid is used. According to Wang et al. [145], nanoparticles can easily penetrate into the sliding contact, form a protective film and convert sliding friction into sliding–rolling composite friction between grains and the workpiece (Fig. 10a). Furthermore, nanoparticles can fill cavities and incomplete spaces on the workpiece surface, repair dents on the friction surface and result in mending effect (Fig. 10b) that can improve workpiece surface quality. Previous studies that utilise nanofluids in the grinding process are listed in Table 4.

Similar to nanofluids, hybrid nanofluids have also been used in the grinding process. Zhang et al. [146] presented that MoS_2/CNT hybrid nanoparticles can significantly improve surface quality compared with the pure nanofluid with a single nanoparticle (Fig. 11). These findings are consistent with those of Zhang et al. [147]. The study noted that hybrid nanofluid MQL grinding is superior over pure nanofluid MQL grinding due to the ‘physical synergistic effect’. Hamid et al. [82] exhibited that MoS_2–WS_2 hybrid nanofluid reduces the specific grinding energy and grinding force by 39% and 27%, respectively, when compared with deionised water; meanwhile, the hybrid nanofluid also reduces chipping layer depth and surface roughness by 86% and 41%, respectively, compared with flood grinding.

4.4 Milling

The milling process is operated by removing the chip with rotational and multi-teeth tool on a fixed workpiece [123].

Fig. 9 SEM of burr formation using **a** flood **b** pure MQL **c** MQL-nanofluid. Reprinted from [130], Copyright 2020, with permission from Springer

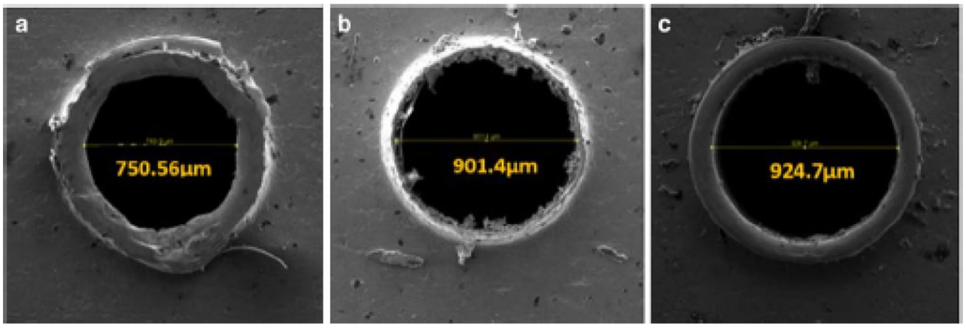


Table 3 Application of nanofluids in drilling

References	Type of nanoparticles	Base fluid	Size (nm)	Concentration	Workpiece material	Cutting tool/insert	Important findings
Nam et al. [131]	Nanodiamond	Paraffin Oil and Vegetable Oil	30	0.0, 2.0 and 4.0 wt%	Aluminium	Uncoated carbide twist drill	Nanofluids give a significant impact on drilling torque and thrust forces
Garg et al. [132]	Nanodiamond	Vegetable Oil	30	0.0, 2.0 and 4.0 wt%	Aluminium	Uncoated carbide	By using 1.4 wt% and 4 wt% of nanofluid concentration, the lowest torque and thrust force were achieved
Mosleh et al. [133]	MoS2, nanodiamond	Boelube 70104	70–100 3–5	MoS_2: 2% and 4% Nanodiamond: 0.5% and 1%	AISI 4340 steel	High steel speed cobalt drill	MoS_2 nanoparticles can improve the performances of the baseline lubricant
Salimi-Yasar et al. [134]	TiO_2	Soluble Oil	20	0.3, 0.6 and 1 wt%	steel workpiece	Drill 6-model: MOBINES-HSS-CO5	Nanoparticle in the soluble oil can improve the cutting fluid's heat transfer properties
Mosleh et al. [135]	hBN, MoS_2	Boelube 70104	70, 70-100	2 wt%	Titanium 6A14V (Ti)	Tungsten carbide	MoS_2 nanofluid resulted in low transfer film buildup on the tool, lower surface temperature and less variation of frictional force during machining
Pal et al. [136]	Graphene	Vegetable Oil	5–10	0.5, 1.0 and 1.5 wt%	AISI 321 stainless steel	High speed steel drill bit	1.5 wt% nanofluid produced lower torque, thrust force, coefficient of friction and surface roughness compared to pure MQL
Sirin et al. [137]	Graphene nanoplatelets (GNP), hBN	Vegetable–based oil	30 70–90	Mono – 0.6 vol% Hybrid – 0.3 vol% + 0.3 vol%	Nickel based Hastelloy X superalloy	TiAIN- coated drills	hBN/GNP hybrid nanofluid with SDS surfactant gave the best result of hole quality, cutting force, tool wear and burr height

Table 4 Application of nanofluids in grinding

References	Type of nanoparticles	Base fluid	Size (nm)	Concentration	Workpiece material	Grinding wheel	Important findings
De Oliveira et al. [148]	Graphene	Semi-synthetic oil	1 μm^2 surface area, 4 to 10 nm thick	0.05 and 0.10 wt%	Inconel 718 nickel-based alloy	Vitrified bond silicon carbide (SiC) conventional wheel	Grinding with 0.05 wt% MQL multilayer graphene nanofluid can reduce the formation of microcracks, improve surface finish and require lower grinding power
de Paiva et al. [149]	Multilayer graphene (MLG) platelets	Semi-synthetic vegetable based fluid VASCO 7000	1–20 μm length and 1–30 nm thick	0.025, 0.050 and 0.075 wt%	SAE 52100 steel	Al_2O_3 grinding wheel (38A60K6V)	Low MLG concentrations improved tribological conditions in the cutting zone, resulting in better surface quality and morphology but had no effect on electrical power
de Souza et al. [150]	Multilayer graphene (MLG) platelets	Semi-synthetic oil	1–20 μm length and 1–20 nm thick	0 and 0.05 wt %	Inconel 625 and Inconel 718	Green silicon carbide (GC) grinding wheel	The presence of MLG dispersed in the cutting fluid improved the surface finish of Inconel 718 ground surfaces but adversely affected the surface finish of Inconel 625
Prabhu and Vinayagam [151]	SWCNT	Water soluble oil	1–2	0.2 wt%	Glass	CBN Diamond Bonded	By using CNT nanofluid, nano level surface finish can be obtained
Mao et al. [152]	MoS_2 Al_2O_3	Canola oil, deionised water	40,80,70	0.25, 0.75, 1.25 and 4.8 wt%	AISI 52100 steel	Al_2O_3 grinding wheel with vitreous bond	In comparison to lower concentrations, higher nanofluid concentrations resulted in lower grinding force, grinding temperature and surface roughness
Jia et al. [153]	MoS_2 ZrO_2 PCD	Soybean oil	50	2, 4, 6, 8 and 10%	45 steel	White fused alumina ceramic bond	With 6% of mass fraction of MoS_2 nanoparticles, frictional coefficient, specific grinding energy and grinding force were reduced. When mass fraction is less than 6%, lubrication effect improved as the mass fraction increased. Meanwhile, when mass fraction is more than 6%, lubrication effect was reduced

Table 4 (continued)

References	Type of nanoparticles	Base fluid	Size (nm)	Concentration	Workpiece material	Grinding wheel	Important findings
Mao et al. [154]	Al_2O_3 MoS_2	Canola oil, deionised water	10 70	1 wt%	AISI 52100 steel	White aluminium oxide	Nanofluid shows a superior anti-wear behaviour and smoother surface morphology compared to pure liquid
Zhang et al. [155]	MoS_2	Liquid paraffin, soybean oil, palm oil, rapeseed oil	50	2, 4, 6 and 8 wt%	45 steel	Corundum	Optimal concentration of MoS_2 nanoparticles was 6 wt%; the excessive nanoparticles may result agglomeration on the nanofluid that will give negative effect of the lubricating property
ManojKumar and Ghosh [156]	MWCNT	Deionised water	50	0.6, 0.8, 1.0, 1.2 and 1.4 vol%	AISI 52100 steel	Alumina wheel	By using MWCNT nanofluid, best retention on chip morphology and best dissipation of heat from grinding zone can be seen
Zhang et al. [157]	MoS_2 CNT ZrO_2	Soybean oil	50	1, 2 and 3 vol%	Hardened 45# steel	Ceramic bond Al_2O_3	2 vol% of CNT nanofluid effectively cooled the grinding surface
Zhang et al. [158]	MoS_2 ZrO_2 CNT	Colza oil	50	1, 2 and 3 vol%	Hardened Steel 45	Vitrified bond alumina WA80MV12P	2 vol% of MoS_2 gave the best grinding surface lubrication
Prabhu et al. [159]	MWCNT	SAE 20W40	10–20	2 wt%	AISI D3 tool steel	Vitrified alumina grinding wheel	With CNT nanofluid, better surface roughness can be obtained
Zhang et al. [160]	MoS_2 CNT MoS_2 -CNT	Synthetic oil	30	2, 4, 6, 8, 10 and 12 wt%	GH4169 Ni-based alloy	Corundum	With 8 wt% of MoS_2-CNTs, surface quality of workpiece can be improved
Li et al. [161]	CNT	Palm oil	50	0.5, 1, 1.5, 2, 2.5, 3, 3.5 and 4 vol%	Nickel-based alloy GH4169	White corundum	Optimum concentration of 2 vol% gave lowest grinding temperature, grinding force and lowest proportionality coefficient by 42.7%
Wang et al. [162]	MoS_2 SiO_2 ND CNT ZrO_2 α-Al_2O_3	Palm oil	50	2 vol%	440 C material	Corundum vitrified-bond	Al_2O_3 nanofluid improved the average friction coefficient by 19.3% and mass wearing ratio by 65%

Table 4 (continued)

References	Type of nanoparticles	Base fluid	Size (nm)	Concentration	Workpiece material	Grinding wheel	Important findings
Sinha et al. [163]	Ag ZnO	Deionised water	10 25	0.01, 0.1 and 0.5 vol%	Inconel 718	Vitreous bonded white alumina wheel	ZnO nanofluid can reduce grinding forces, coefficient of friction and improve the integrity of ground surface
Singh et al. [164]	Graphene Graphite MoS_2	Canola oil	3–8	0.5, 1, 1.5, 2 and 2.5 wt%	Ti6Al4V–ELI	Cubic boron nitride (CBN)	The best nanofluid in canola oil was graphene compared to graphite and MoS_2. 1.5 wt% of graphene in canola oil has shown the best result in term of surface roughness, grinding energy and coefficient of friction
Gao et al. [165]	CNT	Palm oil	50	-	CFRP	Diamond wheel	CNT nanofluid could produce lower surface roughness compared with dry grinding
Qu et al. [166]	Carbon	Deionised water	40	1, 3, 5 and 7 g/L	Carbon fibre-reinforced ceramic matrix composites (C_f/SiC)	Diamond wheel	In comparison to dry, flood, and MQL conditions, carbon nanofluid produced a superior surface quality and lower grinding force
Peng et al. [167]	Al_2O_3	Soybean oil	20	0.5–2.5 wt%	Inconel 718	Slotted grinding wheel with 80# CBN grain	Best surface integrity and lowest grinding temperature were achieved with Al_2O_3 nanofluid

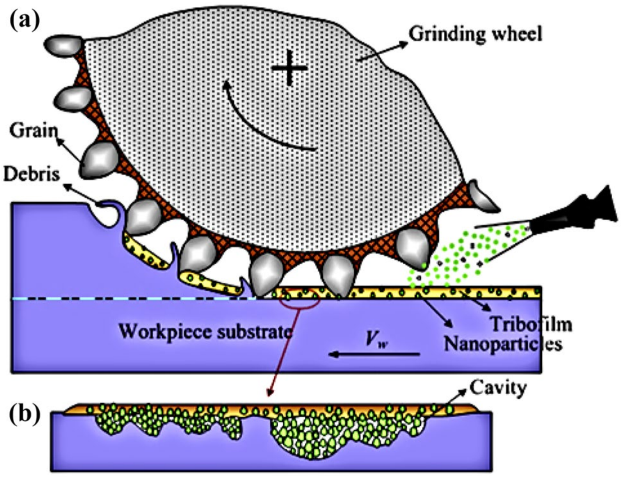


Fig. 10 **a** Protective films and **b** mending effect of nanoparticles in grinding. Reprinted from [145] with permission from Elsevier

Many studies on the use of nanofluids in the milling process have demonstrated significant improvement in machining performance. For example, Kim et al. [168] indicated that the hBN nanofluid MQL with chilly CO_2 gas can produce better surface finish and reduce the coefficient of friction and tool wear. Their findings are supported by Kim et al. [169], and the results showed that chilly CO_2 gas with only 0.1 wt% of nanodiamond nanofluid in MQL can reduce milling forces and coefficient of friction. According to Sirin and Kivak [18], hBN nanofluid can obtain better surface roughness, lower cutting force and improved tool wear compared with the MoS_2 and graphite nanofluid. The machined surface with graphene nanofluid MQL can also produce a smoother surface without adhesion and large furrows compared with machining under dry and gas conditions [170]. The summary of previous studies that utilise nanofluids in the milling process is presented in Table 5.

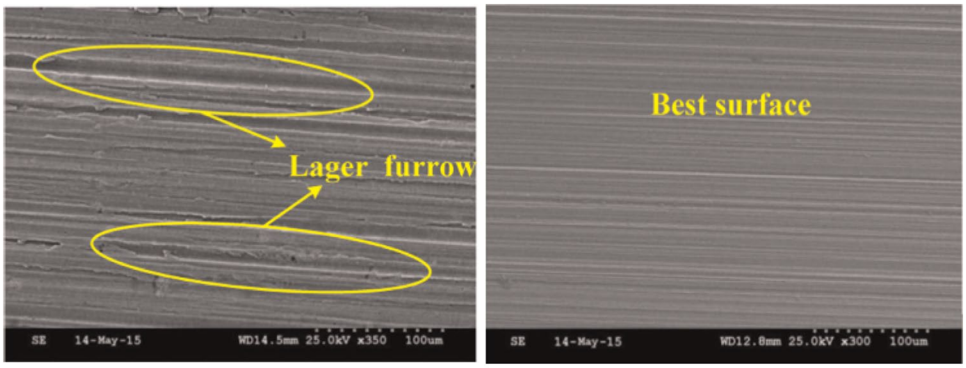
Researchers have also attempted to examine the milling machining performance using hybrid nanofluids. Sahid et al. [171] revealed that the combination of cutting parameters and MQL-hybrid nanocoolant is critical in attaining enhanced surface roughness, satisfactory material removal rate and reduced tool wear. Jamil et al. [172] reported that due to the tribo-film formation of Al_2O_3-MWCNT hybrid nanofluid, variable-sized nanoparticles function as spacers to reduce the severity of tool rubbing on the workpiece surface, fill microvoids on the workpiece surface and function as ball bearing in the rolling action. As a result, tool life and surface finish can be improved.

5 Optimisation of machining performances under nanofluid and hybrid nanofluid

Many research papers have been published demonstrating the effectiveness of optimisation techniques for machining process under nanofluid and hybrid nanofluid. For example, Chakma et al. [19] utilised the Taguchi orthogonal array design to optimise the turning parameters of an aluminium metal matrix nanocomposite. The researchers discovered that high cutting speeds and low feed rates can significantly improve the surface quality when carbon nanotube nanofluid is used. Liew et al. [186] carried out multi-response optimisation in turning D2 steel using the Taguchi-RSM integration method. The experimental results revealed that a cutting speed of 144.58 m/min, feed rate of 0.14 mm/rev and usage of carbon nanofiber nanofluid as coolant produce the optimal tool wear and surface finish.

Besides that, in the milling of Inconel 718, Barewar et al. [187] incorporated the Taguchi grey relational analysis (TGRA) to investigate the effect of cutting speed, feed rate and machining environment (Ag/ZnO hybrid nanofluid-MQL, dry and MQL) on the surface roughness and cutting temperature. They concluded that at the cutting speed of 30 mm/min, feed rate of 0.036 mm/tooth and Ag/ZnO hybrid nanofluid-MQL cutting environment, multi-response–optimised machining performance can be achieved. Jamil et al. [172] also reported that by using Taguchi method, the desirability function attempts to obtain a balanced operating level to achieve minimal

Fig. 11 SEM image of workpiece using different machining conditions. Reprinted from [146] with permission from Elsevier



a) Pure nanofluid **b)** MoS_2 and CNT hybrid nanofluid

Table 5 Application of nanofluids in milling

References	Type of nanoparticles	Base fluid	Size (nm)	Concentration	Workpiece material	Cutting tool/insert	Important findings
Najiha and Rahman [9]	TiO_2	Deionised water	40	1.5 vol %	Aluminium alloy	Uncoated tungsten carbide	MQL with water-based nanofluid lubricant shows a very little chipping and edge fracture
Kulkarni et al. [52]	Copper coated aluminium oxide (Al_2O_3@Cu)	Vulcan strub oil futura	20	1 wt%	7075-T6 Aluminium Alloy	Uncoated carbide end mill	Nanofluid was effective to decrease the temperature at the tool work interface without affecting the milling performance characteristic
Yuan et al. [173]	Copper, Silicon carbide, Diamond	Soybean oil, Canola oil, Natural77 oil	40 40 100	1 vol%	7050 aluminium alloy	Insert coated with diamond like carbon (DLC) film	Canola oil–based diamond nanofluid has lowest cutting force with reduction of 10.71% and lowest surface roughness was from natural77 oil–based diamond nanofluid with reduction about 14.92% compared to dry condition
Sayuti et al. [174]	SiO_2	Ecocut SSN 322 oil	5–15	0.0, 0.2, 0.5 and 1.0 wt%	Aluminium (AL6061-T6)	HSS with 2 flutes	SiO_2 nanoparticles that appeared on the cutting fluid helps to increase the lubrication effect on the tool thus decrease the cutting temperature
Sayuti et al. [175]	Carbon onions	Alumicut oil	5–20	0.0, 0.5, 1.0 and 1.5 wt%	Duralumin AL-2017-T4	SEC-ALHEM2S8 end mill	1.5 wt% of carbon onion concentration reduced surface roughness and cutting force by 46.32% and 21.99%, respectively, compared with conventional lubrication oil
Rahmati et al. [176]	MoS_2	Ecocut HSG 905S	20–60	0.0, 0.2, 0.5 and 1.0 wt%	Aluminium alloy (AL6061-T6)	Tungsten carbide (AE302100) tool, 2 flutes	Surface quality was superior by using 0.5wt% MoS_2 nanofluid compared to pure oil and other concentrations
Sayuti et al. [177]	SiO_2	Ecocut SSN 322 oil	5–15	0.0, 0.2, 0.5, 1.0 wt%	Aluminium (AL6061-T6)	High-speed steel with two flutes	Using 0.2 wt% of nanoparticle can help to reduce the cutting force. With the smallest amount of nanoparticle concentration, cutting temperature has been reduced whilst with higher concentration, surface roughness was improved
Rahmati et al. [178]	MoS_2	Ecocut HSG 905S	20–60	0.0, 0.2, 0.5, 1.0 wt%	Aluminium AL6061-T6	Tungsten carbide (AE302100) with two flutes	1 wt% nanoparticle have reduced cutting force, whilst 0.5 wt% nanoparticle concentration resulted in the lowest cutting temperature and best surface roughness
Songmei et al. [179]	Cu Graphite MoS_2 Al_2O_3	Natural-77 oil vegetable	40	1.0 and 2.0 vol%	Ti-6Al-4 V	ACM300 insert	Surface roughness and cutting force were reduced by 14.74% and 8.84%, respectively, by using copper nanofluid. Meanwhile, graphite nanofluid decreased the surface roughness and cutting force by 21.96% and 5.51%, respectively

Table 5 (continued)

References	Type of nanoparticles	Base fluid	Size (nm)	Concentration	Workpiece material	Cutting tool/insert	Important findings
Minh et al. [180]	Al_2O_3	Soy bean oil	30	0.5 vol%	60Si_2Mn steel	Uncoated cemented carbide	Al_2O_3 nanofluid gave better cooling and lubricating effect. Nanofluid helps to lower surface roughness and cutting forces almost 177–230% and 35%-60%, respectively
Zhou et al. [181]	Fe_3O_4	Conventional cutting fluid	80	0.5%	Ti-6Al-4 V	YG6X- cemented carbide	Nanofluid cutting condition reduced the surface roughness, cutting force and tool wear rate at 38.4%, 27.75% and 63.3%, respectively
Liew et al. [182]	hBN	Deionised water	70	0.00, 0.02, 0.06 and 0.10 wt%	Ti-6Al-4 V	Coated carbide insert	By using 0.1 wt% of hBN nanofluid, tool wear, cutting force and surface roughness were lowered by 63.9%, 16.1% and 33.3%, respectively, compared with deionised water
Dong et al. [183]	MoS_2	KOH solution	10–20	0.5 and 1.5 wt%	AISI D2 Steel	PVD submicron carbide insert	Cooling and lubricating effect significantly enhances when MoS_2 nanofluid was used
Duan et al. [184]	Al_2O_3	Cottonseed oil	50	0.5 wt%	7050 aluminium alloy	Spiral angle cutting tool	The optimal combination of nozzle position parameters using nanofluid was a target distance of 30 mm, an incidence angle of 35° and an elevation angle of 60°
Sen et al. [185]	Si	Palm oil	50	0.5, 1.0, 1.5 vol%	Inconel 690	Coated carbide insert	1 vol% is the optimum concentration that gives longer tool life, best surface roughness, lower temperature and cutting force

energy consumption, enhanced surface quality and high material removal rate in the milling of Ti–6Al–4 V alloy when hybrid nanofluids Al_2O_3-MWCNTs is added.

Furthermore, Junankar et al. [188] used multi criteria decision-making hybrid approach to optimise the turning parameters under CuO and ZnO nanofluid-MQL. They found that CuO nanofluid showed better enhancement by reducing the surface roughness and machining temperature as compared to ZnO nanofluid. Huang and Chen [189] used ANN and TGRA to develop a highly accurate micro drilling predictive model and reported that the parameter combination for predicting the optimal micro drilling force and torque deviated from the experiment results by just 0.44% and 1.24%, respectively. Garg et al. [132] revealed that genetic programming (GP) has performed better than the ANFIS model on the thrust force and material removal rate in micro drilling process.

6 Challenges and future works

On the basis of previous studies, maintaining the stability of nanofluids and hybrid nanofluids remain challenging in actual application despite their ability to improve the machining performance compared with conventional fluids. The stability of nanofluid was mainly affected by the agglomeration and the formation of large clusters of suspended particles [94]. The nanoparticle agglomeration causes not only the settlement and clogging of micro channels but also a reduction in the thermal conductivity of nanofluids [60]. Therefore, surfactants have been used to enhance the stability of nanofluid [60]. Although the addition of surfactant can effectively enhance nanoparticle dispersibility, surfactants may cause some problems. For example, the addition of surfactants may contaminate heat transfer media; produce foam during the heating process [190] and likely degrade the viscosity, thermal conductivity and chemical stability of nanofluids when an excessive amount of surfactant is added [191]. Therefore, the stability of nanofluid and hybrid nanofluid requires further investigation. The machinist should use a stirrer or ultrasonic vibration in the coolant tank to assist the machining process and ensure excellent output when nanofluids or hybrid nanofluids are used as coolant in machining. The stirrer or ultrasonic vibration of nanofluids may help disperse nanoparticles in the suspension and avoid sedimentation during the machining process.

In addition to the stability issue of nanofluids, high production cost is another major factor that may hinder the practical industrial application of nanofluids and hybrid nanofluids. The entire procedure adds to the overall cost because it requires the appropriate selection of nanoparticles, natural extracts, equipment and hardware [192]. Hence, the researcher or machinist may consider using a green nanofluid that contains eco-friendly nanoparticles to reduce the cost. The use of green nanofluids as coolant in machining combined with optimum machining parameters that affect the process should be investigated further.

7 Conclusion

An overview of various cooling–lubrication techniques as well as the use of nanofluids and hybrid nanofluids in turning, milling, grinding and drilling processes is presented in this study. Thermal conductivity and viscosity of nanofluids and hybrid nanofluids are strongly affected by the temperature, mass volume fraction, nanoparticle size and type. The majority of experimental studies revealed that nanofluids and hybrid nanofluids can achieve better machining performance than other cooling–lubrication techniques due to their heat transfer and lubrication capabilities. The formation of a tribo-film, the sliding–rolling action and the mending effect of nanoparticles are the main mechanisms that contribute to the improvement of surface finish and reduction of cutting temperature, tool wear and cutting force during machining with nanofluids and hybrid nanofluids. Multi-response optimisation using various optimisation techniques such as Taguchi, RSM and ANN is useful to predict the optimum parameters for enhancing the machining efficiency under nanofluid and hybrid nanofluid cutting environment.

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