

Carbon-based nanomaterials as cutting fluid additives: A review

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Abstract: Metalworking fluids are commonly used in the machining processes of diverse equipment components to provide cooling, cleaning, rust prevention, and lubrication. The incorporation of cutting fluid additives further enhances their performance. In recent years, carbon-based nanomaterials have attracted attention as environmentally friendly additives for cutting fluids. This work reviews the research

progress on carbon-based nanomaterials as cutting fluid additives, analyzes the effects of factors such as the dispersibility of carbon-based nanomaterials, cutting fluid types, and cutting parameters on machining performance, and discusses the friction reduction and anti-wear mechanisms of carbon-based nanomaterials. Finally, current challenges and future prospects for carbon-based cutting fluid additives are outlined. This review aims to provide guidance and references for achieving efficient and environmentally friendly machining of difficult-to-process materials.

Keywords: cutting fluid; additives; carbon-based nanomaterials; friction reduction and anti-wear mechanisms.

1 Introduction

With the rapid development of equipment manufacturing in fields such as aerospace, ocean vessels, and new energy vehicles, the demand for machining difficult-to-process materials is growing, such as titanium alloys [1], heat-resistant alloy steels [2], nickel-based alloys [3]. Prolonged dry cutting generates high temperatures, which reduce tool hardness and lead to severe wear, thereby compromising surface quality and machining precision [4, 5]. To mitigate these issues, wet machining with cutting fluid cooling has been widely adopted in mechanical processing. Its primary functions include cooling the tool, lubricating the interface between the cutting tool and workpiece, removing chips produced during machining, and preventing oxidation of

the tool surface. These effects collectively reduce tool wear and extend tool life [6-9]. Traditional cutting fluids often contain extreme pressure additives such as sulfur and phosphorus, posing challenges related to their poor biodegradability, environmental pollution, and potential health hazards to operators [10]. Consequently, the development of new environmentally friendly green additives has become a key area of research in the field of cutting fluids.

In recent years, researchers have discovered that nanoscale lubricating particles possess high specific surface area, excellent thermal conductivity, and superior friction and wear reduction properties [11, 12], which adding to cutting fluids can effectively reduce tool wear. Studies have shown that suspending nanoparticles in base fluids to form nanofluids can enhance heat transfer efficiency due to the high specific surface area of the nanoparticles. As the concentration of nanoparticles increases, the thermal conductivity also improves, which contributes to better cooling performance of the cutting fluid [13]. Nano-additives such as nano-graphene [14] and carbon nanotubes (CNTs) [15] can form dense friction films at the friction interface to reduce friction; metal oxides like titanium dioxide [16] and silica [17] exert a “rolling bearing effect” at the tool-workpiece interface to minimize tool wear.

Compared to metal oxide and sulfide nanoparticles, carbon-based nanomaterials like graphene, CNTs, carbon quantum dots (CQDs), and graphene-like carbon nitrides offer distinct advantages. The two-dimensional layered structure of graphene has been demonstrated to form a stable graphite-like lubricating film, with a friction coefficient of less than 0.05 [18]. The hollow tubular structure of multi-walled carbon nanotubes

(MWCNTs) enables the construction of highly efficient thermal conduction pathways [19]. CQDs combine stable dispersibility with ease of modification, allowing them to form chemical tribofilms at friction interfaces [20]. Additionally, compared to most metal nanoparticles, carbon-based materials not only demonstrate superior biocompatibility but also exhibit excellent chemical stability and environmental friendliness. For example, carbon fibre composites have been widely adopted as critical lightweight structural components in aerospace [21] and other fields, enabling green manufacturing practices that align with the development demands of green production under the carbon peak and carbon neutrality goals. Notably, integrating nano-additives with minimum quantity lubrication (MQL) technology substantially reduces cutting fluid consumption, replacing high-consumption overflow cooling methods [22], and significantly enhances the surface finish of workpieces. This approach is widely recognised as a more sustainable, environmentally friendly machining technology [11, 23].

Research on carbon-based nano-additives currently encompasses various aspects, including material preparation, mechanism analysis, performance evaluation and application. In light of the rapid advancements in this field, there is an obvious requirement for a systematic review of the relevant developments. This review summarises the classification of carbon-based nano-additives in cutting fluids, the key factors influencing machining performance and lubrication mechanisms in recent years. It also discusses the potential health risks associated with carbon-based materials and measures for safety and prevention, and offers insights into future directions. The aim

is to provide a scientific reference for theoretical research and engineering applications in this area, thereby promoting the large-scale adoption of nano-additives in green, efficient machining processes.

2 Categories and characteristics of carbon-based nanomaterials as cutting fluid additives

Commercial cutting fluid additives primarily achieve lubrication through oily additives and extreme-pressure (EP) additives. Oily additives contain polar molecules that adsorb onto metal surfaces via van der Waals forces and hydrogen bonding, forming a low-temperature lubricating film to reduce friction. However, they decompose or oxidize above 300 °C, making them unsuitable for high-speed, heavy-duty machining with localized high temperatures. Extreme-pressure additives, such as chlorinated paraffins and sulfurated phosphates, undergo tribo-chemical reactions to form lubricating films under high-temperature and high-pressure conditions. Nevertheless, their sulfur, phosphorus, and chlorine content is corrosive and can damage metal surfaces. Compared with commercial additives, carbon-based nanomaterials exhibit unique advantages in friction reduction and anti-wear performance, positioning them as next-generation green and environmentally friendly cutting fluid additives. Among these materials, graphene excels in friction reduction, wear resistance, and thermal conductivity due to its two-dimensional layered structure but suffers from aggregation and dispersion instability. CNTs offer high thermal conductivity but are prone to deformation under high shear stress. CQDs demonstrate

superior dispersibility and functionalization potential, yet their lubrication and thermal performance lag behind other carbon-based materials. fullerene C60 provides effective ball-bearing lubrication and chemical stability but is limited by low solubility, agglomeration, and high production costs. **Table 1** summarizes the advantages and disadvantages of carbon-based nanomaterials in metalworking lubrication.

Table 1 Advantages and disadvantages of carbon-based nanomaterials as cutting fluid additives

Material	Advantages	Disadvantages	Ref.
graphene	Interlayer sliding reduces tool friction, high load-bearing capacity minimizes wear.	Prone to agglomeration, requiring dispersion processing.	[24, 25]
CNTs	Excellent thermal conductivity, significantly reduces cutting temperature.	Poor dispersion stability, moderate wear resistance.	[26, 27]
CQDs	Easy to functionalize, exhibits great dispersion stability.	Relatively low load-bearing capacity.	[28]
Fullerene C60	Nano-rolling friction effect, stable chemical properties	Friction and wear resistance are not outstanding.	[29]

Against the backdrop of rapid advancements in sustainable manufacturing and green processing technologies, the environmental friendliness and occupational health compatibility of cutting fluids have become key factors in evaluating their overall performance. Bhaumik et al.[30] systematically assessed a composite lubrication system composed of glycerin-based fluid with micron-sized graphite (GRT), reduced graphene oxide (RGO), and nano-zinc oxide (ZnO). The surface quality achieved with the carbon-based additive system was comparable to that of conventional cutting fluids, demonstrating excellent film-forming capability and lubrication durability. This suggests that cutting fluids incorporating carbon-based materials can effectively serve

as alternatives to hazardous conventional fluids, aligning well with the principles of green machining. However, while carbon-based nanomaterials circumvent the chemical toxicity associated with traditional additives, their introduction also raises new health concerns. During machining processes, these materials may form nanoparticle-containing aerosols, which can subsequently enter the human body through the respiratory tract. Notably, certain carbon materials with high aspect ratios, such as carbon nanotube-like structures, exhibit asbestos-like fibrogenic potential and may induce pulmonary inflammation or fibrotic lesions [6]. These potential risks warrant more in-depth investigation within the current research landscape of green cutting fluids.

2.1 Graphene-based materials as cutting fluid additives

2.1.1 Graphene nano-additives

As a two-dimensional material with a thickness of a single atomic layer, graphene exhibits exceptional mechanical strength, with a theoretical Young's modulus reaching 1.0 TPa and an intrinsic tensile strength of 130 GPa. Pure, defect-free monolayer graphene possesses a thermal conductivity as high as 5300 W/mK [31, 32]. The interconnection of graphene layers is facilitated by weak van der Waals forces. During friction, interlayer slip has been shown to reduce friction, and physical adsorption at the friction interface has been observed to form a friction film with low shear strength [33]. Each carbon atom in graphene adopts sp^2 hybridization, thus forming a hexagonal planar lattice. The highly ordered atomic arrangement gives rise to a substantial increase in the bonding energy between carbon atoms, accompanied by a reduction in

resistance to lattice vibration propagation. This phenomenon facilitates a low-loss pathway for heat conduction. Moreover, the two-dimensional planar structure of graphene restricts the propagation direction of energy quanta, thereby resulting in a significantly higher interatomic transfer efficiency in comparison to three-dimensional materials [34].

Graphene possesses ultra-high mechanical strength, a readily sliding layered structure, and excellent thermal conductivity. It can effectively support loads, reduce friction coefficients, and facilitate cooling and heat dissipation, making it an ideal cutting fluid additive. Ibrahim et al. [35] prepared nanofluids with varying concentrations of graphene nanoplatelets (GNPs) based on palm oil. As demonstrated in **Fig 1a**, the nanofluid containing 0.1 wt% GNPs exhibited optimal performance, reducing specific grinding energy by 91.78% compared to dry processing and by 80.25% compared to the pure commercial cutting fluid Acculube LB2000. The synergistic effect of palm oil's highly polar, long-chain molecular structure and GNPs enhanced the fluid's anti-wear and heat dissipation capabilities. Pal et al. [36] investigated the drilling performance of AISI 321 stainless steel using nano-graphene-enhanced vegetable oil-based cutting fluid. The study demonstrated that employing a 1.5 wt% graphene nanoparticle concentration under MQL drilling conditions significantly reduced thrust force (by 27.4%), surface roughness (by 33.8%), and friction coefficient (by 51.7%), while also improving tool life, as illustrated in **Fig. 1b–d**. Gong et al. [37] utilised graphene nanomaterial-enhanced vegetable oil-based cutting fluids for the turning of Inconel 718 alloy. The present study utilised graphene nanoplatelets with dimensions

of 5 μm and 15 μm to comparatively analyse the influence of nanoparticle size on the performance of cutting fluids. The results indicate that nanofluids containing graphene nanosheets of minimal dimensions promote optimal surface quality, reducing surface roughness by 6% at the highest cutting speed and 15% at the lowest cutting speed.

Compared to dry cutting and flood cutting methods, the application of graphene-based nanofluids demonstrates a significant reduction in cutting temperature, tool wear, and surface roughness. Babu et al. [38] investigated different machining approaches (dry, MQL, and graphene-based nanofluid) for cutting Hastelloy C-276 nickel alloy. In the context of the graphene nanofluid cutting condition, the lowest recorded values for cutting temperature, flank wear, and chip thickness were observed. Anandan et al. [39] employed graphene nanofluids with ethylene glycol as the base fluid for turning M42 steel in both dry and oil environments. The results showed that in the dry environment, the graphene nanofluid significantly reduced surface roughness by 91%, tool wear by 95%, and cutting temperature by 82%. In the oil environment, it reduced surface roughness by 66%, tool wear by 86%, and cutting temperature by 57%.

Graphene nano-cutting fluid forms a stable solid lubrication film at the cutting interface through interlayer slip action, combined with the adsorption of highly polar long-chain molecules in the cutting oil. This effectively suppresses adhesive wear and abrasive wear during the cutting process, significantly reducing interfacial friction resistance. Nano-graphene can establish efficient heat transfer pathways within the cutting fluid, thereby preventing issues such as workpiece thermal deformation and tool damage, and providing robust support for machining stability.

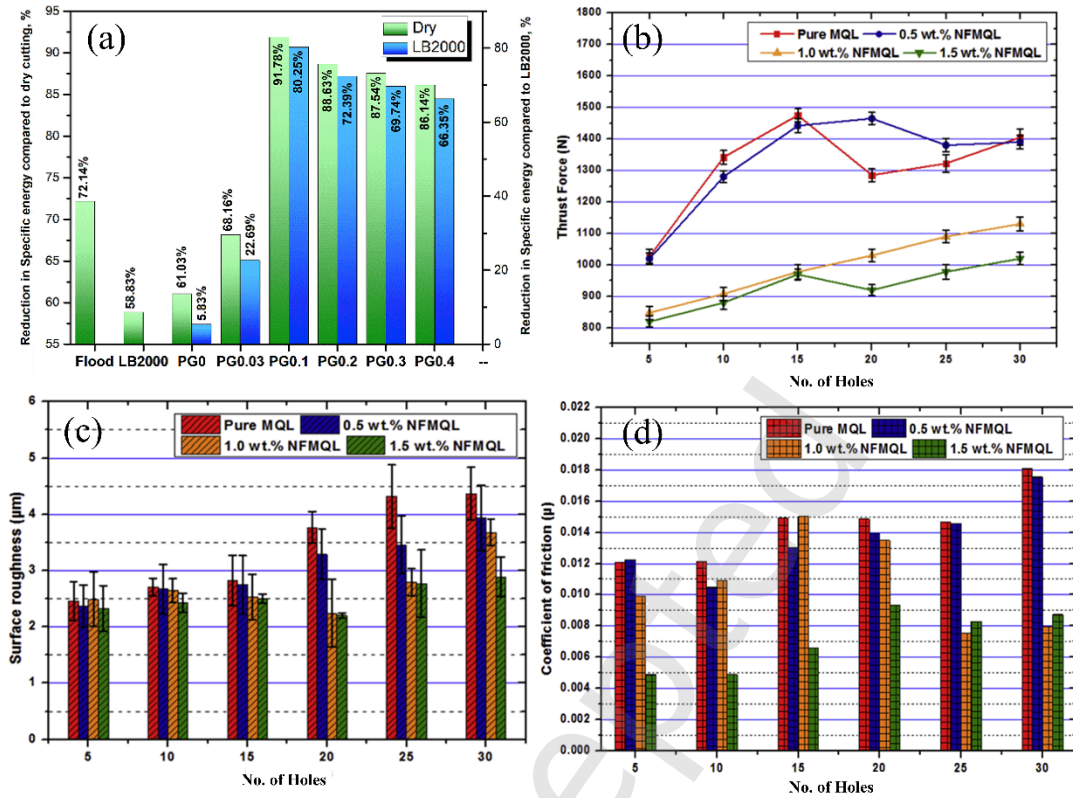


Fig. 1 (a) Effect of lubrication mode on grinding energy. Reproduced with permission from Ref. [35], © Elsevier, 2020. Drilling process of AISI 321 stainless steel under different cooling conditions: (b) Thrust force variation, (c) Average surface roughness, (d) Coefficient of friction. Reproduced with permission from Ref. [36], © Elsevier 2020.

2.1.2 Graphene oxide nano-additives

Graphene oxide (GO) features surface oxygen-containing functional groups such as hydroxyl, carbonyl, and carboxyl groups. This results in GO possessing a high specific surface area, excellent hydrophilicity, mechanical properties, and outstanding dispersion stability in water and most organic solvents [40]. The abundant surface functional groups of GO facilitate surface modification or composite formation with other materials, enhancing its anti-wear and anti-friction capabilities or imparting new functionalities. During friction, the material readily adsorbs onto the friction interface

to form a dense friction film, and undergoes friction chemical reactions via its oxygen-containing functional groups [41, 42]. In contrast to graphene, the presence of saturated sp³ bonds and oxygen atoms in graphene oxide results in its non-conductive nature, hinders heat transfer, and facilitates phonon scattering. Surface defects in graphene oxide result in reduced thermal conductivity [43].

Graphene oxide exhibits outstanding anti-friction and cooling properties in machining processes. Yi et al. [44] systematically investigated the effects of GO nanofluids and conventional coolants during titanium alloy machining. Compared to traditional coolants, cutting forces decreased by up to 50.83%, and tool flank wear reduced by 77.78%. As shown in **Fig. 2a**, GO nanofluids effectively minimized tool wear and built-up edge formation. Khatai et al. [45] synthesized mineral oil-based GO nano-cutting fluids at varying concentrations. Compared to conventional mineral oil, increasing the nanofluid concentration from 0.05% to 0.5% resulted in viscosity and thermal conductivity improvements of 28.83% and 29.54%, respectively, while simultaneously reducing cutting temperature and surface roughness (**Fig. 2b**). Tian et al. [46] conducted a comparative study on the lubrication properties of water-based nanofluids composed of two-dimensional materials MXene and GO during titanium alloy machining. Graphene oxide nanofluids exhibited a lower coefficient of friction and reduced wear volume compared to MXene nanofluids. Smith et al. [47] investigated the effects of carbon-rich graphene oxide colloidal suspensions as cutting fluids on diamond tool machining of low-carbon steel alloys. As shown in **Fig. 2c**, compared to dry machining conditions, cutting temperatures decreased by 50% and cutting forces

reduced by 20–30%. GO forms a stable graphene oxide film between the cutting tool and workpiece. This film may act as a chemical barrier preventing graphitized carbon from diffusing from the tool to the workpiece, effectively reducing wear on diamond cutting tools. Yang et al. [48] investigated the thermodynamic and mechanical behaviors of GO nanosheets as cutting fluid additives during the drilling of Ti-6Al-4V titanium alloy. They developed force and thermal models for the drilling process, integrating finite element simulations with experimental measurements. The results demonstrated that adding GO nanosheets to the cutting fluid significantly enhanced mechanical performance by reducing cutting forces and minimizing fluctuations, thereby decreasing tool wear, improving machining efficiency, and enhancing overall processing performance.

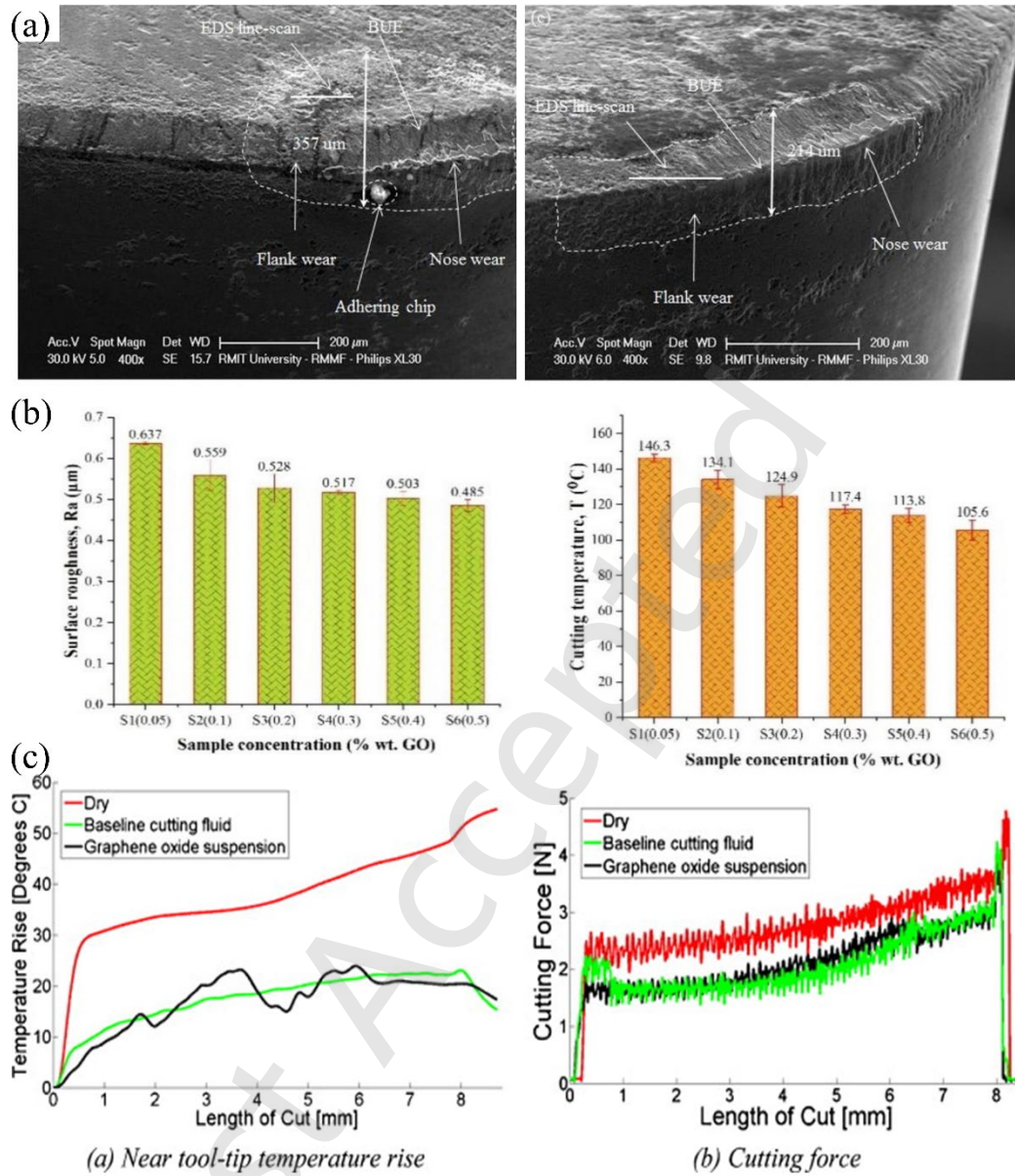


Fig. 2 (a) SEM images of tool flank wear under dry cutting and GO nanofluid conditions. Reproduced with permission from Ref. [44], © Elsevier 2020. (b) Comparison of surface roughness and cutting temperature under different concentrations of GO nanofluid. Reproduced with permission from Ref. [45], © Elsevier 2024. (c) Trends in cutting temperature and cutting force under three machining conditions. Reproduced with permission from Ref. [47], © Elsevier 2014.

2.1.3 Graphene composite nano-additives

Graphene nanomaterials alone already exhibit outstanding lubricating properties. In recent years, researchers have developed composite systems combining graphene with other materials, leveraging synergistic effects between different components to achieve enhanced lubrication, cooling, and anti-wear performance. Among these, composite systems integrating graphene with various metal nanoparticles and their oxides have garnered significant attention.

The layered structure of graphene can isolate metal oxide nanoparticles, preventing their agglomeration. Meanwhile, the metal oxide nanoparticles reduce friction through rolling effects and surface repair mechanisms. Anand et al. [49] investigated the synergistic effects of TiO_2 and GNPs additives on the rheological properties and machining performance of rice bran oil. Single-component nanofluids (rice bran oil/ TiO_2) and hybrid nanofluids (rice bran oil/ TiO_2 /GNPs) were experimentally prepared. The results demonstrated that the hybrid nanofluid exhibited superior machining performance compared to the single-component TiO_2 nanofluid, achieving a 38% reduction in tool flank wear and an 11% decrease in surface roughness. These improvements can be attributed to the synergistic interaction between the ball-bearing effect of TiO_2 and the friction reduction and thermal conductivity enhancement provided by GNPs. Sharma et al. [50] prepared hybrid nanofluids consisting of graphene and alumina (volume ratio 90:10) in a water-oil emulsion for the turning of AISI 304 steel. The study results indicated that, compared to pure alumina nanofluids, the hybrid nanofluids demonstrated lower tool wear and friction coefficients, as shown in **Fig. 3a-b**. Li et al. [51] prepared hybrid nanofluids comprising graphene and Al_2O_3

using oleic acid as the base fluid. The lubricating performance of these hybrid nanofluids with varying concentrations and ratios was evaluated under MQL conditions. The hybrid nanofluid exhibits significant synergistic lubrication effects, with optimal performance observed under AG151 conditions at a GNPs concentration of 15%. Compared to dry grinding conditions, the specific grinding energy, coefficient of friction, and temperature rise were reduced by 73.92%, 46.57%, and 65.69%, respectively.

Metal nanoparticles exhibit excellent ductility, enabling them to deposit on friction surfaces and form stable friction layers. This significantly enhances load-bearing capacity while reducing cutting forces and tool wear. Cui et al. [52] prepared GNPs-Cu/ZrO₂ hybrid nanofluids for machining Inconel 718 alloy. Compared to LB2000 base oil, the addition of multi-component nanoparticles significantly enhanced the base fluid's thermal conductivity, wettability, and base viscosity. Under MQL conditions, surface roughness, cutting temperature, cutting force, and tool wear decreased by 65.68%, 66.67%, 55.75%, and 44.79%, respectively, compared to dry machining (**Fig. 3c-d**). Micro-rolling, ball-bearing, and surface polishing mechanisms induced by hard nanoparticles significantly reduce the risks of adhesive wear and chip formation. The incorporation of nano-copper and zirconia further enhances the stability of graphene self-assembled films.

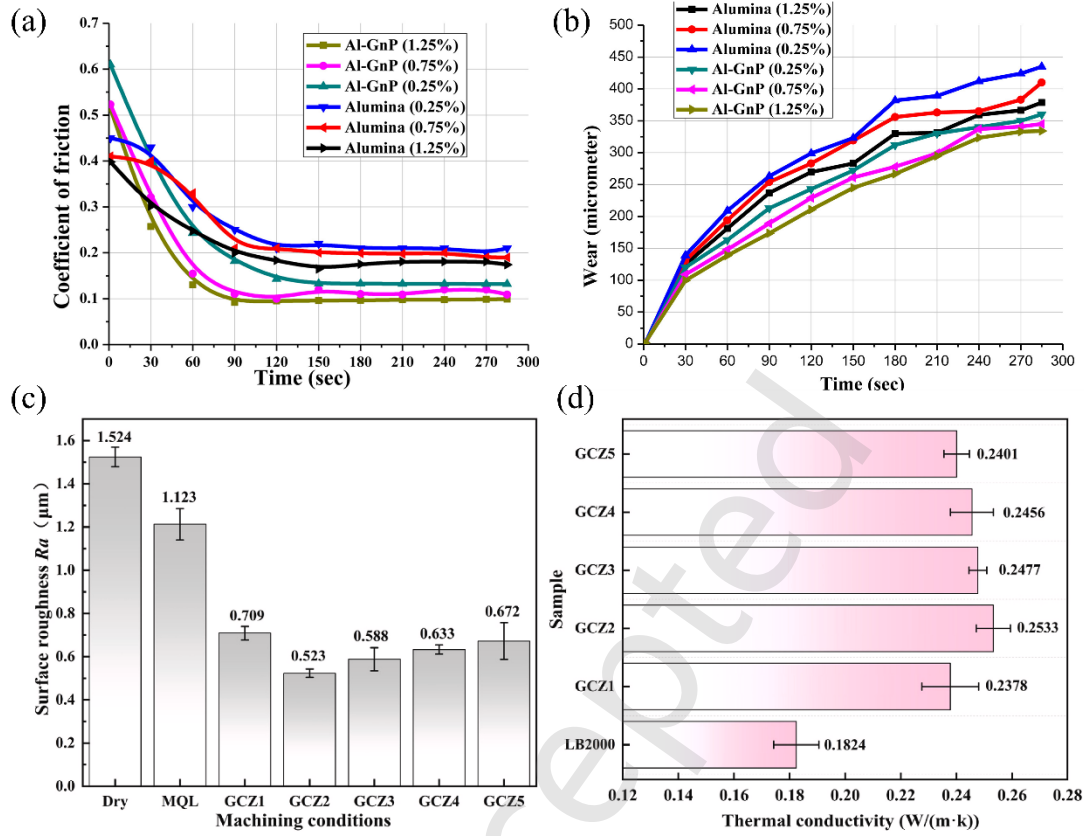


Fig. 3 (a) Friction coefficient and (b) wear volume of graphene/alumina hybrid nanofluid. Reproduced with permission from Ref. [50], © Elsevier 2018. Effects of different machining conditions on (c) surface roughness of machined surfaces and (d) thermal conductivity of hybrid nanofluid versus base oil. Reproduced with permission from Ref. [52], © Elsevier 2025.

Graphene and its derivative nanomaterials hold broad application prospects in the field of lubrication. Extensive research has explored the use of graphene family materials as additives; however, significant variations exist in wear reduction rates, cutting force reduction rates, and coefficient of friction reduction rates across different systems and processing environments, with complex influencing factors. **Table 2** lists the types of graphene-based materials used as cutting fluid additives, the base fluid types, the types of processed materials, and the core performance indicators.

Table 2 Machining performance of graphene-based cutting fluids

Category	Base fluid	Machined alloy	Machining performance	Ref.
Graphene	Palm oil	Ti-6Al-4V	Compared to cutting fluid LB2000, specific grinding energy reduced by 80.25%.	[35]
Graphene	Sunflower seed oil	AISI321	Compared to pure oil, cutting force is reduced by 27.4%, friction coefficient is reduced by 51.7%, and surface roughness is reduced by 33.8%.	[36]
Graphene	Rapeseed oil	C276	Surface roughness is reduced by 32% compared to dry cutting, and maximum cutting temperature is reduced by 86%.	[38]
Graphene	Ethylene Glycol	M42 steel	Surface roughness reduced by 66%, tool wear reduced by 86%.	[39]
Graphene	Water	Ti-6Al-4V	Compared to LB2000 base oil, the coefficient of friction is reduced by 12.79%, and the tangential grinding force is reduced by 26.36%.	[53]
Graphene/Sulfur-based extreme pressure additive	Rapeseed oil	Ti-6Al-4V	Compared to pure oil, surface roughness is reduced by 56.4%, and cutting force is reduced by 27%.	[54]
Graphene/ TiO ₂	Rice bran oil	M2 steel	Compared to titanium dioxide nanofluid, tool rake face wear is reduced by 38%, and surface roughness is reduced by 11%.	[49]
Graphene - Cu/CrO ₂	LB2000	Inconel718	Compared to LB2000 base oil, surface roughness is reduced by 65.68%, cutting force is reduced by 55.75%, and tool wear is reduced by 44.79%.	[52]

GO	Castrol Cleardge 6519	AISI 12L14	Compared to dry cutting, tool wear is reduced by 74%, cutting temperature is lowered by 50%, and cutting force is reduced by approximately 20%. [47]
GO/SiO ₂	Ethylene Glycol/Water	AISI304	The coefficient of friction is reduced by 19.5%, and surface roughness is reduced by 6.1% compared to LB2000 base oil. [55]
GO/MWCNTs	Water	Inconel718	The average friction coefficient decreased by 22.3%, and the wear rate decreased by 40.2%. [56]

2.2 CNTs as cutting fluid additives

CNTs are one-dimensional quantum materials with a unique structure, featuring a radial dimension at the nanoscale and an axial dimension at the micrometer scale. Consequently, CNTs exhibit a high aspect ratio and exceptional thermal exchange properties along their length, demonstrating excellent heat transfer capabilities [57]. The physical structure of CNTs consists of a grid-like cylindrical arrangement formed by sp²-hybridized carbon atoms. Their exceptionally high aspect ratio facilitates rapid heat transfer along the axial direction, with thermal conductivity ranging from 3000 to 6000 W/(m·K) [58]. CNTs exhibit exceptional compressive strength and Young's modulus. Under high stress, they deform rather than fracture immediately, demonstrating notable toughness. The weak van der Waals forces between the walls of MWCNTs allow for interlayer sliding, which reduces friction. When introduced as additives into the cutting zone, they mitigate tool wear through mechanisms such as micro-bearing effects and filling surface defects [59-61].

CNTs enhance tool wear resistance, deformation resistance, and failure resistance during machining processes. Their extremely high aspect ratio endows them with outstanding axial thermal conductivity. Sarkar et al. [62] systematically evaluated the performance of nanofluids prepared from coconut oil and MWCNTs under nanofluid minimum quantity lubrication (NMQL) conditions during the turning of Inconel 718 alloy. Compared to dry cutting, both MQL and NMQL significantly reduced cutting forces and tool temperature. In terms of tool wear, NMQL effectively suppressed flank wear under low-speed cutting conditions. Ross et al. [63] investigated the effectiveness of MWCNTs suspended in vegetable oil as a cutting fluid. Under various cutting speed conditions, the NMQL formulation consistently reduced cutting temperatures and surface roughness, effectively minimizing friction in the cutting zone. Sharmin et al. [64] utilized the surfactant SDS to prepare a stably dispersed carbon nanotube water-based cutting fluid. Compared to machining without any fluid, the application of carbon nanotube nanofluid reduced surface roughness by 34% and cutting temperature by 29%. Among the tested samples, the one containing 0.3% volume fraction of CNTs exhibited the highest stability. Kishore et al. [65] examined water-based MWCNTs nanofluids under MQL during Inconel 625 grinding. Higher nanofluid concentrations improved cooling and lubrication, with the 0.1 vol% formulation performing optimally—significantly lowering grinding forces and enhancing surface quality. It is noteworthy that the lubrication-enhancing effect of CNTs is maintained within a certain concentration range. Excessively high concentrations may lead to performance degradation due to agglomeration effects.

Additionally, combining CNTs with microtextured cutting tools enables efficient heat dissipation from the cutting zone due to CNTs' exceptionally high thermal conductivity. Meanwhile, the microtexture synergistically reduces cutting forces and friction coefficients by minimizing contact area between the tool and chips, storing lubricant, and promoting chip flow. Ribeiro et al. [66] investigated the machining performance of micro-grooved cutting tools filled with CNTs during the turning of AISI 1045 steel. The CNTs-filled tools demonstrated outstanding wear resistance. Among them, the tool with a 0.25 mm deep texture and CNTs filling performed optimally, achieving a 33.11% reduction in cutting force and a 30% decrease in cutting temperature. Khani et al. [67] analyzed the influence of surface texturing and lubrication with CNTs-enriched nanofluids on the cutting performance of carbide tools during the turning of aluminum alloys. The experimental results demonstrated that using micro-groove textured tools oriented perpendicular to the chip flow direction, combined with CNTs-enriched nanofluid lubrication, significantly reduced cutting forces, surface roughness, and friction coefficients, as illustrated in **Fig. 4**.

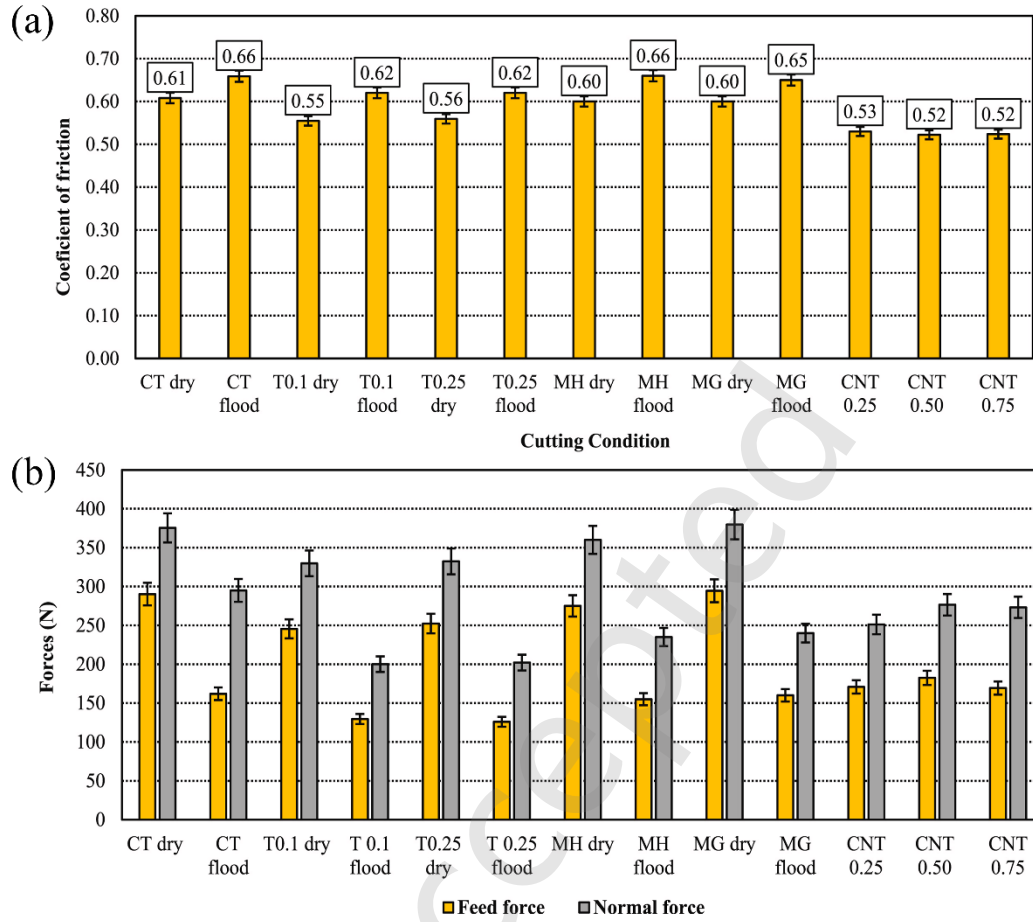


Fig. 4 (a) Cutting friction coefficient and (b) cutting force under different conditions for conventional tools, micro-textured tools, and micro-textured tools filled with carbon nanotubes. Reproduced with permission from Ref. [66], © Nature 2023.

Researchers have combined CNTs with other functional nanomaterials to achieve optimization in multiple properties, including thermal conductivity, wear resistance, and friction reduction. Gugulothu and Pasam [68] investigated the performance of CNT/MoS₂ hybrid nanofluids at different concentrations under MQL conditions during the turning of AISI 1040 steel. Compared to dry cutting and base oil machining, the 2 wt% nanofluid reduced the friction coefficient by 93.77% and 82.9%, respectively. The hybrid nanofluid effectively lowered cutting forces, surface roughness, and cutting

temperatures. Zhang et al. [69] studied the lubrication performance of $\text{Fe}_3\text{O}_4@\text{CNTs}$ nanofluids and micro-textured tools in machining Ti-6Al-4V alloy under magnetic field assistance. Under a 1200 Gs magnetic field, micro-textured tools combined with 0.5 vol% hybrid nanofluid achieved minimal cutting force and surface roughness. The $\text{Fe}_3\text{O}_4@\text{CNTs}$ nanofluid significantly reduced adhesive tool wear, decreased cutting zone temperatures, and exhibited excellent thermal lubrication properties along with favorable dispersion stability. Guan et al. [70] prepared $\text{CNTs}@\text{T321}$ composite nanomaterials by filling acid-treated CNTs with isobutylene sulfide (T321), and evaluated this composite nanofluid for milling C45 steel under MQL conditions. Compared to the single-CNT nanofluid, the composite nanofluid demonstrated superior milling performance, reducing cutting force, machining temperature, and surface roughness by 12%, 20%, and 15%, respectively.

2.3 Other types of carbon-based materials as cutting fluid additives

In addition to graphene and CNTs, commonly used carbon-based cutting fluid additives also include CQDs and fullerene C_{60} . CQDs are zero-dimensional carbon nanomaterials with notable fluorescence properties, composed of ultrafine, dispersed, quasi-spherical carbon nanoparticles with sizes below 10 nm [71]. Compared to traditional carbon nanomaterials, small and uniform CQDs exhibit excellent dispersibility in base lubricants. Furthermore, the abundant surface functional groups of CQDs facilitate chemical modification to enhance their lubricating performance in various cutting fluids [72]. Unlike the physical friction reduction mechanisms of

graphene interlayer slip and carbon nanotube rolling bearings, CQDs primarily reduce tool wear and friction by forming a chemical protective layer at the interface through friction chemical reactions.

Yu et al. [73] synthesized CQDs nanofluids via thermal decomposition of citric acid (CA), which exhibited continuous fluidity and excellent tribological behavior at room temperature. The nanofluid containing 7.5 wt% CQDs/CA achieved a low friction coefficient of 0.091 and reduced wear by 52% compared to PAO-4. Ross et al. [74] developed a novel cutting fluid using rice bran oil as the base fluid and carbon nanodots (CNDs) as nano-additives. The results showed that under NMQL conditions, tool flank wear was reduced by 55–61%, cutting temperature decreased by 26–29%, and surface roughness improved by 18–24%. The superior performance is attributed to the thermal conductivity and lubricity of CNDs nanoparticles, which form a lubricating film at the machining interface, enhancing cooling and reducing friction.

The surface groups of CQDs can be structurally modified based on the physicochemical properties of the cutting fluid, enhancing their dispersion stability in the base oil without requiring additional auxiliary reagents or post-treatment. This broadens their applicability and practicality significantly [75]. Wu et al. [76] synthesized four types of modified CQDs with varying alkyl chain lengths using a hydrothermal method. The modified short-chain CQDs readily entered the contact zone and formed stable films through friction. By adjusting the carbon chain length, the tribological properties of the modified CQDs could be effectively controlled. Zhang et al. [77] synthesized CQDs nanofluids functionalized with KH570 and M2070.

Incorporating these nanofluids into a polyimide (PI) matrix notably improved the coating's wear resistance. Molecular dynamics simulations indicated that the CQDs restricted PI molecular chain mobility, enhancing mechanical properties, while also mitigating composite deformation under tribological stress.

Fullerene is a hollow molecule composed entirely of carbon, structurally similar to graphite. Among them, the fullerene C60 molecule exhibits a spherical shape with characteristics such as low surface energy, chemical stability, and strong load-bearing capacity. Its incorporation into polymers can effectively enhance the mechanical properties of composites [78-81].

C60's unique spherical structure reduces friction through the micro-bearing effect while simultaneously forming a protective film to enhance wear resistance. Pan et al. [82] proposed a thermodynamic coupling modeling method for milling that considers MQL and cooling effects. They developed a differential unit model for cutting force and temperature and evaluated cutting force, temperature, and residual stress through milling experiments under different conditions. The results showed that C60 NMQL significantly reduced residual stress by 41.6%, 28.1%, and 19.6% compared to dry cutting, flood cooling, and conventional MQL, respectively. This reduction is attributed to the synergistic effects of its friction reduction properties and efficient heat dissipation. Huang et al. [79] studied the dispersion stability and tribological performance of fullerene C60 nanospheres as an additive in HM32 anti-wear hydraulic oil. Four-ball friction tests showed that at the optimal concentration of 0.02 wt%, the friction coefficient was reduced by 41.28% and the wear scar diameter decreased by 10.40%.

However, when the C60 concentration exceeded 0.02 wt%, nanoparticle agglomeration led to a decline in frictional performance. Pan et al. [83] incorporated fullerene C60 nanoparticles into water-based cutting fluids to enhance titanium alloy milling performance through NMQL. The results indicated that the friction coefficient was minimized at a C60 concentration of 0.02 wt%, with maximum cutting forces reduced by 26% and 16.4% compared to dry machining and pure MQL, respectively. The researchers also developed a force-thermal coupling model for titanium alloy milling that accounts for lubrication conditions. Using finite element analysis to compute cutting forces on the cutting edge, the model's predicted milling forces showed general agreement with measured values in both trend and magnitude when compared to experimental data from side milling.

3. Influence of different factors on the performance of carbon-based nanomaterial cutting fluids

The machining of high-performance alloys is often challenging due to high-temperature accumulation in the cutting zone and the high mechanical strength of the workpiece. This can lead to rapid tool wear and deformation, increased surface roughness of the workpiece, and the occurrence of surface defects such as grooves and cracks [4]. Cutting fluid nano-additives significantly reduce tool friction and wear. When combined with various cooling methods, they lower temperatures in the machining zone, thereby minimizing metal softening and deformation. Researchers continue to explore different combinations of nano-cutting fluids and optimal

machining parameters to achieve extended tool life, improved surface integrity, and reduced tool wear [11, 84]. The performance of carbon-based nanomaterials in cutting fluids is influenced by a combination of factors. The following sections discuss the tribological properties and machining characteristics of carbon-based materials under various influencing factors, providing insights for future researchers to design cutting fluids with superior lubrication and cooling performance.

3.1 Influence of dispersion techniques

Dispersion stability directly determines the stability and performance consistency of carbon-based nano-cutting fluids. Only cutting fluids that maintain stable lubricating properties can be reliably applied in industrial manufacturing. The physical parameters of nanomaterials, such as particle size, morphology, concentration, and dispersion medium, significantly influence the dispersibility of nano-cutting fluids [85]. Interaction forces between carbon-based nanoparticles play a dominant role in influencing the dispersion behaviour of nanofluids, often resulting in aggregation. It has been reported that the shape of the nanoparticles also affects the attractive interactions between adjacent particles. Due to their larger contact areas, graphene sheets and carbon nanotube rods exhibit stronger attractive forces between neighbouring nanoparticles, resulting in a greater tendency to form aggregates [86]. Researchers predominantly employ physical and chemical modification methods to enhance the dispersibility of carbon-based nanomaterials in base fluids.

Traditional dispersion methods for nano-cutting fluids include the “one-step

method” and the “two-step method,” primarily employing ultrasonic dispersion to uniformly distribute nanoparticles within the cutting fluid. This process achieves proper dispersion by utilizing the cavitation effect to disrupt nanoparticle agglomerates and reduce their size [87]. Wang et al. [88] employed a novel ultrasonic method to disperse high-concentration graphene into HVIH-5 base oil without the use of dispersants (**Fig. 5a**). The high-concentration graphene-HVIH-5 system remained stable for approximately 20 days. Compared to using the base oil alone, the lubricant with high-concentration graphene reduced friction and wear by 47.2% and 42.8%, respectively. This indicates that well-dispersed high-concentration graphene lubricants can form tribofilms with superior lubrication properties, effectively preventing direct contact between friction pairs. In reference [45], GO nanoparticles were dispersed into mineral oil using mechanical stirring (1400 rpm, 30 min) followed by ultrasonication. While all nanofluids remained stable for the initial three days, sedimentation occurred in nearly all samples after 21 days. Adjusting the pH improved dispersion, and increasing GO concentration from 0.05 wt% to 0.5 wt% significantly enhanced both dispersion stability and lubrication performance.

Although ultrasonic treatment can effectively break up nanoparticle aggregates, this physical dispersion method often proves unstable. Under the influence of van der Waals forces, particles readily agglomerate and settle. In contrast, chemical modification methods can alter the chemical properties of nanoparticles, enabling long-term stable dispersion of nanofluids. Li et al. [89] assembled 4-tert-butylcatechol (TBC) onto the surface of carbonyl-modified CNTs and ultrasonically dispersed them in water.

Fig. 5b demonstrates that TBC-CNTs exhibit superior dispersion stability in water compared to commercial CNTs. The optimal concentration of TBC-CNTs was 0.2 wt%, which reduced friction by 30.6% and wear by 28.3% compared to water lubrication under an 8 N load. The TBC-CNTs nanofluid enhanced the water film thickness within the contact area and formed a lubricating film at the friction interface, thereby minimizing friction (**Fig. 5c**). Guan et al. [70] utilized a mixture of Tween-80 and dodecylbenzene sulfonate as surfactants to prepare CNTs@T321 composite nanofluids via mechanical stirring and ultrasonication. Testing revealed that the composite nanofluids exhibited superior dispersion stability compared to pure CNTs nanofluids, while the surfactants and T321 also enhanced the wettability and thermal conductivity of the cutting fluid.

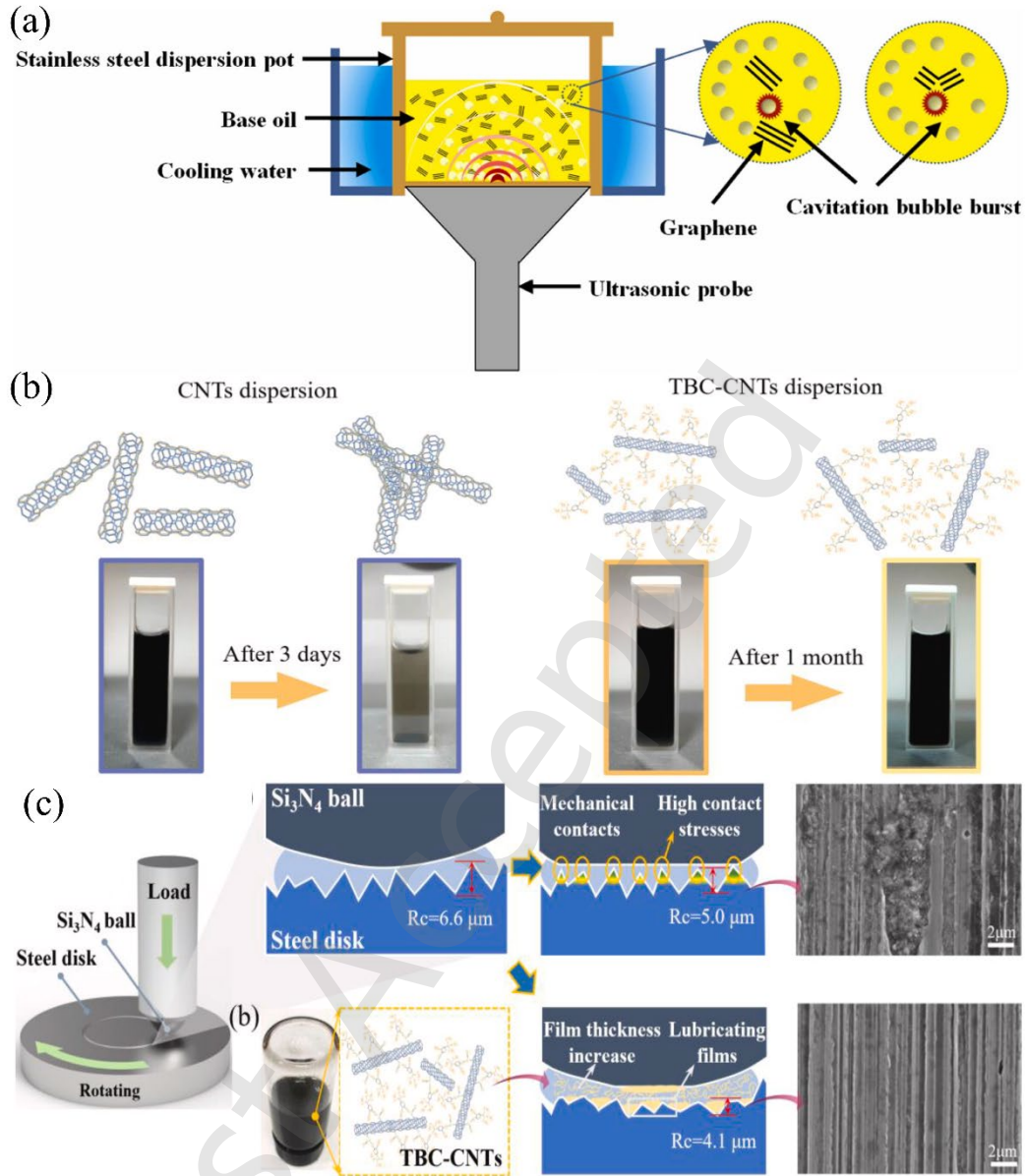


Fig. 5 (a) Ultrasonic dispersion method for graphene. Reproduced with permission from Ref. [88], © Elsevier 2024. (b) Comparison of dispersion stability between carboxylated carbon nanotubes and commercial carbon nanotubes, (c) Friction and wear reduction mechanism of TBC-CNTs. Reproduced with permission from Ref. [89], © Elsevier 2024.

Stable dispersibility ensures that nanoparticles form a stable lubricating film at the interface. Poorly dispersed nanoparticles agglomerate and settle in the base fluid,

making it difficult for them to penetrate the friction interface to reduce friction. Moreover, larger agglomerates act as abrasive particles, accelerating tool wear and causing scratches on the workpiece. The dispersion stability of nanofluids also determines their thermal conductivity and viscosity. Nanoparticles significantly enhance the fluid's heat transfer performance, attributed to the random motion of suspended particles under Brownian motion within the fluid. This motion increases energy transfer between particles and liquid, thereby improving the thermal conductivity coefficient of nanofluids [90]. For example, SDS-modified multi-walled carbon nanotube dispersions exhibit approximately 42% higher thermal conductivity than conventional cutting fluids [91], while ultrasonically dispersed graphene nanoplatelet-ethylene glycol nanofluids show an enhancement rate of up to 86% [43]. Furthermore, individual nanoparticles contribute to lubrication through ball-bearing effects and surface polishing. Consequently, the dispersibility of nano-additives directly determines their effectiveness at the metal processing interface.

3.2 Influence of nanomaterial structural properties

The addition of different types of nanoparticles, due to their unique thermal conductivity and lubrication mechanisms, leads to significantly distinct improvements in cutting force, temperature, and surface quality during machining. For example, C60 and graphene share the same hybridized carbon structure, yet exhibit distinct tribological properties. Song et al. [92] investigated the tribological behavior of carbon nanomaterials under vacuum conditions, where graphene and C60 demonstrated

friction coefficients of 0.018 and 0.125, respectively. C60's inability to form a layered structure leads to progressive degradation during friction, resulting in its higher coefficient of friction. Touggui et al. [93] compared the performance of MWCNTs, molybdenum disulfide, and nano-graphene as additives in vegetable-based cutting fluids during AISI 304 turning. Nano-graphene alone achieved the lowest cutting force, while carbon nanotube nanofluids yielded the lowest cutting temperature. Adding graphene to other nanofluids notably enhanced both cooling and lubrication.

When carbon-based nanomaterials are added to different types of base cutting fluids, the dispersion properties, thermal conductivity, and film-forming capability of the nanofluids at the machining interface are significantly affected. This effect is fundamentally related to the compatibility between the cutting fluid and the machining conditions. Baldin et al. [94] found that adding graphene nanoplatelets to mineral oil (MQL14) increased tool wear and reduced tool life when milling AISI 1050 steel. However, their addition to vegetable oil (MQL15) and LB1000 effectively enhanced tool lubrication and reduced wear. When graphene sheets were added to mineral oil, they may have acted as particulate contaminants, exacerbating abrasive wear. In reference [91], surfactants were required to enhance the dispersion stability of carbon nanotube nanofluids in water-based cutting fluids. The thermal conductivity of CNTs in water-based fluids was approximately 42% higher than that of conventional cutting fluids. However, when coconut oil or other vegetable oils were used as the base fluid, nanofluids with effective lubrication could be prepared simply through ultrasonic dispersion. In this case, the nanofluids significantly reduced cutting forces and

minimized tool wear [62].

In addition, the physical and mechanical properties of different alloy types vary, and the primary wear mechanisms affecting machining also differ when processing these alloys. The effectiveness of various carbon-based materials as cutting fluid additives also exhibits differences. Ruzzi et al. [95] employed a semi-synthetic environmentally friendly oil enriched with multi-layer graphene (MLG) to grind nickel-based superalloys (Inconel 625 and Inconel 718). The presence of MLG improved the surface finish of Inconel 718 but exacerbated plastic deformation on the surface of Inconel 625. Oliveira et al. [96] reported that multi-layer graphene-enhanced cutting fluids under MQL exhibit alloy-dependent performance variations. For high-strength Inconel 718, graphene reduces friction, promotes continuous chip formation, and enhances machining efficiency. For ductile Inconel 625, while graphene lowers friction, it may increase abrasive plowing and plastic deformation. For brittle SAE 52100, the improvement is limited due to the material's tendency toward abrasive detachment rather than adhesion. In contrast, Singh et al. [97] demonstrated that using vegetable oil-based nanofluids with added MWCNTs effectively reduced tool wear and surface abrasion when machining Inconel 625 alloy. MWCNTs exhibit superior heat dissipation compared to graphene, significantly reducing thermal deformation during machining and inhibiting abrasive adhesion.

The concentration and size of nanoparticles in cutting fluids influence their dispersion stability and the formation of lubricating films. Li et al. [98] studied how graphene-based cutting fluid concentration, flow rate, and gas pressure influence TC4

alloy milling. Concentration had the greatest impact: too low reduced film load capacity, while too high caused particle agglomeration and increased wear. The optimal parameters were 0.1 wt% concentration, 60 ml/h flow rate, and 0.6 MPa gas pressure, confirming concentration as the key factor for lubrication and cooling performance. Gupta et al. [99] analyzed the effectiveness of Al₂O₃-MWCNT hybrid nanofluids in soybean oil at different concentrations and ratios on tool wear during the turning of AISI 304 stainless steel. They found that increasing the nanoparticle mass fraction from 1 wt% to 2 wt% enhanced the thermal conductivity of the nanofluid but also increased its viscosity, which hindered chip removal. The minimum flank wear was achieved with a hybrid nanofluid concentration of 1.5 wt% and an Al₂O₃ to MWCNT ratio of 6:4. Gong et al. [37] used two sizes of graphene nanoplatelets (5 μ m and 15 μ m) as additives in vegetable oil to form nanofluids and evaluated their effectiveness in sustainable turning of Inconel 718 alloy under an MQL strategy. Across all tested cutting speeds, the experimental group with 5 μ m graphene achieved the smoothest surfaces, reducing surface roughness by 26% compared to dry cutting.

High-speed or high-feed machining induces higher temperatures and shear stresses at the tool-workpiece interface. In such scenarios, appropriately increasing the concentration of carbon-based nanoparticles can promote the formation of a thicker tribofilm while enhancing the cooling capability of the cutting fluid. It is worth noting that when the nanoparticle concentration exceeds a certain threshold, the excessive viscosity of the nanofluid can exacerbate viscous heating, thereby diminishing the heat dissipation advantages of the nanoparticles. During high-speed machining, nanofluids

with excessively high viscosity and flow resistance are less capable of adsorbing onto the contact zone to form a lubricating film. Instead, nanoparticles tend to be squeezed out of the contact area, failing to provide effective lubrication. The trade-off between lubrication enhancement and hydrodynamic losses can be systematically investigated using the Stribeck curve to identify the optimal nanoparticle concentration or viscosity. Below the critical concentration, the high thermal conductivity and lubricating capability of nanoparticles are the dominant factors; above this threshold, the adverse effects of viscous heating and fluid loss become increasingly pronounced.

3.3 Influence of machining process parameters

The high performance of cutting fluids is not static. Parameters such as cutting speed, feed rate, and depth of cut determine the temperature, pressure, and lubrication requirements at the tool-workpiece interface. Different combinations of machining parameters significantly affect the penetration ability, film stability, and heat dissipation efficiency of nanomaterials. Yi et al. [100] used a novel graphene oxide cutting fluid for drilling titanium alloys and analyzed the influence of parameters such as spindle drilling speed and feed rate. Increasing the feed rate led to higher surface roughness, while increasing the spindle speed reduced chip thickness and cutting force. At higher cutting speeds, the shear zone area decreased and an elastic zone formed, resulting in thinner chips that slid more easily along the groove, thereby reducing cutting forces. Okokpuije et al. [101] dispersed MWCNTs particles in a mineral oil-based fluid for turning Al-Si-Mg alloy, investigating the effects of cutting speed, feed rate, and depth

of cut on tool wear. The experiments demonstrated that increasing the depth of cut raised tool wear. At lower cutting speeds, the feed rate had a more significant impact on wear, whereas at higher cutting speeds, the influence of feed rate on tool wear diminished. Additionally, higher cutting speeds exacerbated tool wear regardless of whether MWCNTs cutting fluid was used. Ross et al. [102] used a cutting fluid consisting of a mixture of carbon nanodots and soybean oil to machine Hastelloy C276. They analysed its performance in terms of cutting temperature, surface roughness and tool wear. They discovered that, while increasing the cutting speed improved the surface finish of the machined part, it also accelerated tool wear and reduced tool life.

At high feed rates, the heat generated during machining may exceed the cooling capacity limits of nanofluids, significantly reducing the effectiveness of the cutting fluid. To maximize the performance advantages of nano-cutting fluids in MQL applications, excessively high feed rates should be avoided. Hegab et al. [103] examined the effect of multi-walled carbon nanotube cutting fluids on the machining of Ti-6Al-4V. By varying cutting speed, feed rate, and MWCNTs concentration, they assessed surface quality outcomes. The optimal performance was achieved with a 2 wt% MWCNTs nanofluid at 120 m/min cutting speed and 0.1 mm/rev feed rate, reducing surface roughness by 50%. Feed rate emerged as the most influential factor: increasing it from 0.1 mm/rev to 0.4 mm/rev raised cutting forces and heat generation, thereby deteriorating surface quality. Oussama et al. [104] evaluated the performance of MWCNTs nanofluids under MQL conditions during the turning of AISI 316L stainless steel, analyzing the effects of different cooling conditions, cutting speeds, and feed rates.

Compared to dry machining, the use of pure MQL and NMQL strategies reduced the feed force by approximately 22.84% and 28.53%, respectively, while the cutting temperature decreased by 28.71% and 42.38%, respectively. During the turning process, the feed force decreases as the cutting speed increases, and the surface finish improves. Conversely, increasing the feed rate significantly raises the feed force, cutting temperature, and surface roughness.

The extant research indicates that cutting speed exhibits a negative correlation with surface roughness, meaning that roughness improves as cutting speed increases. However, it should be noted that elevated cutting speeds can also accelerate tool wear, particularly in conditions where lubrication is inadequate. In such cases, elevated temperatures can exacerbate chip adhesion, leading to increased wear of the tool. Feed rate is one of the parameters that significantly influence surface roughness, and its increase directly leads to higher roughness. An increase in the depth of cut expands the contact area between the cutting edge and the workpiece, as well as the volume of material removed, resulting in a linear or near-linear substantial rise in cutting force. Therefore, under MQL cooling and lubrication conditions, researchers typically employ smaller cutting depths, higher cutting speeds, and appropriate cutting depths to machine difficult-to-cut metals.

4. Lubrication mechanisms of the carbon-based nanomaterials

Whether it is the enhancement of anti-friction and anti-wear in cutting fluids by single carbon-based materials or the optimization of adaptability to complex machining

conditions by carbon-based composite systems, the outstanding effectiveness relies on the unique lubrication mechanisms of carbon-based materials at the tool-workpiece-chip interface. As shown in **Fig. 6**, the lubrication mechanism of nanomaterials can be primarily attributed to the following four aspects: converting sliding friction into rolling friction by acting as nano-balls; forming solid lubrication films/chemical friction films to reduce friction; filling surface micro-damage to achieve self-healing; and polishing the workpiece surface to enhance surface finish [102]. Building upon the lubrication mechanisms of conventional nanomaterials, the size effects, surface defects, liquid–solid interfacial interactions, and dependence on friction pair materials of carbon-based nanomaterials exert a deeper regulatory role on tribological behavior. For two-dimensional materials such as graphene, the smaller the lateral size, the easier it is to enter the contact interface, enabling the rapid formation of a continuous and dense lubricating film during the running-in period; the fewer the walls of MWCNTs, the greater their flexibility and the stronger their ability to penetrate the friction interface. On one hand, surface defects of carbon-based nanomaterials can serve as active sites to promote tribochemical reactions and surface modification; on the other hand, they can enhance the liquid–solid interfacial interaction between the nanomaterials and the lubricating medium, thereby improving dispersion stability. In addition, the surface properties of the friction pair also determine the adsorption and film-forming capabilities of carbon nanomaterials. This chapter will focus on discussing the fundamental lubrication mechanisms of single carbon-based materials and the synergistic lubrication mechanisms of carbon-based composite additives.

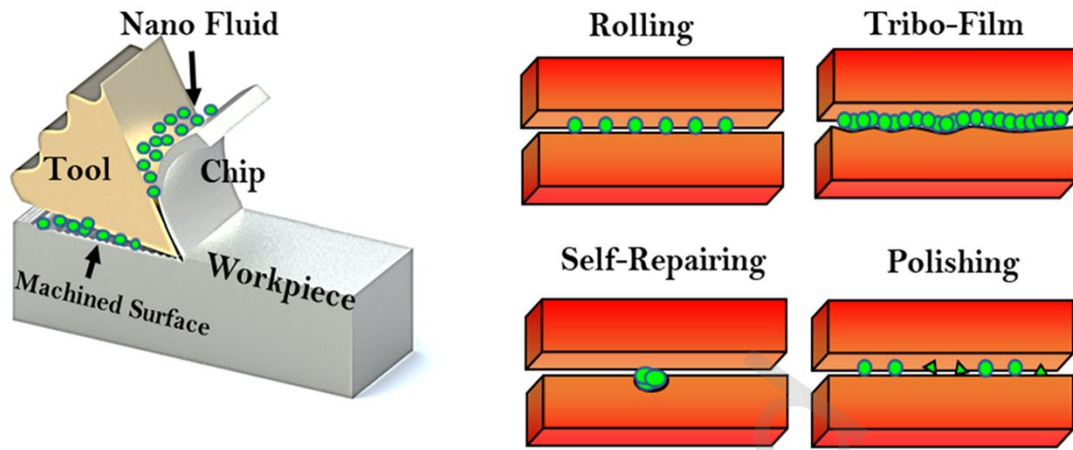


Fig. 6. Mechanism of nanoparticle cutting. Reproduced with permission from Ref. [63], © Elsevier 2023.

4.1 Lubrication mechanism of graphene-based nano-additives

Graphene-based materials exhibit extremely low shear strength and reduce friction coefficients through interlayer sliding during friction. Chemical or physical modification of graphene, as well as the construction of composite structures with other nanomaterials, is considered an effective approach to enhancing tribological performance [105]. Graphene nanomaterials can readily enter the friction interface during the friction process, preventing direct contact between friction pairs and forming a protective tribofilm. Furthermore, graphene nanoplatelets undergo complex tribochemical reactions to form stable chemical tribofilms. The load-bearing capacity of graphene nanomaterials enhances the mechanical strength of the tribofilm, while their ability to adsorb onto surface asperities and defects helps repair worn surfaces and improve friction performance.

Graphene nanofluids significantly inhibit tool wear during cutting processes. Wang et al. [106] investigated the suppression mechanism of graphene nanofluids on diamond tool wear. As shown in **Fig. 7a**, in dry micro-milling, alternating loads are directly applied to the tool tip, and the impact of cutting vibrations exacerbates tool wear and even leads to tool failure. **Fig. 7b** illustrates the interaction mechanism at the contact interface within the graphene nanofluid MQL environment, transforming direct contact into indirect contact. The in-plane elasticity of graphene effectively absorbs the impact of external loads on the workpiece. Under shear forces, graphene layers undergo relative sliding, thereby effectively separating the friction surfaces. This converts direct metal-to-metal contact into low-shear-force sliding between graphene layers. Babu et al. [38] reported the use of graphene nanofluid-enhanced cutting oil to alter the boundary conditions at the tool-chip-workpiece interface during dry cutting. The van der Waals forces between graphene layers are extremely weak, readily forming a low-shear interface. As the layers move, nanoparticles form a film at the interface, thereby reducing friction (**Fig. 7d**).

The most direct reason for the inhibition of tool wear by graphene nanofluids is the barrier effect of graphene. It prevents adhesion between the tool surface and the workpiece material, thereby suppressing bonding behavior induced by high stress and thermomechanical coupling effects.

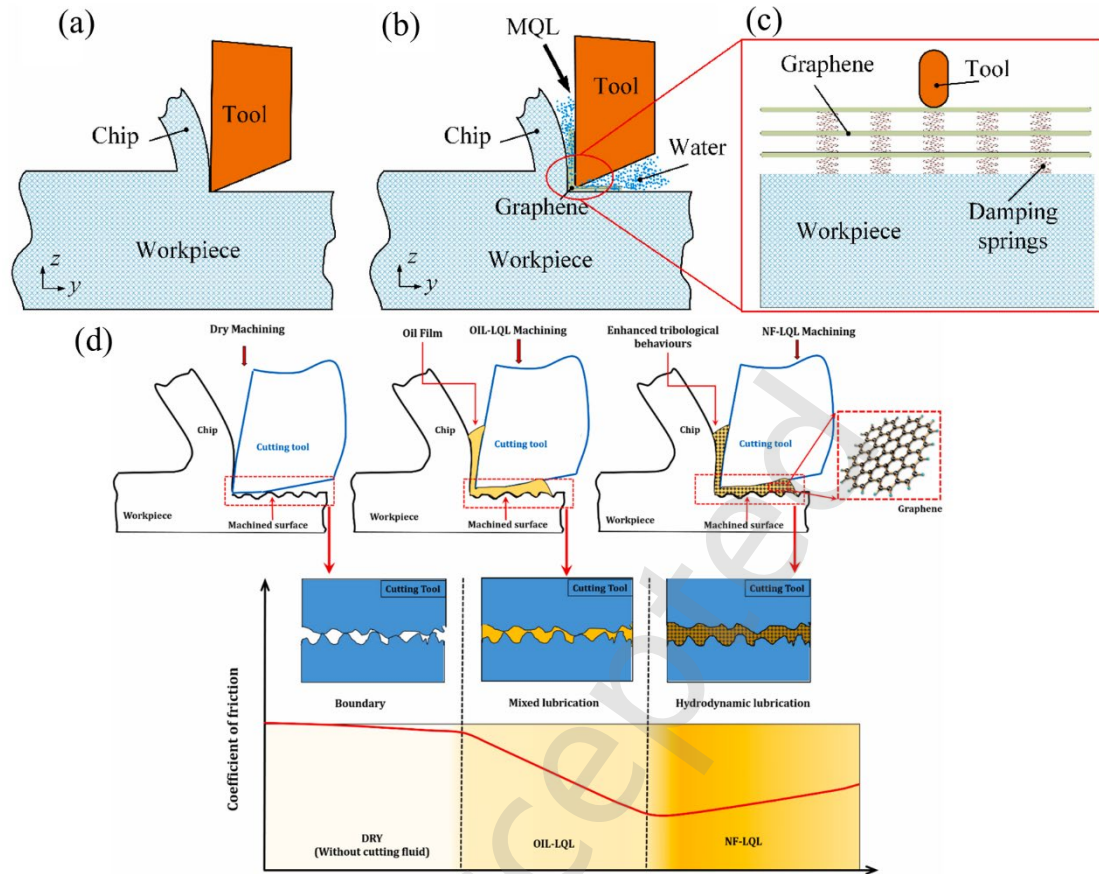


Fig. 7. Schematic representation of potential mechanisms at the contact interface of cutting tools under graphene nanofluid lubrication. Reproduced with permission from Ref. [106], © Elsevier 2023, Ref. [38], © Elsevier 2022

Unlike the friction reduction mechanism via interlayer sliding in graphene, GO is rich in oxygen-containing functional groups on its surface, which ensures excellent dispersibility in water-based cutting fluids. This enables stable adsorption onto friction pair surfaces through interactions such as hydrogen bonding, thereby achieving more efficient lubrication [107].

During friction, functional groups such as hydroxyl and carboxyl groups on the surface of graphene oxide enable it to adsorb at the friction interface and form a friction film. These groups also provide abundant reaction sites for functionalization. Numerous

researchers have investigated the lubrication mechanism of modified graphene oxide nanomaterials [108, 109], offering significant flexibility for diverse application scenarios. **Fig. 8** illustrates the lubrication mechanism of graphene oxide in friction reduction and wear resistance. During sliding, graphene oxide continuously penetrates the friction interface and fills wear pits, thereby reducing tool wear. Additionally, tribochemical reactions at the interface form chemical films composed of oxides and carbides, along with solid GO tribofilms, establishing a stable lubrication layer. This facilitates interlayer physical sliding and enhances lubrication performance.

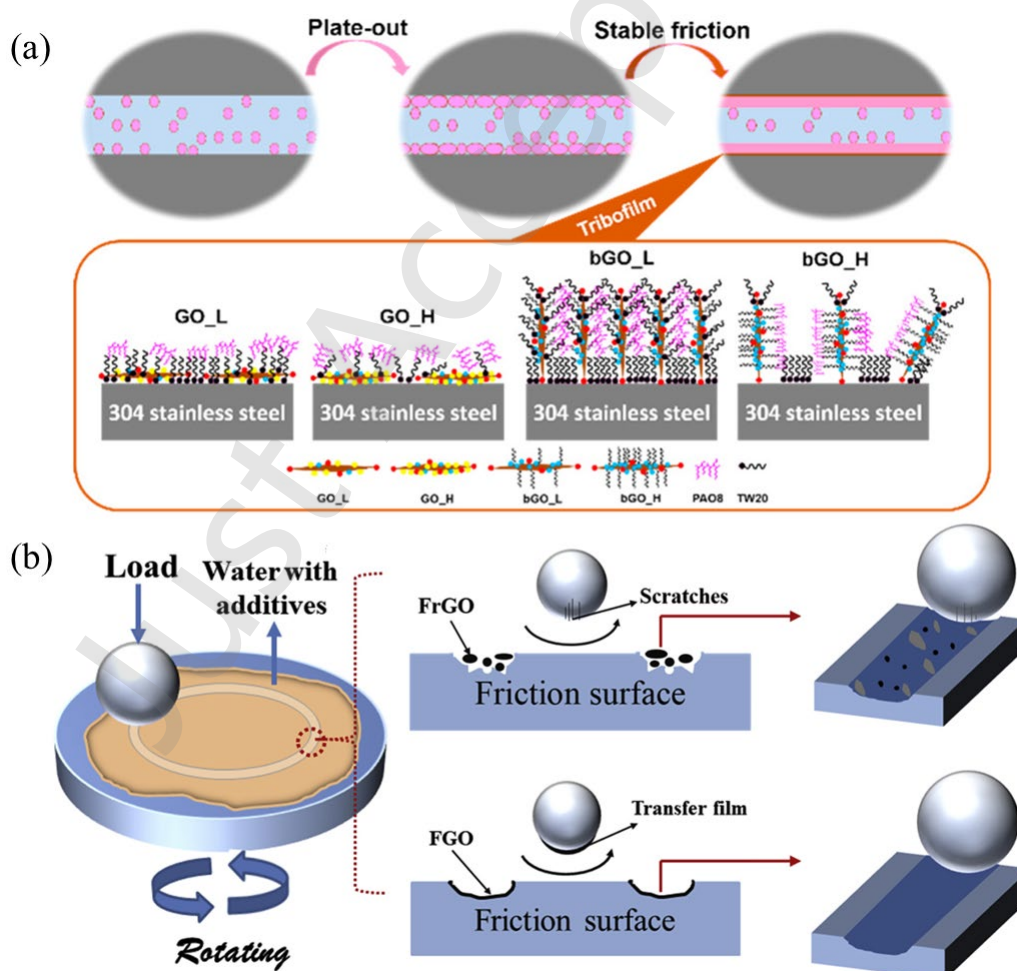


Fig. 8. Lubrication mechanisms:(a) alkylamine-modified graphene oxide. Reproduced with permission from Ref. [109], © ACS Publications. (b) fluorinated graphene oxide. Reproduced with

permission from Ref. [108], © Elsevier 2019.

The lubrication performance of single nano-additives is limited and susceptible to variations in machining conditions. Through rational design and preparation methods, graphene nanocomposites can be developed to play a significant role across diverse working conditions. Vats et al. [110] synthesized hBN/graphene hybrid nanofluids and studied their tribological performance in metal drilling. As shown in **Fig. 9A**, spherical hBN particles act as rolling elements, reducing direct surface contact and friction while forming a protective layer to mitigate wear. Their mild abrasiveness also aids chip removal, enhancing surface finish. Meanwhile, graphene reduces friction through interlayer sliding and improves load capacity due to its high strength and lubricity. Cui et al. [52] discovered that GNPs-Cu/ZrO₂ hybrid nanofluids achieve synergistic lubrication through soft/hard phase interactions. Graphene nanosheets form a friction film at the contact zone, reducing friction via interlayer slip. Cu nanoparticles loaded onto GNPs effectively prevent GNP layer restacking, while the Cu particles exhibit self-healing properties to fill pits on the workpiece surface. Micro-rolling and surface polishing mechanisms induced by the hard ZrO₂ nanoparticles significantly reduce the risk of adhesive wear and spalling (**Fig. 9B**). Furthermore, Al₂O₃/GNPs hybrid nanofluids effectively reduce friction and wear through synergistic lubrication mechanisms [51]. As shown in **Fig. 9C**, graphene nanoplatelets provide lubrication via interlayer sliding and the formation of a lubricating film, while Al₂O₃ nanoparticles contribute to load-bearing and rolling effects due to their small size and spherical structure, thereby reducing wear. The two-dimensional sheet-like graphene can

encapsulate spherical Al_2O_3 nanoparticles, forming an interlayer structure that enhances synergistic lubrication. The smooth and extensive surface of graphene allows Al_2O_3 nanoparticles to roll freely, while the spherical Al_2O_3 nanoparticles fill microscopic pits on the workpiece surface, promoting graphene sliding. The interlayer structure formed by graphene and Al_2O_3 nano-additives also significantly improves the load-bearing capacity of the nanofluid.

Analyzing factors such as the size effect, surface defects, and liquid-solid interface interactions can provide a deeper understanding of the lubrication mechanisms of graphene-based nanoadditives. Liu et al. [111] investigated the tribological behavior of GO nano-additives with different lateral sizes in water-based lubrication. Small-sized GO nanosheets (50–200 nm) more readily slide into the contact interface of the friction pair during the running-in period, rapidly forming a continuous and dense physical tribofilm. Meanwhile, under shear stress, the small-sized GO undergoes pronounced tribochemical changes, transforming into a graphite-like structure with low shear strength, thereby effectively isolating the direct contact of asperities. In contrast, large-sized GO (>500 nm) exhibits difficulty in entering the intimate contact region, resulting in a discontinuous tribofilm and lower chemical activity. Chen et al. [112] employed three types of micron-sized GO with different lateral sizes as water-based lubricating additives between ceramic surfaces. Larger-sized GO nanosheets exhibit fewer interlayer gaps and less overlap, thereby providing better coverage and interfacial smoothing effect in the contact region. In contrast, smaller-sized GO struggles to fully cover the contact area during the friction process, making it prone to local dry friction.

It can therefore be observed that the size effect of nanomaterials is closely related to differences in the contact interface: In a well-dispersed medium on a smooth surface, larger graphene-based additives can more fully cover the contact surface, preventing direct contact between sliding solid surfaces and enabling low-friction sliding through weak interlayer van der Waals forces; whereas on rough surfaces or under high-load conditions, smaller graphene-based additives can more rapidly form a lubricating film at the contact interface of the friction pair, rather than being squeezed out of the contact area.

The thickness (number of layers) of graphene nanomaterials significantly affects their load-bearing capacity and slip behavior. For single-layer or few-layer graphene, the interlayer van der Waals constraint is weakened, resulting in a decrease in interlayer sliding resistance as the thickness reduces, thereby facilitating interlayer slip. However, thin-layer graphene possesses low load-bearing capacity and is prone to local wrinkling deformation under high contact stress, at which point the surface sliding resistance increases significantly, and the coefficient of friction becomes higher than that of multilayer graphene. As thickness increases to multilayer graphene, the greater number of layers enhances load-bearing capacity and suppresses wrinkling. Under the synergistic action of tribochemistry and mechanical stress in the cutting zone, multilayer graphene readily undergoes interlayer cleavage, forming a transfer lubricating film with a low friction coefficient. Excessively thick graphene, however, tends to agglomerate and settle in the base fluid due to van der Waals attraction, rendering it ineffective as a lubricant. Chen et al. [113] investigated the layer number

effect and synergistic lubrication mechanism in an ionic liquid/GO composite water lubrication system. Multilayer GO, benefiting from its increased bending stiffness and interlayer van der Waals coupling, preferentially undergoes low-resistance interlayer slip during shearing, thereby converting interfacial friction into intra-layer relative motion. Molecular dynamics simulations indicate that with increasing layer number, the abundant oxygen-containing functional groups and expanded interlayer space of GO facilitate the construction of a three-dimensional hydrogen bonding network, forming a dense and dynamically stable hydration layer that effectively isolates the friction pair and dissipates thermal energy (Fig. 9C).

Qiu et al. [114] used molecular dynamics simulations to investigate how the defect density of graphene nanosheets affects their agglomeration kinetics and tribological behavior. An increase in defect density induces spontaneous wrinkling of the graphene, leading to greater out-of-plane deformation and a relative reduction in the lateral dimensions of the nanosheets. Although an increase in the defect degree reduces the liquid–solid interaction energy, the steric hindrance induced by wrinkling becomes dominant, thereby improving dispersion stability instead. Meanwhile, the 'carbon nanotube-like' structures induced during the friction process are unfavorable for low interlayer shear slip, leading to an increase in the coefficient of friction. Appropriate defects can help graphene nanosheets anchor at the friction interface, promote frictional chemical reactions to form lubricating films with low shear strength, and induce out-of-plane wrinkles that enhance steric effects, thereby improving dispersion stability and load-bearing capacity. However, excessive defects significantly increase frictional

chemical reactivity, leading to adhesion or chemical bonding between the nanosheets and the counterpart surface, which disrupts structural superlubricity and may even trigger abrasive wear.

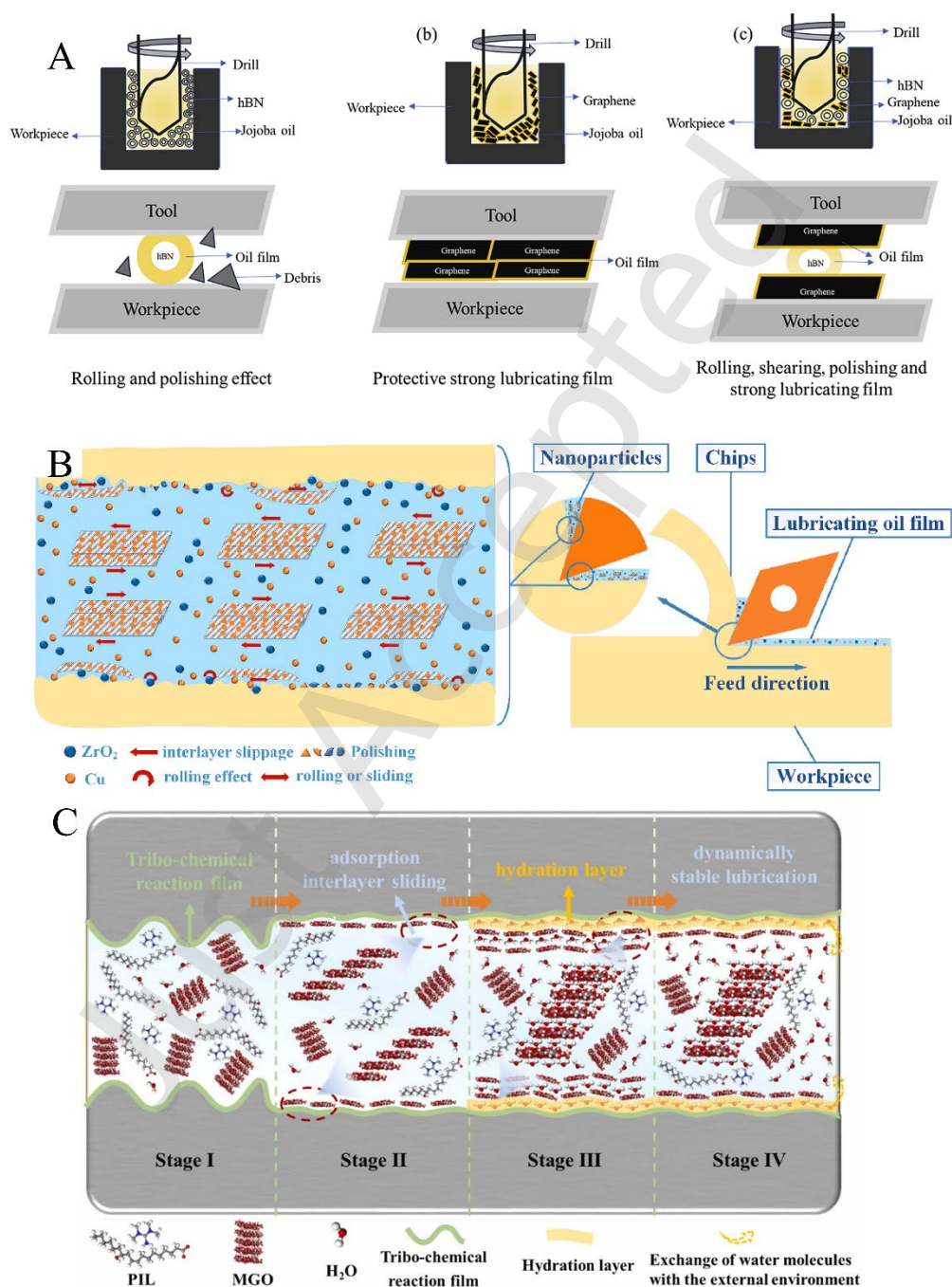


Fig. 9. (A) Friction mechanism of hBN/GNPs. Reproduced with permission from Ref. [110], ©

Elsevier 2025. (B) Synergistic lubrication via soft/hard phase interaction in GNP-Cu/ZrO₂ hybrid

nanofluid. Reproduced with permission from Ref. [52], © Elsevier 2025. (C) Lubrication mechanism of multilayer GO/ionic liquid. Reproduced with permission from Ref. [113], © Elsevier 2026.

In summary, graphene-based nano-additives for cutting fluids exhibit exceptional lubricating properties. Their layered structure forms an efficient lubricating film at friction interfaces, effectively replacing direct metal-to-metal contact through interlayer sliding, thereby significantly reducing tool friction and wear. Simultaneously, graphene's outstanding thermal conductivity suppresses cutting temperature increases and minimizes the formation of built-up edges. Numerous researchers have combined graphene with other materials to enhance lubrication. For instance, metal oxide nanoparticles (e.g., Al_2O_3 , TiO_2) contribute to synergistic lubrication through high load-bearing capacity and rolling effects, while soft metals (e.g., Cu, Ag) can fill surface pits on workpieces, repairing surface defects. Composites with other two-dimensional materials further reduce interfacial shear stress and friction coefficients. The size of graphene-based nano-additives determines the film-forming rate and surface area at the interface, while the degree of defectivity affects the liquid-solid interaction with the lubricant; the lubrication mechanisms of these additives are not entirely the same under different operating conditions. The synergistic effects of these multiple mechanisms significantly enhance the overall lubrication and cooling performance of cutting fluids, providing an important direction for the design of high-performance machining fluids.

4.2 Lubrication mechanism of CNTs nano-additives

CNTs, with their unique hollow tubular structure, exceptional tensile strength, and low friction characteristics, have emerged as important nano-additives for enhancing the lubrication performance of cutting fluids. Due to their nanoscale diameter, CNTs can penetrate micro-cracks, pits, and other surface defects, serving as fillers or acting as nano-roller bearings to generate low rolling friction. Moreover, during the friction process, dense tribofilms are gradually formed, composed of CNTs fragments, graphitized products, or compounds generated through reactions with the substrate [115-117]. Notably, under applied stress, the inner layers of MWCNTs slide relative to the outer layers along the axial direction with ultralow friction, exhibiting no atomic-scale wear or fatigue [118, 119].

CNTs demonstrate significant advantages in the field of composite tribology as high-performance nanoadditives or solid lubricant coatings. Wang et al. [120] investigated the tribological behavior of plasma-sprayed CNT-reinforced TiO₂ coatings. During friction, CNTs gradually rotate and align nearly perpendicular to the sliding direction, promoting rolling friction. They also tightly integrate with titanium oxide wear debris to form a dense lubricating film, significantly reducing the friction coefficient. Concurrently, CNTs undergo frictional degradation, leading to structural disordering and partial exfoliation of graphene-like layers, which collectively transform into graphene-like materials, enhancing solid lubrication (**Fig. 10A**). Yang et al. [121] summarized the formation and mechanism of ionic liquid-modified GO/CNTs solid

adsorbed films. During friction, fragmented nanomaterials, including GO nanosheets and CNTs, enhance the lubricity of the lubricant through interlayer sliding and rolling effects. The ionic liquid-modified GO/CNTs materials adsorb onto the metal surface, forming a continuous and stable adsorbed film (**Fig. 10B**). Besides that, Zhang et al. [69] prepared $\text{Fe}_3\text{O}_4@\text{CNTs}$ nanofluids and applied an external magnetic field during titanium alloy cutting. As shown in **Fig. 10C**, under magnetic field assistance, $\text{Fe}_3\text{O}_4@\text{CNTs}$ nanofluids are directionally transported to the workpiece/chip interface, where Fe_3O_4 forms elongated chain structures that effectively isolate the tool from the chips. CNTs readily adhere to the friction interface, forming a stable protective film. Their excellent thermal conductivity, combined with the chain-like structure, facilitates efficient heat dissipation in the contact area, thereby suppressing titanium alloy softening and adhesion while enhancing the surface quality of both the tool and workpiece.

The rolling mechanism of CNTs and the lubrication mechanism of protective tribofilms are interpretations derived from the overall motion behavior of CNTs and the level of tribochemical products. Taking a further step to focus on the microstructure of CNTs themselves, their friction-reducing and anti-wear mechanisms depend on the structural integrity of the CNTs. The number of wall layers in CNTs can influence their ability to slide between layers and their capacity for friction-induced structural deformation. Guiderdoni et al. [122] investigated the tribological behavior of CNTs with different numbers of wall layers. The inner and outer walls of double-walled carbon nanotubes form a non-commensurate interface in terms of atomic arrangement,

allowing the walls to slide against each other with virtually no resistance and protecting the CNTs structure through elastic or plastic deformation. As the number of wall layers in CNTs increases, the shear resistance of the outer tube walls decreases significantly, making them more prone to fracture and exfoliation during friction. The resulting carbonaceous debris participates in the formation of a solid lubricating film, thereby reducing friction and wear.

Defects in CNTs exhibit a dual nature in the friction mechanism. The introduction of defects disrupts the perfect interlayer geometry, leading to local fluctuations in the interlayer potential energy landscape and an increase in the sliding barrier, which in turn causes a sharp rise in friction and energy dissipation [116]. However, defects are not entirely detrimental; the introduction of oxygen-containing functional groups such as carboxyl and amino groups onto the sidewalls of carbon nanotubes through covalent functionalization, although at the expense of compromising the local sp^2 structural integrity, can significantly reduce the surface energy of the carbon nanotubes, improve their dispersion uniformity in the matrix, and play a critical interfacial regulatory role during frictional shearing. Moderate intrinsic defects and functionalization sites can act as stress concentration points during friction, causing the carbon nanotubes to gradually fracture along the defect sites and release graphene fragments and amorphous carbon, which then participate in the formation of a tribological lubricating film [123, 124].

CNTs consistently demonstrate excellent tribological performance in diverse lubrication systems. During frictional contact, CNTs undergo deformation, shear, and eventual degradation, gradually transforming into highly disordered nanocrystalline

graphite. This process leads to the formation of a carbon-based protective tribofilm on the sliding interface. The film effectively reduces the friction coefficient and suppresses wear by isolating the contacting surfaces. The lubrication mechanism of CNTs encompasses aspects such as the rolling bearing effect, tribofilm formation, filling and repairing, as well as efficient heat conduction, providing theoretical foundations and technical support for the design and optimization of high performance cutting fluids.

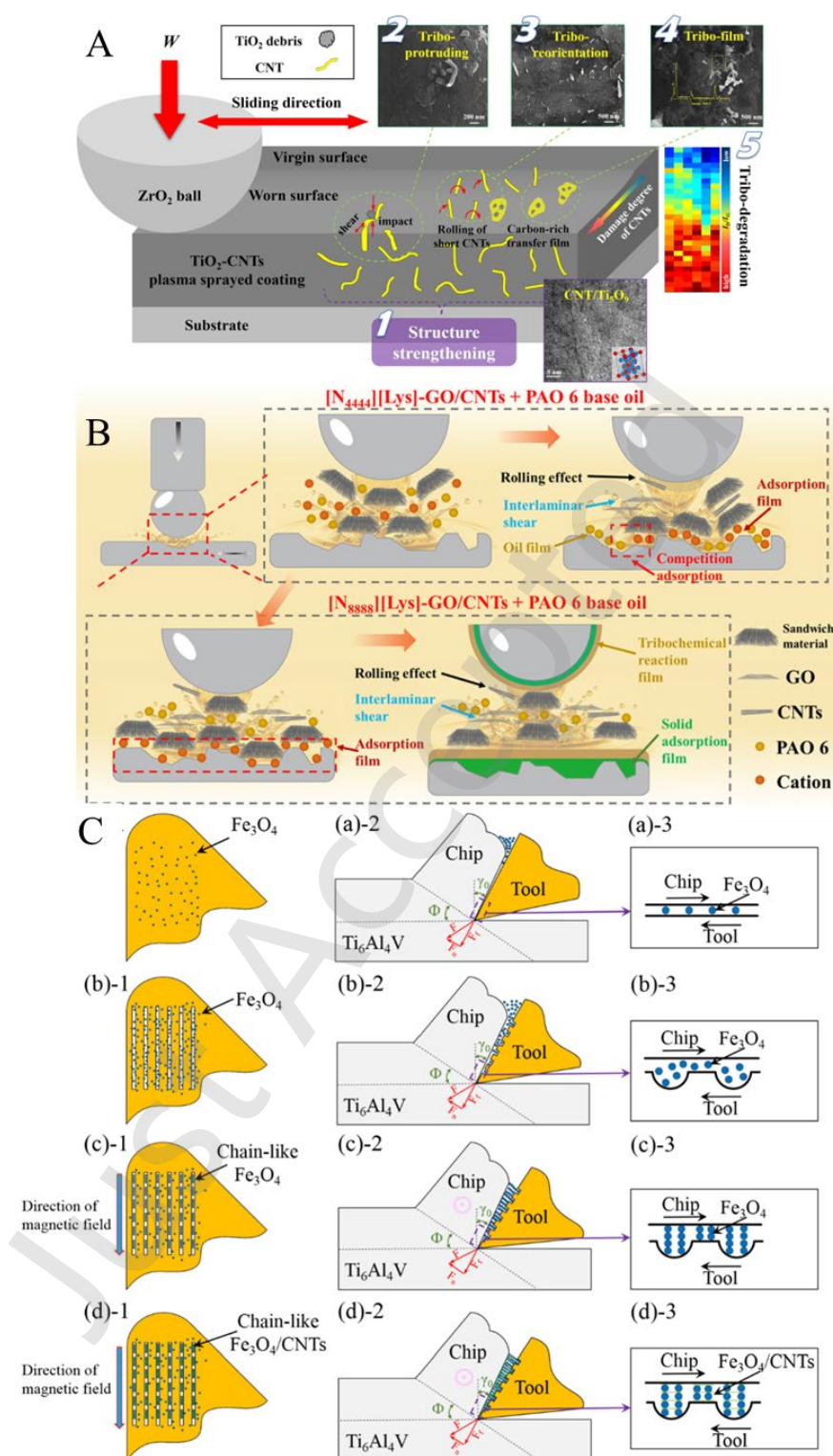


Fig. 10 (A) Wear mechanism induced by CNTs in plasma-sprayed ceramic coatings. Reproduced with permission from Ref. [120], © ECS 2018. (B) Lubrication mechanism of ionic liquid-graphene oxide/carbon nanotube composite material. Reproduced with permission from Ref. [121], © ACS

Publications 2025. (C) Wear mechanisms in titanium alloy cutting under different environments: (a) Fe_3O_4 nanofluid, (b) micro-texture + Fe_3O_4 nanofluid, (c) magnetic field + micro-texture + Fe_3O_4 nanofluid, (d) magnetic field + micro-texture + $\text{Fe}_3\text{O}_4@\text{CNTs}$ nanofluid. Reproduced with permission from Ref. [69], © Elsevier 2023.

4.3 Lubrication mechanism of CQDs nano-additives

As a novel zero-dimensional carbon-based material, CQDs possess the advantages of nanoscale dimensions and an abundance of oxygen-containing surface functional groups. Unlike graphene and CNTs, which rely on physical lubrication mechanisms, CQDs exhibit a friction reduction and wear-resistant mechanism primarily governed by permeation, adsorption, and tribochemical reactions.

Oxygen-containing functional groups not only provide active sites for surface modification but also significantly enhance the dispersion stability of CQDs in lubricating base oils through covalent grafting with other modifying agents. As shown in **Fig. 11**, the metal friction pair surface becomes positively charged during friction. Modified CQDs readily adsorb onto the friction surface via electrostatic/van der Waals forces, forming a stable adsorption film [125, 126]. At low loads, CQDs readily penetrate the friction surface to form a physical friction film, which is subsequently replaced by a friction chemical film during friction.

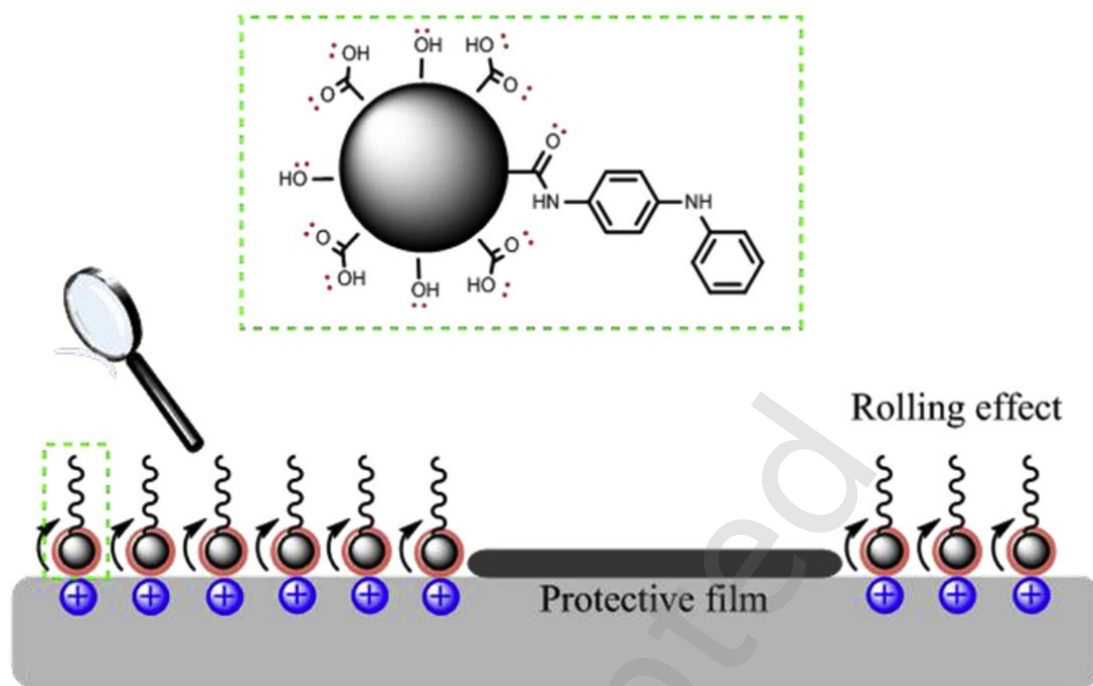


Fig. 11 Friction adsorption mechanism of CQDs-N. Reproduced with permission from Ref. [126],

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Yang et al. [127] synthesized size-uniform Ser-CA/CQDs via a one-step pyrolysis method using amino acid ionic liquids (Ser-TEA) and citric acid (CA), demonstrating excellent friction reduction and anti-wear properties along with long-lasting dispersion stability. As shown in **Fig. 12a**, the lubrication mechanism can be attributed to synergistic lubrication from multiple factors. During the early friction stage, nanoparticles continuously and rapidly enter the friction interface to repair pits and microcracks. They adsorb onto the metal surface via electrostatic and van der Waals forces to form an adsorbate film, serving both repair and physical isolation functions. Subsequently, under the combined effects of external mechanical stress and frictional thermal stress, Ser-CA/CQDs participate in friction chemical reactions, forming a chemical friction film that isolates the contact between friction pairs. Xue et al. [128]

prepared zwitterionic dopamine sulfonate functionalised carbon quantum dots (CQDs-ZDS), which easily adhered to the surface of the friction pair via electrostatic adsorption. Subsequent friction caused the CQDs-ZDS to participate in the formation of a stable, carbon-based composite protective film. This film effectively prevented direct contact between the friction pair, significantly reducing friction and wear. Furthermore, CQDs-ZDS can deposit or adsorb into cracks, scratches, or pits on friction surfaces, providing a repair function. Simultaneously, the nanoscale spherical particles act as ball bearings, converting sliding friction into rolling friction (**Fig. 12b**).

In addition to surface modification methods, researchers have also combined CQDs with other lubricating materials to investigate their synergistic lubrication mechanisms. Wang et al. [129] assembled nitrogen-doped CQDs onto layered MXene, forming a transfer film composed of nitrides and metal oxides under the influence of frictional heat and pressure. MXene reduces friction through interlayer sliding at the friction interface, while the small-sized CQDs act as rolling bearings. Their combination demonstrates synergistic lubrication performance, as shown in **Fig. 12c**.

The studies referenced above demonstrate that CQDs, as an emerging zero-dimensional carbon-based nanolubricant additive, exhibit a distinct primary lubrication mechanism compared to graphene and CNTs. They effectively reduce friction and wear through multifaceted actions, including physical adsorption, tribochemical film formation, and surface repair. Their nanoscale size and rich surface functional groups confer exceptional permeability, facile modifiability, and robust dispersion stability. By engineering composite materials, researchers have further

improved the machining performance of CQDs, underscoring their considerable potential in the design and development of environmentally friendly cutting fluids.

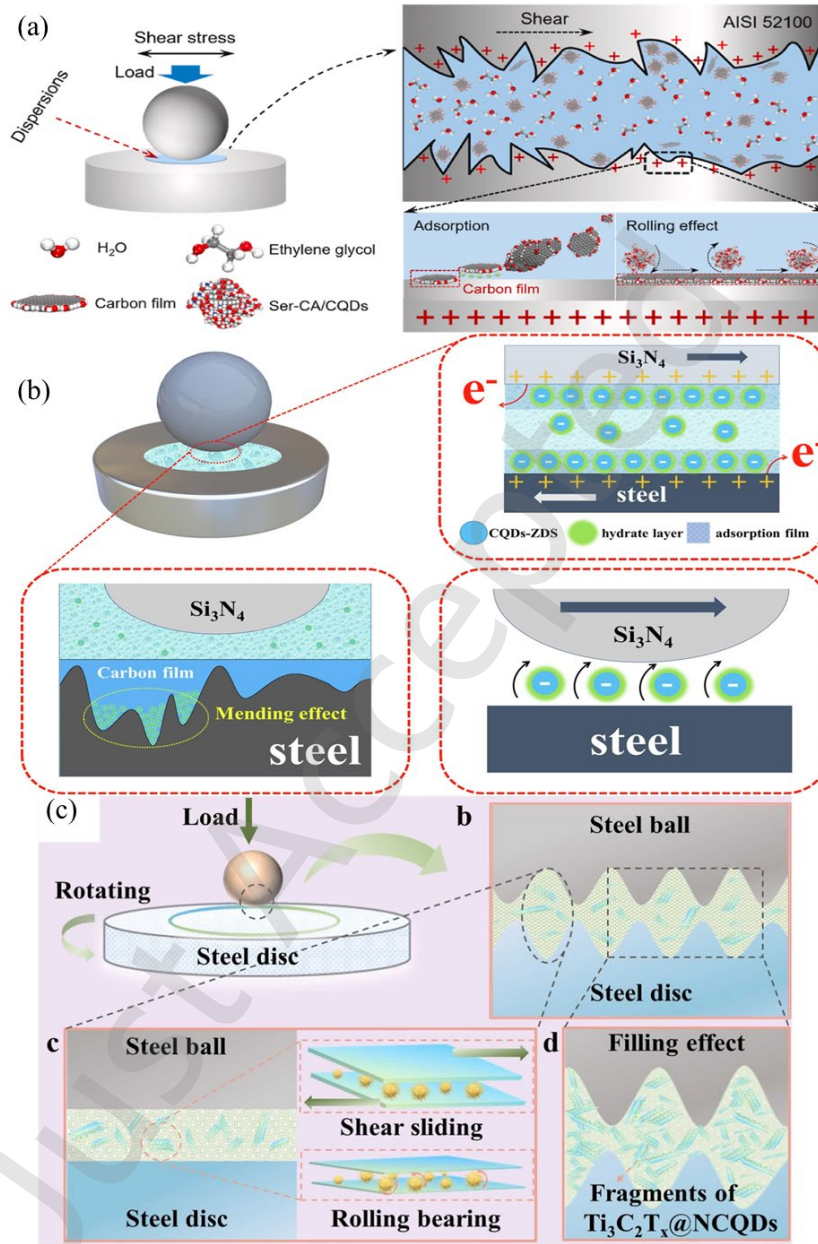


Fig. 12 (a) Lubrication mechanism of ionic liquid-modified Ser-CA/CQDs. Reproduced with permission from Ref. [127], © Elsevier 2025. (b) Lubrication mechanism of CQDs-ZDS as an additive in water-based lubricants. Reproduced with permission from Ref. [128], © Elsevier 2023. (c) Synergistic lubrication mechanism of NCQDs@MXene. Reproduced with permission from Ref. [129], © Elsevier 2023.

5 Occupational health and industrial safety: prevention and control

5.1 Potential health risks of carbon-based nanomaterials

By discussing the excellent performance of different carbon-based nanomaterials in cutting machining applications, it is not difficult to find that while these materials enhance friction-reducing and anti-wear properties, their inherent nanoscale characteristics also pose non-negligible health and safety risks. CNTs with a high aspect ratio share similarities with asbestos fibers in terms of morphology and surface activity, raising serious concerns about their fibrogenic and carcinogenic effects. Nel [130] systematically summarized the pathogenicity of CNTs. CNTs with a high aspect ratio are more likely to deposit in the deep lung regions of the human body and are difficult to be effectively phagocytosed by macrophages, thereby inducing persistent inflammatory responses. Animal experimental results indicate that long and straight MWCNTs exhibit carcinogenic potential similar to that of asbestos fibers, attributed to their prolonged retention in the body, which causes DNA damage and silences of tumor suppressor genes. Dust and gas generated during the production and processing of graphene-based nanomaterials can be inhaled by humans, leading to acute lung injury and pulmonary fibrosis. Furthermore, graphene-based nanomaterials can enter cells and induce elevated levels of reactive oxygen species, causing cellular damage [131].

In NMQL cutting processes, the cutting fluid containing carbon-based nanomaterials is sprayed onto the cutting zone as fine droplets. Under the action of high-speed rotating tools, flying chips, and transient high temperatures, the droplets

undergo further fragmentation, evaporation, or condensation. Due to their extremely small particle size, carbon-based nanoparticles can easily escape from the droplet confinement and mix with chip dust and oil mist, forming a stable suspended aerosol [132]. Operators can easily inhale these aerosols during work. Among them, particles with a diameter of less than 100 nm are capable of breaching the defense mechanisms of the human respiratory tract, penetrating deep into the alveoli, and even entering the bloodstream, thereby causing organ damage [133].

5.2 Industrial safety and security measures

In response to the health hazards posed by carbon-based nanomaterials in the metalworking field, the literature provides guidance and recommendations for the safer design of nanoparticles. In MQL systems, the base oil of the cutting fluid plays the primary lubricating role. Selecting lubricants with low viscosity, high boiling point, and high flash point to replace conventional mineral oils can provide better lubrication performance and less vapor. Compared with mineral oils, vegetable oils possess higher molecular weight and thermal stability, resulting in lower evaporation rates and a reduced tendency for atomization. In addition, vegetable oils are renewable, low-toxicity, and biodegradable[134]. Oils such as soybean oil, castor oil, palm oil, and rapeseed oil have been widely used in research on MQL cutting machining. These vegetable oils contain abundant fatty acids and triglycerides, which facilitate the formation of a dense lubricating film on metal surfaces, effectively reducing cutting forces and surface roughness. Selecting vegetable oil as the base fluid instead of mineral

oil can reduce aerosol generation while ensuring the quality of the machined surface [135].

Electrostatic minimum quantity lubrication (EMQL) adds a high-voltage electrostatic power supply to conventional minimum quantity lubrication. Through an electrode embedded inside the oil pipe, the lubricant is directly charged. When compressed air atomizes it, the resulting droplets carry electrostatic charges, and the charged droplets can more efficiently adsorb onto the tool–workpiece interface, thereby significantly reducing the amount of lubricant used while enhancing the lubrication effect. Lv et al. [136] used a 0.5 wt% SiO₂ water-based nanolubricant in EMQL milling, and the concentrations of respirable particulate matter PM10 and PM2.5 oil mist decreased to 0.9 mg/m³ and 0.52 mg/m³, respectively, which were 47.1% and 35.2% lower than those under MQL conditions. Xu et al. [137] investigated the EMQL milling process using a water-based Al₂O₃ nanofluid as the lubricating medium. Under a charging voltage of -6 kV, the generated PM10 and PM2.5 levels were reduced by 20.3% and 42.9%, respectively, compared to those under conventional MQL conditions with the Al₂O₃ nanofluid. The use of EMQL technology can effectively overcome the problems of high oil mist concentration and the tendency of nanoparticles to become aerosolized in conventional NMQL.

Efficient capture of aerosols in the processing zone and ventilation control are key engineering measures for reducing the occupational exposure risk of carbon-based nanoparticles. Traditional reliance on natural ventilation or conventional updraft exhaust hoods often fails to effectively isolate aerosols, making it necessary to

introduce efficient purification methods. Local ventilation combined with purification devices can effectively reduce the dispersion of aerosols. The ventilation system promptly captures aerosols generated during cutting processes, and the particulate matter therein is then separated and removed through physical or chemical actions of the purification device. Wei et al. [138] proposed an improved displacement ventilation device that supplies air from the lower part of support columns in a large machining plant, utilizing the thermal plumes generated by equipment and personnel to form a unidirectional airflow that carries oil mist away from the work zone. Compared with conventional mixed ventilation, this system reduces the oil mist concentration in the worker's breathing zone by more than 70%. Xu et al. [139] designed a polyvinylidene fluoride (PVDF)-polysulfone (PSF) blend fiber membrane that enhances aerosol deposition through the synergistic effect of electrostatic capture and nanofiber mechanical capture mechanisms. The results showed that the membrane achieved a filtration efficiency of 99.10% for 0.3 μm oil mist and 99.81% for NaCl solid particles of the same size. Well-designed machining ventilation conditions and novel filtration and purification devices can provide new approaches for the efficient capture of aerosols in cutting fluid processing zones and for addressing occupational exposure risks.

6 Conclusions and outlook

This work systematically reviews research progress on carbon-based nanomaterials as cutting fluid additives, analyzing the cooling and lubrication

properties of representative carbon-based materials from aspects including structural characteristics, influencing factors, and lubrication mechanisms. Graphene, CNTs, fullerene C60, and CQDs exhibit unique cooling and lubrication advantages during machining due to their distinctive structures. As research on cutting fluid additives advances, traditional carbon-based nanomaterials still face limitations such as dispersion stability and sustained lubrication performance under extreme conditions. Cutting fluid additives are evolving toward long-term stable dispersion and intelligent functionality. Investigations into the friction reduction and anti-wear mechanisms of nano-cutting fluids can be further enhanced by combining macroscopic characterization with microscopic molecular simulations. The main conclusions and outlook are as follows:

6.1 Conclusions

(1) Different carbon-based materials demonstrate irreplaceable advantages during machining processes, including reduced tool wear, cutting forces, temperatures, and surface roughness. Nano-graphene exhibits excellent friction and wear reduction due to its unique two-dimensional layered structure, which replaces direct contact between friction pairs through interlayer sliding during friction. Due to their high aspect ratio, CNTs demonstrate superior axial thermal conductivity and are commonly used in high-temperature machining conditions. CQDs and fullerene C60, as zero-dimensional materials with extremely small sizes, offer enhanced dispersion stability in cutting fluids. Moreover, CQDs possess abundant active surface sites that facilitate chemical

modification.

(2) Stable dispersibility effectively inhibits nanoparticle aggregation into larger particles, thereby preventing increased friction caused by particle size growth. Furthermore, this characteristic facilitates the formation of a continuous and stable lubricating film at the friction interface by nanomaterials, significantly reducing the friction coefficient and wear rate. The ultrasonic-mechanical synergistic dispersion process primarily achieves de-agglomeration of nanomaterial clusters and particle size refinement through physical action: ultrasonic dispersion utilizes cavitation effects generated by high-frequency vibrations to disrupt agglomerated structures among nanoparticles; mechanical stirring further promotes uniform distribution of nanoparticles within the medium, thereby enhancing dispersion effectiveness. Surface chemical modification methods enhance the compatibility between nanoparticles and base fluids, inhibiting particle agglomeration through electrostatic isolation and steric hindrance effects. The synergistic action of these two dispersion processes endows the cutting fluid with long-term stability.

(3) Carbon-based materials exhibit cutting lubrication mechanisms that include the formation of friction films, rolling bearing effects, pit-filling and repair, surface polishing, and synergistic lubrication. Graphene nanosheets can undergo interlayer slip at the friction interface, transforming solid contact friction into relative sliding between layers, thereby significantly reducing friction. Additionally, through complex tribochemical reactions, they generate chemical tribofilms that mitigate tool wear. CNTs leverage their unique hollow tubular structure to act as nano-rollers, generating

low rolling friction. During friction, nano-fragments can repair microcracks, pits, and other defects on the friction surface, forming a dense tribofilm. CQDs possess abundant surface oxygen-containing functional groups, which facilitate their adsorption onto the friction interface. During the friction process, they contribute to the formation of both physical carbon films and chemical tribofilms, thereby effectively reducing friction.

(4) The dispersion stability of carbon-based nanomaterials varies across different types of cutting fluids, affecting their film-forming capability at the machining interface. Besides, highly ductile metals are prone to deformation during machining, while machining high-hardness metals often leads to tool chipping. The same carbon-based nanomaterial may exhibit completely opposite performance characteristics when processing different metals.

6.2 Outlook

(1) Carbon-based nanomaterials currently studied can maintain stable dispersion in cutting fluids for several days or even months. However, nanoparticles subjected to physical treatment tend to agglomerate over extended periods, and chemical modification may mask the natural properties of the nanoparticles. Therefore, further research is needed to improve dispersion methods, aiming to achieve ultra-long-term dispersion on a yearly scale through material modification and optimization of cutting fluid formulations. This will prevent the agglomeration of additive particles within the cutting fluid, which can lead to lubrication failure and workpiece surface damage, thereby meeting the requirements for industrial-grade cutting fluids.

(2) The development of intelligent cutting fluids is beneficial for functioning effectively in high-temperature and high-friction zones, enabling precision lubrication that significantly enhances cutting efficiency and machining surface integrity. For materials prone to generating cutting heat and causing tool wear, such as titanium alloys and high-temperature alloys, temperature-responsive materials undergo phase transitions under localized high temperatures. This forms a stronger, more resilient friction film at the friction interface, reducing friction and enhancing thermal conductivity. During the machining of different metallic materials, the application of weak electric fields, magnetic fields, or temperature adjustments enables real-time tuning of the lubrication performance of intelligent cutting fluids. This facilitates the convenient processing of complex components, eliminating the need for frequent cutting fluid replacement or parameter adjustments. The incorporation of responsive sensitive materials further enhances the intelligence of modified nanomaterials, improves their compatibility with cutting fluids, and allows them to perform more effectively under complex operating conditions.

(3) Future research on the friction reduction and anti-wear mechanisms of nanomaterials as cutting fluid additives can leverage finite element analysis and molecular dynamics simulations. By combining nanoindentation and tribological wear simulations, the deformation and wear behaviors of different materials during friction can be explored. Establishing a thermo-mechanical coupled molecular dynamics model will enable the calculation of frictional forces and coefficients of cutting fluids under extreme conditions such as high speed, high temperature, and high pressure.

Quantitative analysis of lubrication behavior at the microscale will thereby provide a suitable framework for designing high-performance carbon-based nano-cutting fluids.

(4) Although carbon-based nanofluids exhibit excellent performance in lubrication and heat transfer applications, their high-temperature stability under severe operating conditions remains one of the critical challenges limiting their industrial adoption. At elevated temperatures, surfactant-stabilized systems tend to undergo desorption or thermal degradation, triggering nanofluid destabilization. The consequent agglomeration and sedimentation of nanoparticles lead to the loss of lubricating performance. Currently, research on the thermal degradation behavior of nanoparticles and surfactants in carbon-based nanofluids under extreme high-temperature, high-pressure, and high-shear conditions is still lacking. Future efforts should prioritize the development of thermally stable dispersants and the establishment of tribo-thermal coupling test methods that replicate real-world machining environments. Overcoming these challenges is essential for unlocking the potential of carbon-based nanofluids as next-generation cutting fluid additives.

(5) Carbon-based nanomaterials demonstrate significant potential in enhancing cutting fluid performance and reducing environmental impact. However, in actual machining processes, nanofluids pose potential health hazards. Nanofluid aerosolization may cause respiratory infections in humans. Certain carbon-based nanomaterials with high aspect ratios—such as multi-walled carbon nanotubes—have been shown to exhibit asbestos-like toxicity potential due to their fibrous morphology and biopersistence. While promoting the application of such green cutting fluids, it is

imperative to simultaneously enhance monitoring of nanoparticles in the machining environment and continuously track their impact on operator health. This ensures technological advancement is genuinely grounded in a safe and controllable foundation.

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