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Nanobiolubricant grinding: a comprehensive review

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Abstract Minimum quantity lubrication (MQL), which considers the cost, sustainability, flexibility, and quality, has been actively explored by scholars. Nanoadditive phases have been widely investigated as atomizing media for MQL, aimed at enhancing the heat transfer and friction reduction performance of vegetable-oil-based biolubricants. However, the industrial application of nano-enhanced biolubricants (NEBL) in grinding wheels and workpiece interfaces as a cooling and lubricating medium still faces serious challenges, which are attributed to the knowledge gap in the current mapping between the properties and grindability of NEBL. This paper presents a comprehensive literature review of research developments in NEBL grinding, highlighting the key challenges, and clarifies the application of blind spots. Firstly, the physicochemical properties of the NEBL are elaborated from the perspective of the base fluid and nanoadditive phase. Secondly, the excellent grinding performance of the NEBL is clarified by its distinctive film formation, heat transfer, and multiple-field mobilization capacity. Nanoparticles with high thermal conductivity and excellent extreme-pressure film-forming properties significantly improved the high-temperature and extreme-friction conditions in the grinding zone. Furthermore, the sustainability of applying small amounts of NEBL to grinding is systematically evaluated, providing valuable insights for the industry. Finally, perspectives are proposed to address the engineering and scientific bottlenecks of NEBL. This review aims to contribute to the understanding of the effective mechanisms of NEBL and the development of green grinding technologies.

Keywords Grinding · Minimum quantity lubrication (MQL) · Nanobiolubricant · Physicochemical properties

Abbreviations

MQL	Minimum quantify lubrication
EMQL	Electrostatic minimum quantity lubrication
C=C	Carbon-carbon double bond
–COOH	Carboxyl group
LN_2	Liquid nitrogen
SiO_2	Silicon oxide
MoS_2	Molybdenum disulfide
SiC	Silicon carbide
$scCO_2$	Supercritical carbon dioxide
CTAB	Cetyltrimethylammonium bromide
TEM	Transmission electron microscopy
SDBS	Sodium dodecyl benzene sulphonate
TX100	Triton X100
APE-10	Alkylphenol polyoxyethylene ether 10
HBN	Hexagonal boron nitride
ND	Nanodiamond

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CNTs	Carbon nanotubes
RSm	Average width of the profile (μm)
NMQL	Nanobiolubricant minimum quantity lubrication
CMQL	Cryogenic minimum quantity lubrication
NEBL	Nano-enhanced biolubricant
–OH	Hydroxyl group
LCO_2	Liquid carbon dioxide
ZrO_2	Zirconium oxide
CuO	Cupric oxide
HV	Micro-hardness
GR	Graphene
Al_2O_3	Aluminium oxide
SEM	Scanning electron microscopy
SDS	Sodium dodecyl sulfate
GA	Gum arabic
CMC	Critical micelle concentration
PCD	Polycrystalline diamond
UV	Ultrasonic vibration-assisted

1 Introduction

Limited natural resources and severe environmental problems have driven the need for sustainable development in various industries. Specifically, in the field of machinery manufacturing, manufacturers must adapt to existing policies and laws, and increase their efforts in the research and development of advanced energy-saving and environmentally-friendly technologies to reduce environmental pollution during machining [1–4] and improve worker safety [5].

Cutting fluid is crucial for ensuring surface quality and machining accuracy during machining. However, traditional flood machining, which is based on metalworking fluids (MWFs), remains the main cooling and lubrication method in the manufacturing industry to ensure machining accuracy and reduce tool wear [6–8]. MWFs, which consist of non-renewable mineral oil and minimal water, are often supplemented with a range of additives and biocides to enhance their cooling and lubricating properties and inhibit bacterial growth. These additives can seriously harm the environment and human health [9]. In addition, this method consumes a large amount of the cutting fluid. According to reports, the purchase cost of cutting fluid and waste water treatment cost in flood lubrication account for 7%–18% of the total machining cost [10]. Based on the above environmental, cost, and personnel health considerations, traditional cooling and lubrication methods cannot satisfy the current trend of green development, and it is imperative to achieve a sustainable transformation of the traditional manufacturing industry.

Dry cutting refers to the selective abandonment of cutting fluids with full consideration of workpiece surface machining accuracy and tool life. This can completely eliminate the use of cutting fluids, thus avoiding the associated costs and environmental pressures [11, 12]. However, the absence of cutting fluids leads to severe friction and heat build-up in the machining zone. Especially for grinding processes, scholars have found that the temperature in the grinding zone of dry grinding processes is above 500 °C and may reach up to 1 000 °C [13]. Dry cutting places higher demands on tools, workpiece materials, and process parameters, which significantly limits the range of applications for dry cutting [14].

Minimum quantity lubrication (MQL) is an ideal alternative to dry cutting. Compared to dry grinding, MQL grinding offers better outcomes in terms of grinding temperature, surface roughness, and wheel wear [15–18]. MQL minimizes the use of grinding fluid while ensuring lubrication performance, which is only one thousandth of that of the flood lubrication type, significantly reducing production costs [19, 20]. Compared with flood lubrication, MQL is non-hazardous, sustainable, eco-friendly, and inexpensive, and may lead to improved tribological process performance. Many researchers have used biodegradable biolubricants as base fluids for MQL to improve the sustainability of the process. However, the cooling performance of MQL is insufficient and high temperatures can easily lead to oil film rupture [21, 22]. Thus, MQL technology requires further improvement. After decades of development, MQL has been used to derive many processes to improve efficiency, such as cryogenic medium and nanofluids. The technological development path of MQL is illustrated in Fig. 1.

Cryogenic minimum quantity lubrication (CMQL) compensates for the lack of cooling in MQL by spraying a cryogenic medium into the grinding zone to reduce grinding temperatures [23–25]. Key cryogenic agents include liquid nitrogen (LN_2), liquid carbon dioxide (LCO_2), and supercritical carbon dioxide ($scCO_2$) [26]. Existing literature shows that low-temperature cooling can effectively reduce heat during processing. However, these cryogenic agents increase transportation and storage costs, making the processing cost of CMQL comparable to that of flood lubrication, which does not provide significant economic advantages [27–29]. If the concentration of nitrogen or carbon dioxide in the air is too high, it can cause suffocation of the operators. This places higher demands on the protective measures used in technology. These issues limit the further applications of CMQL.

Nanofluids emerged during the rise of nanotechnology in the 1990s. Nanofluids are widely used in electronic microchannels, engines, spacecraft, nuclear energy, and solar energy fields. Previous studies have shown that the addition of micrometer particles significantly improves the heat transfer performance of mixed fluids [30–32]. However, problems such as particle deposition and microchannel

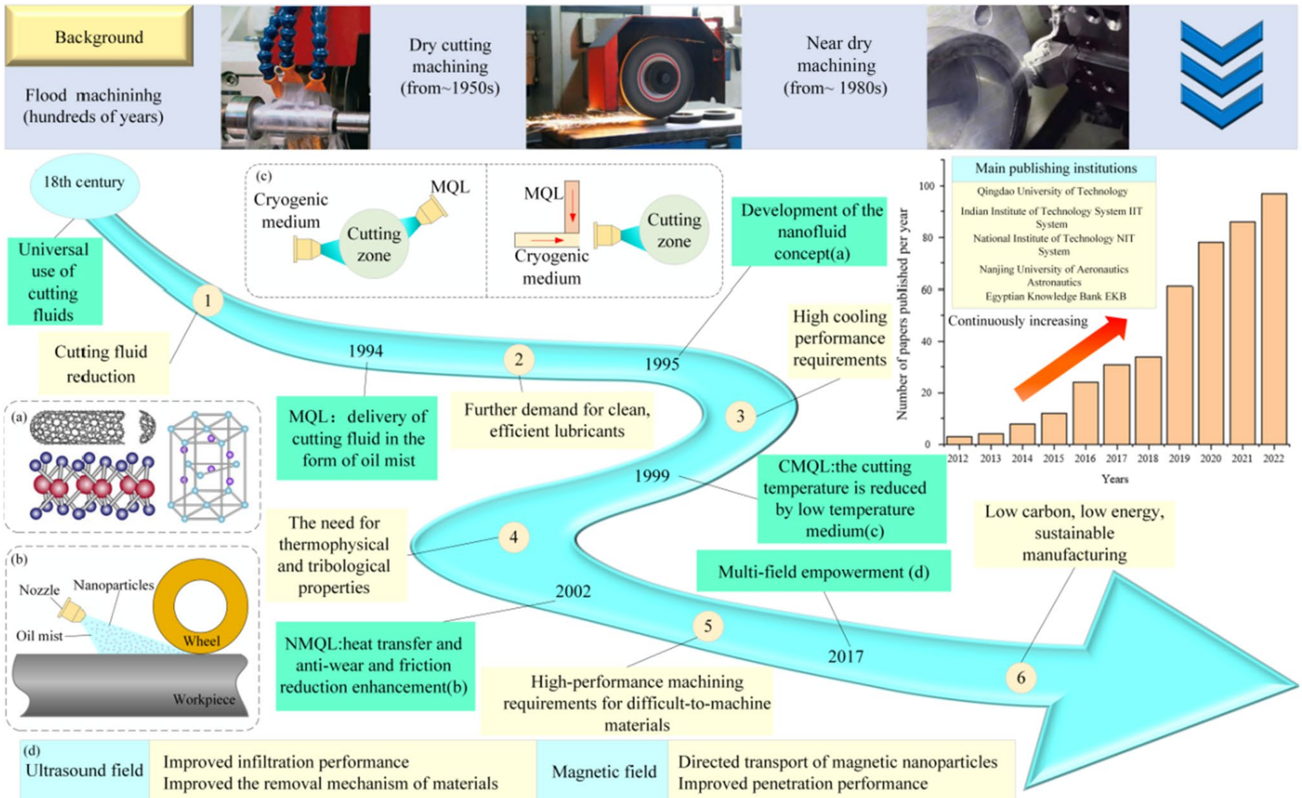

Fig. 1 Milestones in the development of MQL

clogging have prevented the industrial adoption of this technology. The use of nano-sized rather than micron-sized particles can help overcome these limitations [33]. Based on this, scholars have attempted to use nanofluids in MQL to improve the cooling performance. During grinding, the sliding friction, plowing, and chip formation phases consume large amounts of energy, most of which is converted into heat. MQL lubrication can reduce some of the energy consumed during the friction process, thereby reducing the heat generated. Defects in the insufficient cooling capacity limit the application of MQL in grinding. Researchers have found that nanoparticles have higher heat transfer coefficients, which give nanofluids a greater heat transfer ability than pure base fluids. Therefore, the application of nanofluids in MQL is an effective strategy for improving the cooling performance of MQL [34, 35]. Hegab and Kishawy [36] compared the cutting performance of nickel-based Alloy 718 under different working conditions. Owing to the excellent heat transfer performance of the nanoparticles, the cooling performance of the cutting process is improved, and compared to MQL, the cutting temperature and tool wear are significantly reduced. Therefore, the application of nanofluids in MQL is an effective strategy for improving the cooling performance of MQL. In addition, researchers have found that solid nanoparticles are accompanied by synergistic anti wear and friction-reducing behaviors, such as the rolling, film-forming, filling, and polishing effects. Said et al. [37] analyzed the friction and heat transfer mechanisms of nanofluids and found that nanoparticles could act as solid lubricants in the grinding area, forming physical/chemical lubrication films, improving the friction characteristics at the grinding wheel-workpiece interface, and significantly improving the surface integrity of the workpiece. Currently, in order to further comply with the development concept of sustainable manufacturing, nanobiolubricants which use non-toxic, renewable and degradable biolubricants as base fluids are becoming the preferred choice for improving machining performance in the use and study of MQL by both companies and researchers [38–40].

Nanobiolubricant minimum quantity lubrication (NMQL) inherits the advantages of microlubrication while compensating for its insufficient cooling performance. Therefore, NMQL has great potential in terms of sustainability and can serve as an efficient and new low-carbon processing method to solve the bottleneck of heat exchange technology in MQL. However, systematic reviews on the mechanism of action of nanobiolubricants with different physical and chemical properties during processing are lacking. To fill this literature gap and provide a scientific foundation, this study aims to present a comprehensive review and periodic critical assessment of the existing understanding.

The narrative logic of this study can be summarized as follows. Section 2 reviews the characteristics of nanobiolubricants, including their physical composition, preparation, and thermophysical properties. Section 3 elucidates the mechanism of the different physicochemical properties of nanobiolubricants during the grinding process, and reveals their tribological and enhanced heat transfer mechanisms during the grinding process. Section 4 evaluates sustainable processing of nanobiolubricants. Section 5 provides phased conclusions and future prospects based on the current research progress. The logical relationships in this study are shown in Fig. 2.

2 Characteristics of nanobiolubricants

The preparation of nanofluids is the basis of their research and application. High-performance nanofluids are influenced by factors such as the nanoparticle type, base liquid type, preparation method, and dispersion stability.

2.1 Physical component

2.1.1 Base fluid

Many types of basic fluids are used as nanofluids, including esters, water, oil, and oil-in-water mixtures.

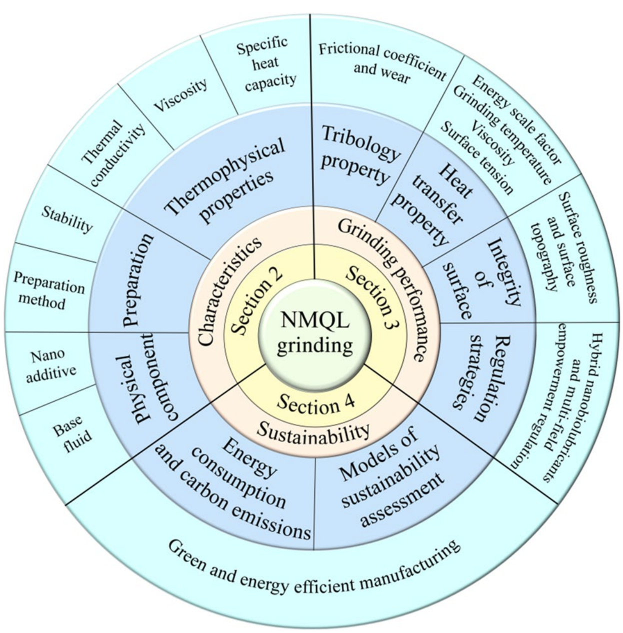

Fig. 2 Paper structure

Water and oil are excellent solvents for dispersing nanoparticles in nanofluids. Compared with oil, the use of easily available and inexpensive water as a base fluid reduces costs. Dispersing nanoparticles in oil resulted in better lubrication properties than dispersing them in water [41]. Mao et al. [42] analyzed the grinding performance of water and oil-based nanofluids. The cooling effect of water-based nanofluids was better than that of oil-based nanofluids. However, their lubricating ability was inadequate, and the use of water-based nanofluids alone could not satisfy the lubrication requirements of strong friction interfaces. Najiha et al. [43] found that water-based nanofluids could also achieve the lubrication like oils by using nanoparticles. In fact, the lubrication performance of the base oils will be further enhanced by the addition of nanoparticles. Moreover, metal workpieces are prone to rusting after machining because of the moisture retained on their surfaces and contact with oxygen [25]. Oil-in-water combines the excellent cooling and lubricating performances of water and oil, respectively. However, the low solubility of water and oil makes it difficult to mix them for a long time, limiting the application of oil-in-water.

Oil-based nanofluids include vegetable, mineral, ester, and synthetic oil-based ones. Regarding the use of mineral oils or vegetable oils, Zhang et al. [44] showed in their previous review that the toxic and hazardous pollutants contained in mineral oils could have adverse effects on health and environment, and seriously affect global sustainability. Therefore, further use of mineral oil is not recommended. Vegetable oils are biodegradable with a high flash point, reducing the formation of smoke and risk of fire, and are environmentally friendly, which is an important direction for sustainable development and has good prospects for application [45]. Vegetable oils possess the properties required for lubricants, including a high viscosity index, low volatility, good lubricity, and excellent solvents for nanoparticles. Moreover, vegetable oils can achieve a lower coefficient of friction than mineral oils [46]. Therefore, vegetable oils that are degradable and easily obtained have widespread application prospects.

With excellent properties, such as easy biodegradation, high flash point, and low pour point, esters and synthetic oils are effective substitutes for traditional mineral oils [47]. Esters include natural and synthetic esters. Generally, natural esters are extracted directly from vegetable oils, and synthetic esters are further modified from natural esters [48]. Gryglewicz et al. [49] used rapeseed and olive oil to prepare neopentyl glycol and trimethylolpropane esters, respectively. They found that trimethylolpropane esters had better thermal stability than pure vegetable oils. Dodos et al. [50] used lunaria oil to synthesize a lunaria trimethylolpropane ester that exhibited excellent lubricating performance. Compared with conventional perfluoropolyether oil, the friction coefficient and wear scar diameter were reduced by 52.4%

and 21.8%, respectively. Wang and Tao [51] synthesized a diisooctyl dimeric acid using the principle of epoxidative isomer esterification of vegetable oils and conducted four-ball wear experiments. Diisooctyl dimerization enhanced wear resistance and load-bearing capacity. Compared to pure soybean oil, the wear spot surface was smoother, and the abrasion marks were shallow and smaller in size. In addition, epoxide isomerization saturates the unsaturated bonds in soybean oil, which significantly improves its oxidative stability of soybean oil. However, complex production processes make esters and synthetic oils more expensive to produce than other base fluids, such as water and vegetable oils.

There is a growing trend of replacing mineral oil-based lubricants with vegetable oils. Vegetable oils mainly consist of triglycerides and small amounts of free fatty acids. A single triglyceride molecule contains three fatty acids and its molecular structure varies from one fatty acid to another. The molecular structure of fatty acids consists mainly of carbon chains and polar groups (hydroxyl, carboxyl, etc.) [19]. As shown in Fig. 3, the main parameters affecting the lubricating properties of vegetable oils include the carbon-carbon double bond (C=C), length of the carbon chain, number of branched chains, and the effect of polar groups. Polar groups are highly adsorptive and favor film formation of biolubricants based on the metal saponification reaction. In addition, oils with longer molecular chains (i.e., more carbon atoms) exhibit better lubricating properties because the adsorption capacity tends to increase with the number of carbon atoms. However, the presence of C=C bends the fatty acid molecules, which is detrimental to the film-forming stability of the biolubricant. Wang et al. [52] experimentally evaluated the frictional characteristics of the grinding wheel and workpiece interface for grinding nickel-based alloy GH4169 using seven typical vegetable oils (soybean, peanut, maize, rapeseed, palm, castor, and sunflower oils). The results showed that lower friction coefficients and wheel wear were achieved with vegetable oil than with flooding. Among them, castor oil exhibited the best lubrication performance and workpiece surface quality. The coefficient of friction and specific grinding energy of castor oil decreased by 50.1% and 49.4%, respectively, compared with those of the cast type. The highest *G* ratio was observed in corn oil (29.15). This section presents several research directions to improve the lubrication performance of vegetable oils.

2.1.1.1 Fatty acids Fatty acids are important factors in the performance of vegetable oils and have been demonstrated in friction and wear tests [53]. The polar groups of fatty acids are chemically active. Depending on the attraction between the atoms or molecules, they can be firmly adsorbed onto the surface of a workpiece or tool to form a layered and oriented molecular grid. Consequently, the friction interface is separated by the adsorbed film, and sliding manifests as external friction between the adsorbed films. This reduces the direct contact between the tool and workpiece with good lubrication properties [25].

Fatty acids are classified into saturated and unsaturated fatty acids, and most vegetable oils contain high levels of unsaturated fatty acids. Unsaturated fatty acids have the right viscosity and surface tension; therefore, they provide a good balance between cooling and lubrication. The C=C bond contained in unsaturated fatty acids is easily oxidized, resulting in poor thermal stability of vegetable oil, making

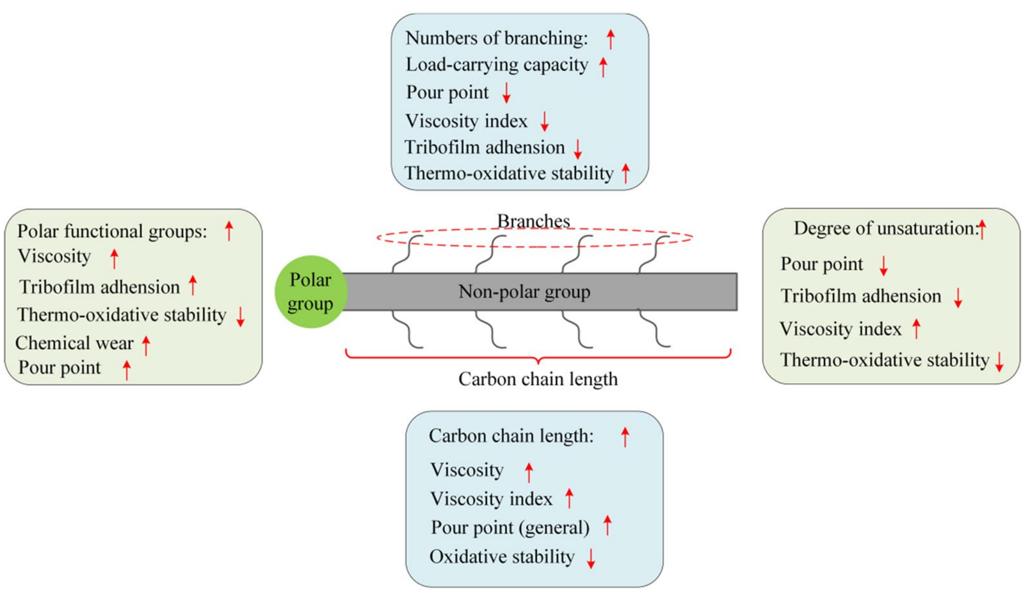

Fig. 3 Evolution of the lubricating properties of vegetable oils

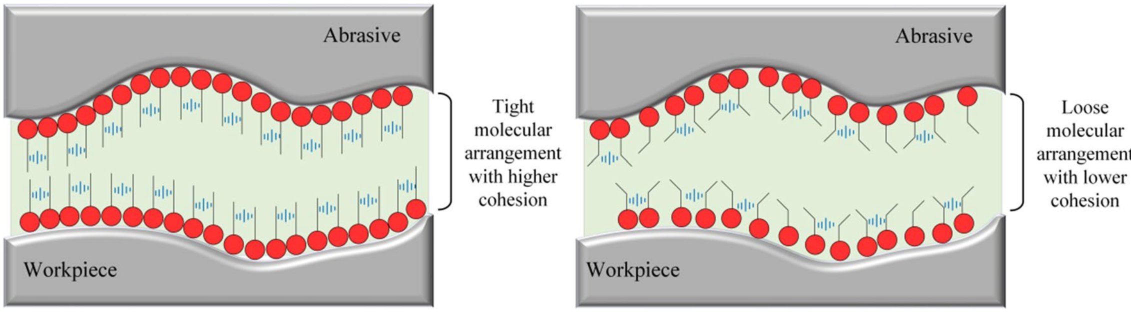

Fig. 4 Lubricant with **a** saturated fatty acids, **b** unsaturated fatty acids [44]

the oil film unstable and the lubricity properties correspondingly reduced [54]. Oils high in saturated fatty acids have received increasing attention. These oils tend to have higher viscosity, and therefore, better lubricating properties. More importantly, as shown in Fig. 4, compared to unsaturated fatty acids, saturated fatty acid molecules can be arranged in thin straight chains because of the absence of C=C bonds. The strong stacking effect improves the intermolecular interactions, resulting in a strong filling effect that contributes to the lubricant film strength. Padmini et al. [55] compared the performance of machining AISI 1040 steel with MoS_2 nanofluid based on three different vegetable oils (coconut, sesame, and canola oils). The coconut oil-based nanofluid exhibited the best processing performance, with 31.58% lower tool wear than that of canola oil. This is mainly due to its saturated fatty acid content of up to 90% with excellent lubrication properties. Zhang et al. [56] compared the machining performances of 45 steel grinding using different vegetable oils (soybean, palm, and rapeseed oils). The best lubrication performance was obtained with palm oil-based nanofluids. Yin et al. [57] systematically revealed the lubrication mechanisms of different vegetable oils (cottonseed, palm, castor, soybeans, and peanuts) with varying physicochemical properties. Palm oil exhibited the best lubricating properties. This is mainly due to the high saturated fatty acid content and viscosity of palm oil, whose main fatty acids are palmitic and stearic acids. The strongest and most diffuse lubricant film was formed at the grinding wheel-workpiece interface.

2.1.1.2 Length of carbon chain Various fatty acids have different carbon chain lengths owing to their different types. Fatty acids with different carbon chain lengths exhibit different oil film strengths. Because the cohesion between molecules is proportional to the number of carbon atoms, the strength and lubricating properties of lubricant films formed using fatty acids with longer carbon chains are stronger than those formed using fatty acids with shorter carbon chains [58]. Erhan et al. [59] found that canola oil exhibited better lubricating properties than soybean oil. This is mainly because canola oil (C22) has a longer carbon chain compared to soybean oil (C18). In general, the longer the carbon chain, the higher the viscosity and better the lubricating properties. However, for the saturated fatty acids, the frictional and wear resistances of the lubricant film peaked and remained constant when the carbon number was greater than 16. In this case, the lubricating effect did not change as the number of carbon atoms in saturated fatty acids increased. For unsaturated fatty acids, the presence of polar unsaturated C=C groups reduces the lubricating properties of vegetable oils by reducing the oxidative and thermal stabilities [60].

2.1.1.3 Stability As shown in Fig. 5a, the C=C content in unsaturated fat is the activity center of many reactions, such as oxidation, and the oxidative stability of oils is a key factor affecting the quality of processing. The main components of most vegetable oils are fatty acid glycerides, and the presence of unsaturated double bonds in the fatty acid carbon chains leads to poor oxidative stability. Regarding the relationship between different saturations and lubricating properties, on the one hand, the presence of C=C makes the unsaturated fatty acids susceptible to oxidation, which leads to the degradation of the vegetable oils, resulting in the failure of the physically adsorbable oil film formed. On the other hand, the higher the percentage of C=C. Quinchia et al. [61] found that canola oil had a lower degree of double bond unsaturation compared to soybean oil. As a result, canola oil has strong antioxidant properties. The addition of antioxidants (e.g., vitamin E) is undoubtedly the most direct way to improve the oxidative stability of vegetable oils. Chemical modification is another method of improving the antioxidant properties of vegetable oils. This method focuses on the chemical reaction between the carboxyl groups and carbon chains of unsaturated fatty acids to change the degree of unsaturation, carbon chain length, and branching of the fatty acids in vegetable oils, thus improving the thermal oxidative stability of vegetable oils. Common modification methods include hydrogenation, esterification, vulcanization, epoxidation, and isomerization.

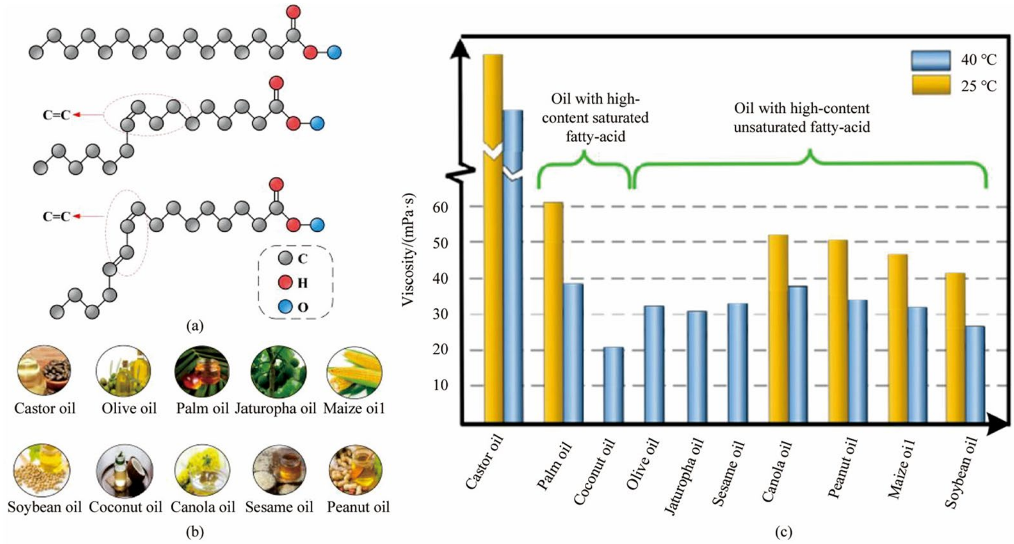

Fig. 5 **a** Molecular structure of fatty acids, **b** common types of vegetable oils, and **c** their viscosity [44]

2.1.1.4 Viscosity Both the oxidative stability and available viscosity range are important factors that limit their application as industrial lubricants [62]. During the grinding process, the viscosity of vegetable oil mainly affects the lubrication and heat transfer properties. Vegetable oils have different viscosities owing to the molecular structures of different fatty acids. Vegetable oils with low viscosity exhibit good cooling performance, whereas those with high viscosity exhibit good lubricating performance. Several common types of vegetable oils and viscosity are shown in Figs. 5b, c.

The high viscosity of the oil molecules results in a strong absorption force between them, thereby generating a high-strength oil film with good lubrication properties. For natural vegetable oils, higher viscosities are usually caused by polar groups (such as –OH and –COOH). The presence of polar groups facilitated the formation of oil films and enhanced the lubricating properties. Zhang et al. [63] discussed the effect of the viscosity of the base oil on friction and found that vegetable oils with high viscosity had good lubrication properties. The main reason for this phenomenon is that a higher viscosity impedes the flow of the nanofluid, and the grinding fluid stays in the grinding zone for a longer period of time, thus improving lubrication at the wheel and workpiece interface and reducing friction and wear. However, excessive molecular absorption leads to an inactive Brownian motion and reduced cooling performance. Temperature can be considered as a composite result of cooling and lubricating properties. If high viscosity oil is used, the lubricating properties are enhanced, and therefore less heat is generated; however, the cooling properties are diminished. Therefore, there should be an optimum viscosity value to achieve a balance between cooling and lubricating properties.

To avoid degradation of the heat transfer performance due to high viscosity, some researchers have proposed mixing high-viscosity oils with low-viscosity oils. Sajeeb and Rajendrakumar [64] mixed saturated coconut oil with highly unsaturated mustard oil for tribological testing. A 1:1 mixture yielded the best performance. Compared to coconut oil, the blend had an 18.18% higher viscosity and a 159.7% lower pour point. Jia et al. [65] mixed castor oil with six other vegetable oils (palm oil, soybean oil, peanut oil, rapeseed oil, corn oil, and sunflower oil) for grinding nickel-based alloy processing experiments. Soybean oil and castor oil had better lubricity properties. This is mainly because the addition of soybean oil to castor effectively reduces the viscosity of castor oil and improves its flow, atomization, heat exchange and wettability. In addition, according to the heat transfer theory, solid materials have a greater heat transfer capacity than liquid materials, whereas liquid materials have a greater heat transfer capacity than gaseous materials. Therefore, the addition of nanoparticles is an effective method to ensure the cooling performance of highly viscous vegetable oils.

In addition, vegetable oils do not satisfy the requirements for friction resistance and heat transfer in the high-temperature and high-pressure working areas of grinding. When the friction load increases to a certain level, the continuous fluid lubricant film breaks. At this point, measures such as increasing the viscosity of the lubricant alone do not work, and polar additives must be added to the lubricant [44]. Ozcelik et al. [66] conducted comparative experiments using different proportions of extreme-pressure additives in rapeseed oil. Rapeseed oil and 8% extreme pressure (EP) additives had the lowest surface roughness and cutting force. Sani et al. [67] conducted experiments on vegetable oil cutting fluids containing phosphorus and ammonia particles. The results showed that the new green cutting fluid had better tribological properties than mineral oil.

However, polar additives can cause ecological damage because they include sulfur, chlorine, and phosphorus. Nanoparticles have become a good alternative to traditional polar additives because of their inherently good heat transfer, anti-friction, and wear reduction properties, as well as their green nature. A comparison of the performances of mineral oil, biolubricant, and nanobiolubricant is shown in Fig. 6.

2.1.2 Nano additive phase

The improvement of the processing performance of basic fluids by adding nanoparticles was widely confirmed in early research [68]. Different material characteristics fundamentally affect nanoparticle performance. Different nanoparticles may have different tribological and thermo-physical properties depending on their chemical composition, as they may affect the contact state and heat transfer between workpiece surfaces [69]. As shown in Table 1, based on their chemical compositions, they can be classified into the following types.

Table 1 Commonly used nanoparticles in manufacturing field

Classification	Nanoparticles
Oxide	Al_2O_3, TiO_2, Al_2O_3, ZnO, CuO, Fe_3O_4, SiO_2, ZrO_2
Carbon and its derivatives	CNTs, GR, ND
Metal	Au, Ag
Sulfide	MoS_2

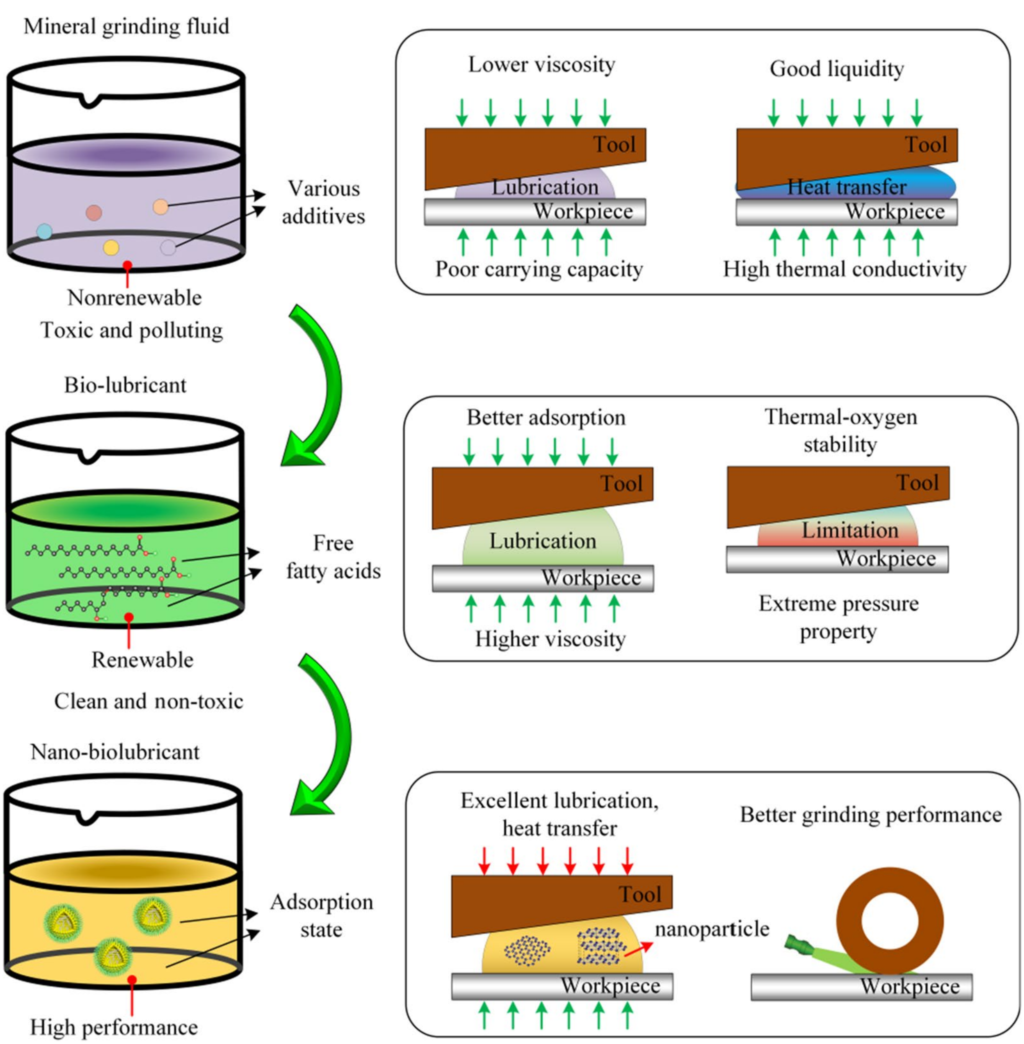

Fig. 6 Comparison of the performance of mineral oils, biolubricants and nanobiolubricants

2.1.2.1 Oxide nanoparticles Oxide nanoparticles are often added to lubricating base fluids to improve their anti-friction and anti-wear properties.

Aluminum oxide (Al_2O_3) nanoparticles are hard and sphere-like in shape, which can enable them to act as a class of bearings in the lubrication process, with excellent friction-reducing and anti-wear properties. They are often used as additives to enhance the anti-wear and anti-wear properties of base fluids because of their ease of enhancing the load-bearing capacity and anti-wear properties of oil films. Titanium oxide (TiO_2) exhibits good anti-wear and load-bearing capacities. They have been widely used because of the easy availability of raw materials, good thermal and chemical stability, and non-toxicity. Ferriferrous oxide (Fe_3O_4) is a common natural compound that has received considerable attention owing to its superparamagnetic properties. The film-forming lubricating ability of Fe_3O_4 nanofluids becomes stronger under the influence of magnetic fields. Cupric oxide (CuO) can form a friction film on a metal surface to reduce friction and wear at the interface. However, the melting temperature of CuO nanoparticles is relatively low compared with that of other materials. Applications under high thermal loads must be discussed in detail. Zinc oxide (ZnO) has attracted considerable attention because of its large surface area, high surface energy, strong adsorption, and easy sintering properties [70]. As a common metal oxide, ZnO nanoparticles are easily prepared. Therefore, their addition to base oils not only improves the tribological properties of lubricants but also significantly reduces costs. However, owing to the low solubility of ZnO in oil, dispersion in base oil may be a challenge [71]. Silicon dioxide (SiO_2) is a widely used ceramic material with good wear resistance, electrical insulation, and high thermal stability. Under the action of stress, SiO_2 nanoparticles can be tightly adsorbed on the grinding wheel and workpiece interface through hydroxyl groups and initially form a physical adsorption film. Thus, friction damage at the interface was reduced to achieve better workpiece surface quality [72]. Zirconium oxide (ZrO_2) nanoparticles exhibit excellent optical and antioxidant properties, wear resistance, high melting points, and thermal stability. Notably, ZrO_2 nanoparticles have a small particle size and large specific surface area, which makes them easier to disperse in a basic solution [73]. Thus, ZrO_2 nanoparticles have a wide range of applications in optics, electronics, and processing.

2.1.2.2 Carbon and its derivatives Carbon nanomaterials have the advantages of high thermal conductivity, stability and wear resistance. Composed of elemental carbon, they do not contain harmful substances and have a low environmental impact compared with other heat transfer materials, which is in line with the requirements of sustainable development. Therefore it has become a popular research topic.

Carbon nanotubes (CNTs) are elongated tubular structures with diameter of 1–2 nm. Owing to their high thermal conductivity, strength, and hardness, they do not grind into hard films under high loads. Its special tubular structure can effectively reduce the sliding friction in the grinding area and improve the lubrication effect of nanofluids [74]. CNTs are considered as promising working nanoparticles owing to their great potential for improving thermal conductivity. Graphene (GR) has a high mechanical strength, excellent thermal conductivity, good tribological properties, and chemical inertness. Monolayer graphene nanoparticles have an ultrathin laminar structure and large specific surface area; therefore, graphene nanoparticles can easily enter the workpiece-abrasive interface. During friction, graphene nanoparticles continuously precipitate and adhere to the surfaces of workpieces and tools, forming an adsorbed friction-reducing layer, which makes it a very promising material for high-load-bearing nanolubrication [75]. Nanodiamonds (NDs) are important carbon nanomaterials. Owing to their high hardness and stable structure, NDs are less prone to deformation and chemical reactions during processing. In addition, some ND nanoparticles may fill the interfacial gaps in the grinding zone, thereby acting as abrasive particles and providing a synergistic effect for material removal.

2.1.2.3 Metal nanoparticles Metal nanoparticles are prepared purely from metal precursors. Because of their localized surface plasmon resonance, these nanoparticles exhibit unique optoelectronic properties. For example, metal nanoparticles such as gold (Au) and silver (Ag) are important in numerous fields such as semiconductors, magnetism, and catalysts because of their unique properties such as optics and electricity, as well as their high thermal conductivity. In recent years, several other properties of metal nanoparticles have attracted the interest of researchers. For example, in addition to their tribological effects, Cu nanoparticles exhibit excellent self-healing properties and are environmentally friendly [58, 76]. However, the introduction of these particles into nanofluids in the manufacturing sector is not cost-competitive, making their use difficult to scale up.

2.1.2.4 Sulfide nanoparticles Molybdenum disulfide (MoS_2) is the most common nanofluidic component in grinding and is favored by researchers owing to its excellent heat transfer and lubrication properties. Owing to the strong Mo–S bond and the weaker bonding of sulfur atoms between the molecular layers, a plane of lower shear was created. This plane fractured along the molecular layer under intermolecular shear, creating a sliding plane. This structure provides the MoS_2 nanoparticles with a certain degree of friability, flexibility, and ductility. When cutting forces are present, the MoS_2 nanoparticles expand into a thin physical film in the cutting zone to reduce the wear and friction coefficients.

In addition, researchers have a positive attitude towards the composite use of different types of nanoparticles. Based on the mechanisms of action of different nanoparticles during processing, comprehensive nanofluids with multifunctional requirements can be achieved. Previous research has shown that the cooling and lubrication mechanisms change significantly after mixed use, and the cooling and lubrication performance can be maintained at a certain level simultaneously [77]. The improvement in the processing performance of the hybrid nanobiolubricants was significantly greater than expected.

2.2 Preparation of nanobiolubricants

Nanobiolubricants are prepared by the appropriate mixing of nanoparticles using the various methods involved, which can be divided into two categories based on the number of steps: one-step and two-step preparation methods.

2.2.1 Preparation methods

2.2.1.1 One-step preparation methods The one-step approach involved dispersing the nanoparticles directly in the base solution during preparation. This method avoids the problems of collecting, storing, and transporting nanoparticles, minimizes the aggregation of nanoparticles, and effectively avoids the oxidation of nanoparticles in air.

2.2.1.2 Vapor phase method The vapor-phase deposition method proposed by Souza et al. [78] has been the most widely used one-step method in recent years. As shown in Fig. 7, the vacuumed vessel contains a liquid of low-pressure vapor, and the liquid is rotated so that it forms a very thin film on the walls [79]. When the vapor of the raw material condenses and settles in the base fluid by interacting with the film, a nanobiolubricant is obtained, and the cooling system is used to prevent the liquid from heating up and increasing the pressure inside the vessel. As the entire process is performed under vacuum, oxidation reactions can be avoided and high-purity metal nanoparticles can be obtained. The Argonne laboratory in the United States prepared Cu nanobiolubricants using this method. The nanoparticles exhibited good dispersion and high suspension stability in basic solutions.

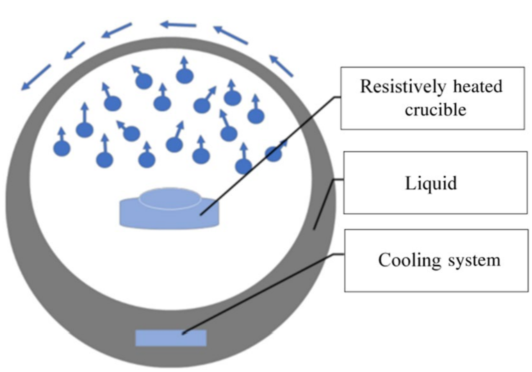

Fig. 7 Schematic diagram of the vapor phase deposition method [79]

2.2.1.3 Chemical liquid phase methods The chemical liquid-phase method involves the preparation of nanobiolubricants by chemical reactions from the molecular and atomic points of view. Sandhya and Nityananda [80] prepared Cu-based nanobiolubricants using this method. They also found that the particle diameter decreased as glucose concentration increased. This is mainly because, as the concentration of the reducing agent increased, the rate of reduction accelerated, and the number of precipitated metal ions increased dramatically, forming more nuclei and thus smaller particles during nucleation. The liquid phase also participates in the chemical reactions and cannot be directly replaced by the base solution. The direct preparation of nanofluids using the liquid-phase method is not as common as that using the gas-phase method.

The one-step method combines the preparation and dispersion of nanoparticles; the prepared nanoparticles have a small particle size and good dispersion stability. This is because of the avoidance of additional dispersion steps and the consequent reduction in the agglomeration of nanoparticles. However, this method is only suitable for the preparation of nanofluids in fluids with low vapor pressure, and is not suitable for high-volume industrial production owing to its high equipment requirements, harsh environmental requirements (e.g., vacuum), and high production costs.

2.2.1.4 Two-step preparation methods As shown in Fig. 8, the two-step method involves the preparation and dispersion of nanoparticles in two steps [81]. Nanoparticles are prepared by certain physical or chemical methods and then dispersed in the base fluid by ultrasonic dispersion, high-pressure homogenization, mechanical stirring, and the addition of dispersants.

The one-step method is mainly suitable for the preparation of nanobiolubricants of metal nanoparticles, as it avoids direct contact with air. However, the two-step method is more suitable for the preparation of nanobiolubricants containing oxide nanoparticles; the two-step method works better [82]. The main disadvantage of the two-step method compared with the one-step method is the large amount of particle aggregation that accompanies the process. However, the one-step method is costly and difficult to operate, whereas the two-step method has the advantages of simplicity, low cost, applicability to almost all types of

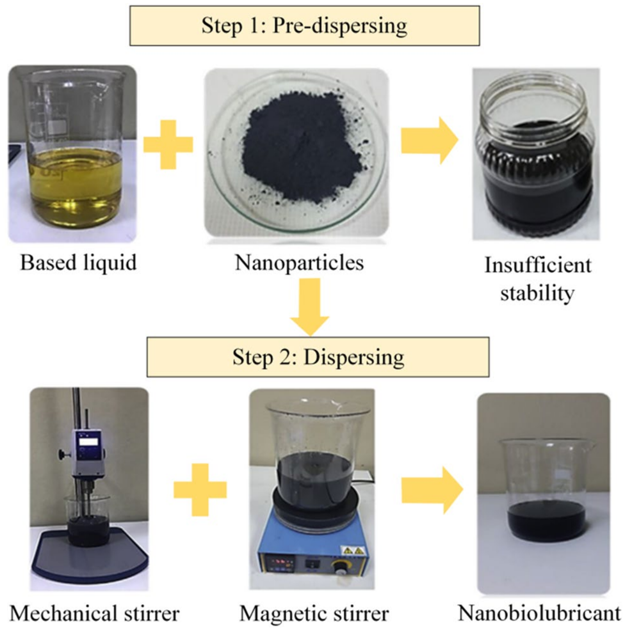

Fig. 8 Flow diagram of a two-step process for the preparation of nanobiolubricants [81]

nanofluid preparations, suitability for practical high-volume production, and high commercialization potential. Therefore, a two-step method is commonly used when preparing nanobiolubricants.

In the process of preparing nanobiolubricants, particles are attracted to each other and tend to aggregate and settle owing to the size effect, especially during the drying, storage, and transport of nanoparticles. Clusters of nanoparticles not only cause settling and blocking of microchannels but also reduce thermal conductivity [83]. In addition, it is difficult to uniformly and stably suspend nanoparticles in a basic solution because of the strong attractive van der Waals forces between the nanoparticles, which lead to collision and aggregation effects. Therefore, when using a two-step process to prepare nanobiolubricants, one of the key requirements is to maintain long-term dispersion homogeneity of the nanobiolubricants suspension and prevent the formation of particle clusters.

2.2.2 *Dispersion stability of nanobiolubricants*

The stability of nanobiolubricants is a key factor affecting their performance. However, nanoparticles are prone to agglomeration because of their high surface energies [84]. Agglomeration is not only a problem regarding stability, but also a problem regarding the application of MQL. The deposition or aggregation of these high-surface-energy particles leads to instability, which degrades thermophysical properties of the nanobiolubricants [85]. Therefore, different techniques are used to properly disperse the nanoparticles into the base solution, such as sonication and the addition of surfactants.

2.2.2.1 *Methods for assessing the stability of nanobiolubricants*

(a) Sedimentation method

Sedimentation is one of the simplest methods for evaluating the stability of nanobiolubricants. A high-resolution camera was used to capture images of the nanofluids to detect precipitation. As shown in Fig. 9, under the influence of gravity, the nanoparticles began to settle in the lower part of the container, and after a certain period, the particles began to cluster. Nanobiolubricants are considered stable when the nanoparticles in a nanofluid are uniformly dispersed and do not precipitate over time. According to the Stokes' theorem, the smaller the number of nanoparticles, the smaller the deposition rate. As a result, smaller nanoparticles settle more slowly than larger ones. However, the size of the nanoparticles must not be small because when the size of the particles is small, the surface energy of the particles increases, resulting in aggregation of the particles [86]. However, this method is not suitable for assessing the stability dark-colored nanobiolubricants.

(b) Zeta potential measurement

Zeta potential is a measure of the strength of the mutual repulsion or attraction between particles and is an important indicator for characterizing the stability of a colloidal dispersion. The higher the absolute value of the zeta potential, the greater the repulsive force between the particles, which prevents particle aggregation, and the more stable the system. Conversely, a lower zeta potential indicates that the attractive forces between the particles exceed the repulsive forces; the dispersion is more easily disrupted; and agglomeration occurs. In general, precipitate formation is observed within a short period of time when the absolute value of the zeta potential is between 15 mV and 30 mV. Nanobiolubricants with zeta potentials greater than 30 mV are relatively stable; those greater than 40 mV have good stability; and those greater than 60 mV are considered to have excellent stability. Kim et al. [87] prepared gold nanobiolubricants using single-pulse laser beams without any dispersant, which still exhibited good stability after one month because of the large negative zeta potential of gold nanoparticles in water.

(c) Electron microscope method

Although transmission electron microscopy (TEM) and scanning electron microscopy (SEM) are primarily used to the characterization of nanoparticles, they also play

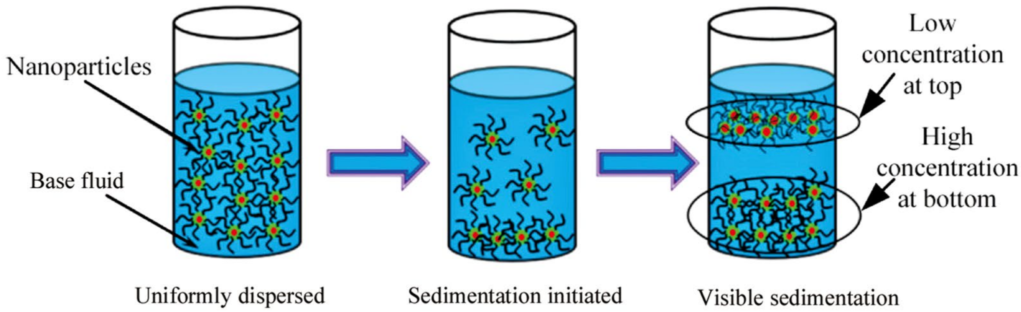

Fig. 9 Schematic of gravity-induced subsidence [44]

important roles in measuring nanofluid stability [88]. When using electron microscopy, the prepared nanobiolubricants are usually dropped onto a copper grid coated with carbon to observe the distribution of nanoparticles on the copper grid when the nanobiolubricants have completely evaporated. Because the evaporation of nanobiolubricants is always accompanied by the aggregation of nanoparticles, TEM is only applied when the concentration of nanoparticles is low [89]. Li et al. [90] studied the stability of 0.1% copper nanobiolubricants with different dispersant types and concentrations at pH 9.5 using TEM technology. The best dispersion was obtained at a concentrations of 0.43% for the dispersants. Xu et al. [8] evaluated the effect of different pH values on the stability of TiO_2 nanofluids with the same nanoparticle concentration using TEM and found the best stability at pH 12. This is mainly because when the pH is above the isoelectric point, the surface charge of the nanoparticles increases as the pH increases, leading to an increase in inter-particle repulsion and therefore an increase in the absolute value of the zeta potential [91].

2.2.2.2 Stability enhancement methods

(a) Ultrasonic dispersion method

Ultrasonic dispersion is an effective method to reduce nanoparticle agglomeration. By placing the nanobiolubricants in an ultrasonic field, the nanoparticles are vibrated by ultrasonic waves of a suitable frequency to overcome the gravitational force between the nanoparticles. This destroys the original agglomeration of the nanoparticles. And it destroys the equilibrium between the nanoparticles and the molecules of the base fluid. Thereby, it improves the stability of the nanofluid.

Sharif et al. [92] treated TiO_2 nanobiolubricants in a magnetic stirrer for 30 min and then in an ultrasonic bath for 2 h and found that the nanobiolubricants were stable for over seven months by stability analysis using TEM. Kalita et al. [93] prepared Fe_3O_4 nanobiolubricants that were stabilized for more than 30 d after 2 h sonication by an ultrasound probe. Sadeghi et al. [94] studied the effect of sonication on the stability of Al_2O_3 nanobiolubricants and found that the zeta potential increased with increasing sonication mixing time, reaching 50 mV with good stability after 150 min.

However, longer ultrasound treatments may change the internal structure and properties of the particles; therefore, a sustained increase in ultrasound time does not necessarily reduce the particle size [95]. Yang et al. [96] prepared gold nanobiolubricants using ultrasound-assisted preparation and found that the number of agglomerated particles decreased with increasing sonication time. However, after 45 min, no change in the particle size was observed. Kole and Khandekar [97] prepared ZnO nanobiolubricants and found that the particle size decreased from 459 nm to 91 nm with increasing sonication time. However, as the ultrasound treatment time increased to 100 h, the particle size increased to 220 nm. This can be attributed to the ability of the ultrasound to provide energy to the molecules. According to the law of energy conservation, the kinetic energy of the nanoparticles increases as the ultrasound time increases. Song et al. [98] found that when ultrasound was used to prepare nanobiolubricants, the temperature of the liquid gradually increased over time. This is mainly because when the ultrasonic energy is sufficiently high, ultrasonic cavitation is generated, creating a large number of microbubbles in the liquid medium. The formation and disappearance of microbubbles in a short period generates a large, localized high temperature and pressure in the liquid, which increases the temperature of the base liquid. This phenomenon leads to an intensification of the motion of the nanoparticles and an increase in the probability of particle collisions, which in turn leads to clusters.

Although the agglomeration size decreased and the stability increased with increasing sonication time, this was inaccurate for longer treatment times. Therefore, further exploration of sonication times is necessary.

(b) Surfactants

Surfactants, also known as dispersants, are a simple and economical way to improve the stability of nanobiolubricants. Surfactants can be adsorbed onto the surface of the particles, thus altering the surface properties of the nanoparticles, creating strong particle-to-particle repulsion, and allowing for proper dispersion [99]. When used, it is often combined with a dispersion method, such as ultrasound, to achieve better results.

As shown in Fig. 10, common surfactants can be classified as anionic, cationic, nonionic, or amphoteric. The choice of dispersant type must be based on the nature of the base fluid and the selection of the dispersant to cover the nanoparticles, which must be compatible with the nature of the base fluid to prevent cluster formation.

To achieve long-term stability, there should be good compatibility between the nanoparticles and base fluid. Hydrophilic nanoparticles are compatible with polar solvents, while hydrophobic nanoparticles are easily dispersed in non-polar solvents. However, if hydrophobic nanoparticles are dispersed in polar base fluids and hydrophilic nanoparticles are dispersed in non-polar base fluids, surfactants need to be added [97].

Different types of surfactants have different hydrophilicities and hydrophobicities; therefore, their compatibility is also different. Anionic surfactants, such as sodium dodecyl sulfate (SDS), are typically suitable for stabilizing hydrophilic nanoparticles. They have hydrophilic head groups and hydrophobic alkyl chains, which can form micellar structures in water and wrap around the nanoparticles. Cationic surfactants such as hexadecyltrimethylammonium bromide (CTAB) are suitable for stabilizing hydrophobic nanoparticles. They contain hydrophilic head groups and hydrophobic alkyl chains that can interact with the hydrophobic nanoparticles to form micellar structures.

Mao et al. [100] compared the dispersion stability of Al_2O_3 nanobiolubricants under the same ultrasonic conditions with and without the addition of SDS. The results showed that Al_2O_3 was more uniformly dispersed in the dispersion system with the application of the dispersant. Gao et al. [101] studied the effects of surfactants with different hydrocarbon chain lengths on the dispersion stability using palm oil as the base oil and CNTs as nanoparticles. The nanobiolubricants containing alkylphenol polyoxyethylene ether 10 (APE-10) exhibited optimal dispersion stability. This is because the length of the hydrocarbon chain of an ionic surfactant affects its hydrophilicity and lipophilicity, the longer the hydrocarbon chain, the more lipophilic it is. Zhou et al. [102] found that when the carbon number of the straight-chain alkane chain of the lipophilic group increased to 16, the long chain curled, thereby increasing the single-molecule cross-sectional area of the surfactant. As a result, the saturated adsorption of surfactants decreases and the adsorption of surfactants decreases, making the dispersion less stable. Table 2 summarizes the results of different studies on the effect of surfactants on dispersion stability based on zeta potential and dispersion time [90, 103–107].

Although the addition of surfactants is an effective way to improve dispersion stability, excessive amounts of surfactants can affect the thermophysical properties of nanofluids by reducing their thermal conductivity [108]. Amrita et al. [109] studied the thermal conductivity of graphene nanobiolubricants using different dispersant types and found that the thermal conductivity tended to increase and then decrease with increasing concentrations of gum arabic (GA) and Triton X100 (TX 100). Wang et al. [110] studied the thermal conductivity of graphite nanobiolubricants at different dispersant concentrations and observed that the maximum value was achieved when the weight ratio of the dispersant to graphite was approximately 3:1. The main reason for this phenomenon is that when the surfactant concentration reaches a critical micelle concentration (CMC), it

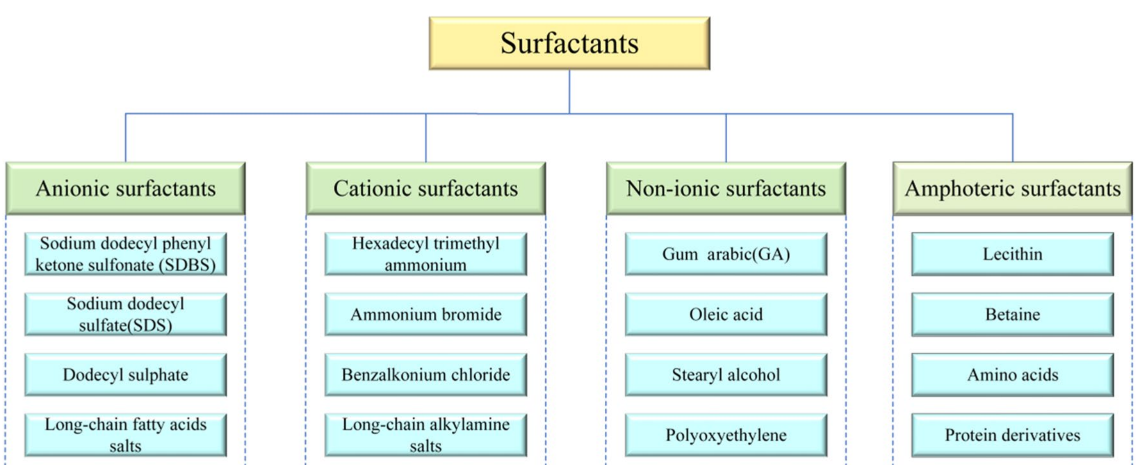

Fig. 10 Types of surfactants

aggregates to form micelles. The formation of micelles can cause sudden changes in the surfactant properties, resulting in local clustering. As shown in Fig. 11, the number of micelles increased with increasing surfactant concentration, which affected the homogeneity of the nano-added phase composition and reduced dispersion stability. In addition, the micelles formed had an insulating layer that prevented heat transfer. Therefore, the dispersant can be effectively adsorbed on the particle surface only when the correct amount of surfactant is added. Considering that the volume fraction of the nano-added phase generally does not exceed 2%, the surfactant concentration should not be too high to avoid affecting physical properties.

Although the addition of surfactants is an effective method for improving the stability of nanoparticle dispersions, the use of surfactant may pollute the heat transfer medium and produce foam at high temperature, thus improving the thermal resistance [111]. In addition, the biodegradability of commonly used surfactants such as GA, SDBS, and SDS has not been reported [112]. Therefore, it is necessary to develop novel and efficient dispersants.

2.3 Thermophysical properties of nanobiolubricants

During machining, the extremely high heat flow density in the grinding zone causes adhesion and wear at the abrasive particle-workpiece interface, which affects machining performance. In recent years, nanoparticles have been preferred for heat transfer applications because of their outstanding influence on the thermophysical properties of the underlying fluid. Different nanoparticles have different effects on the thermophysical properties of the base fluids. Thermal conductivity, viscosity, and specific heat capacity are some of the main parameters that affect the thermophysical properties.

2.3.1 Thermal conductivity

The addition of nanoparticles significantly improves the thermal conductivity of the base fluid. Experimental studies have shown that the thermal conductivity of nanobiolubricants are generally higher than those of conventional fluid [44]. This is because nanobiolubricants are essentially solid-liquid two-phase fluids, and nanoparticles move in random directions when they collide with molecules in the fluid, a motion known as Brownian motion. Nanoparticles constantly undergo irregular micromotion in the base fluid, and

Table 2 Effect of surfactants on the stability of nanobiolubricants

Researchers	Nanobiolubricants	Surfactants	Zeta potential values/mV	Stabilization time
Li et al. [90]	Cu	CTAB	28.1	7 d
		Triton X100	–8.3	7 d
Khairul et al. [103]	Al_2O_3	SDBS	32.2	20 d
Cacua et al. [104]	Al_2O_3	SDBS	32	24 d
Ghadimi and Metselaar [105]	TiO_2	–	–33.3	2 d
		SDS	–55	30 d
Jain et al. [106]	CNTs	–	–30	150 h
		SDS	–40	500 h
Chakraborty et al. [107]	Cu-Zn-Al	–	36.6	12 h
		SDS	–50.6	>24 h

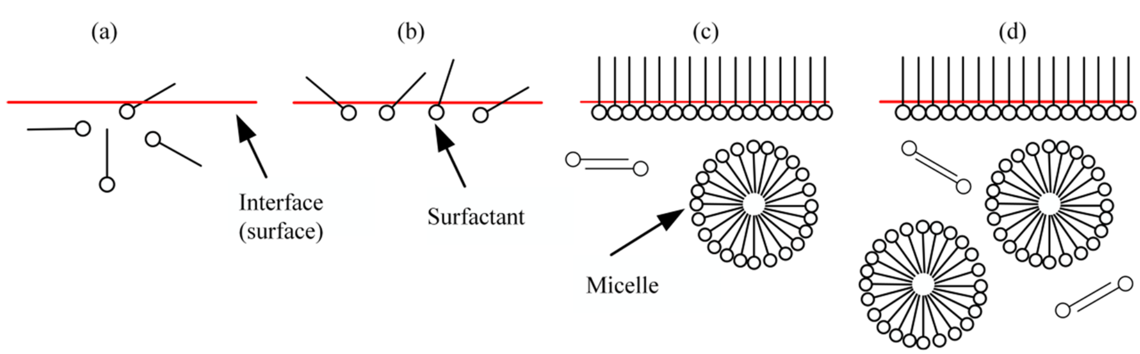

Fig. 11 Micelle formation process [101]

this micromotion causes a weak convection phenomenon between the nanoparticles and the base fluid, which can accelerate energy transfer to the nanobiolubricants, thereby increasing their thermal conductivity [32]. Experimental studies have shown that many factors affect the thermal conductivity of nanobiolubricants, such as the type, size, shape, and temperature of the nanoparticles.

2.3.1.1 Types of nanoparticles The most critical parameter affecting the thermophysical properties of nanobiolubricants is the thermal conductivity. Nanoparticles with higher thermal conductivity are generally considered to exhibit better heat transfer performance. Table 3 lists the thermal conductivity values of several common nanoparticles and the thermal conductivity of water at room temperature as a control.

2.3.1.2 Shape Sen et al. [113] measured the thermal conductivity of Al_2O_3. They concluded that the thermal conductivity of the nanoparticles was highly dependent on their shape. Jeong et al. [114] studied the effect of different shapes of nanoparticles on thermal conductivity and found that the thermal conductivity of nanobiolubricants with rectangular nanoparticles increased by 5.9% compared to that of nanobiolubricants with spherical nanoparticles. This is mainly because with the increase of the length-diameter ratio of nanoparticles, the contact area increased and the collision heat transfer rate increased [115]. Hamid et al. [116] measured the thermal conductivities of TiO_2 nanobiolubricants with different shapes. The cylindrical nanoparticles had greater thermal conductivity than the spherical nanoparticles. This is mainly because the shape factor of cylindrical particles is larger than that of spherical particles. According to the Hamilton-Crosser model, nanoparticles with a large shape factor have a higher thermal conductivity.

2.3.1.3 Effect of particle size The particle size is an important parameter that affects the thermal conductivity. Numerous studies have demonstrated that the thermal conductivity of nanobiolubricants increases with decreasing particle size. This was mainly due to the high surface energy of the nanoparticles, which increased as the size of the nanoparticles decreased for the same volume fraction. The coordination of unsaturated atoms produces a large number of vacant and unsaturated bonds, resulting in an increased activity and Brownian motion of the nanoparticles. This results in a faster separation of the nanobiolubricants from the workpiece and increased perturbation of the workpiece boundary, leading to enhanced heat transfer [117].

Yang et al. [118] studied the dynamic heat flow density during the microgrinding of Al_2O_3 nanoparticles of different sizes. The use of nanoparticles with sizes of 30 nm, 50 nm, 70 nm, and 90 nm reduced the temperature by 21.4%, 17.6%, 16.1%, and 8.3%, respectively. Maheshwary et al. [119] studied the thermal conductivity of particles of different sizes at a concentration of 2%. Compared with the pure base fluid, the thermal conductivity increased by 61% when the particle size was 101 nm and by 96% when the particle size was 31 nm. Sun et al. [120] measured the effective thermal conductivities of SiO_2 nanobiolubricants with particle sizes of 10 nm and 60 nm using a rotating cooter. The thermal conductivity was improved by 13% and 11% at particle sizes of 10 nm and 60 nm, respectively, compared with that of the pure base fluid.

2.3.1.4 Concentration The concentration of the nanobiolubricants had a significant effect on the thermal conductivity. Alawi et al. [32] studied the effect of the volume fraction of nanoparticles on the thermal conductivity of nanobiolubricants. The heat transfer coefficient increased with the volume fraction of Al_2O_3 nanoparticles. Duangthongsuk and Wongwises [121] found that the thermal conductivity increased by 13.2% when the volume concentration of TiO_2 in water increased from 0.2% to 2%.

High concentrations can lead to the agglomeration of nanoparticles and a reduction in thermal conductivity. Makhesana et al. [122] studied the thermal conductivity of MoS_2 nanoparticles added to rapeseed oil at different concentrations (0.5%, 1%, and 1.5%) and found that the thermal conductivity of the nanobiolubricants increased between 0.5% and 1% nanoparticle concentration and decreased slightly after 1%–1.5% concentration. Sahooli et al. [123] prepared CuO nanobiolubricants in the concentration range of 0.01%–0.1%. They found that thermal conductivity increased as the number of nanoparticles added to the base fluid increased. As shown in Fig. 12, Li et al. [124] conducted an experimental study on the grinding of Ni-based alloys with different NMQL concentrations. The lowest grinding temperature of 108.9 °C and the lowest energy scaling factor of 42.7% were obtained with a 2% nanobiolubricants concentration. However, as the concentration increases further, the thermal conductivity begins to decrease. This is because of the formation of clusters of nanoparticles in nanobiolubricants, which makes them unstable.

However, the optimum concentrations obtained by different scholars vary, with the optimum concentration distribution at most processing parameters ranging from 0.5%

Table 3 Thermal conductivity of water and seven nanoparticles

Nanoparticles	ZrO_2	SiO_2	CuO	Al_2O_3	MoS_2	ND	CNTs	Water
Thermal conductivity/$(W\cdot(m\cdot K)^{-1})$	< 2	7.6	19.6	40	138	2 300	3 000	0.6

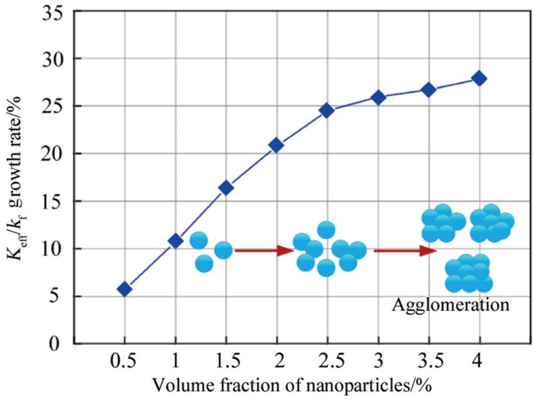

Fig. 12 Growth rate of thermal conductivity of nanobiolubricants with concentration [124]

(volume fraction) to 2.5% (volume fraction). Therefore, to achieve high heat transfer, academics in the field must work together to establish a database that provides a table of optimum concentration recommendations for engineering applications.

2.3.1.5 Temperature Temperature variations in nanobiolubricants have a significant impact on their thermal conductivity by affecting the Brownian motion of the nanoparticles. Sezer et al. [125] found that the thermal conductivity of CNTs nanobiolubricants increased by 69% when the temperature increased from 20 °C to 30 °C at the same concentration. Sharma et al. [126] measured the thermal conductivity of CNTs nanobiolubricants samples at five temperatures (25 °C, 35 °C, 40 °C, 45 °C, and 50 °C) by a transient thermometer. The thermal conductivity of all the nanobiolubricants increased with increasing temperature. In addition, the relative rate of change of the base fluid to the nanofluid determines the thermal conductivity of nanobiolubricants. Therefore, an increase in temperature does not necessarily contribute to the enhancement of thermal nanobiolubricants, and sometimes, the result may be the opposite [127].

2.3.2 Viscosity

Viscosity, an important physical parameter of nanobiolubricants, has a significant impact on heat transfer in grinding processes. Viscosity affects tribological behavior, which in turn affects heat transfer. Grinding fluids with low viscosity are easily damaged by friction at the grinding wheel-workpiece interface owing to their low strength and thickness. An increase in the viscosity can improve the stability and lubricity of the oil film and the tribological properties of the grinding wheel and workpiece interface. This reduces energy consumption during material removal and heat generation. However, at the same time, the fluidity of the grinding interface decreases, leading to the thinning of the temperature boundary layer, thereby reducing the thermal diffusion ability of the nanofluid and weakening its enhanced heat-transfer performance. Simultaneously, the mobility at the grinding interface is reduced, leading to a thinner temperature boundary layer, which reduces the ability of the nanofluid to diffuse heat and weakens its enhanced heat transfer properties [128].

As shown in Fig. 13, Soltani and Akbari [129] studied the effects of temperature and concentration of nanoparticles on the viscosity of nanobiolubricants. The viscosity of nanobiolubricants increased with increasing particle concentration and decreased with increasing temperature. This is due to the interaction between the nanoparticles, resulting in a viscous force between the particles, which increases the viscosity of

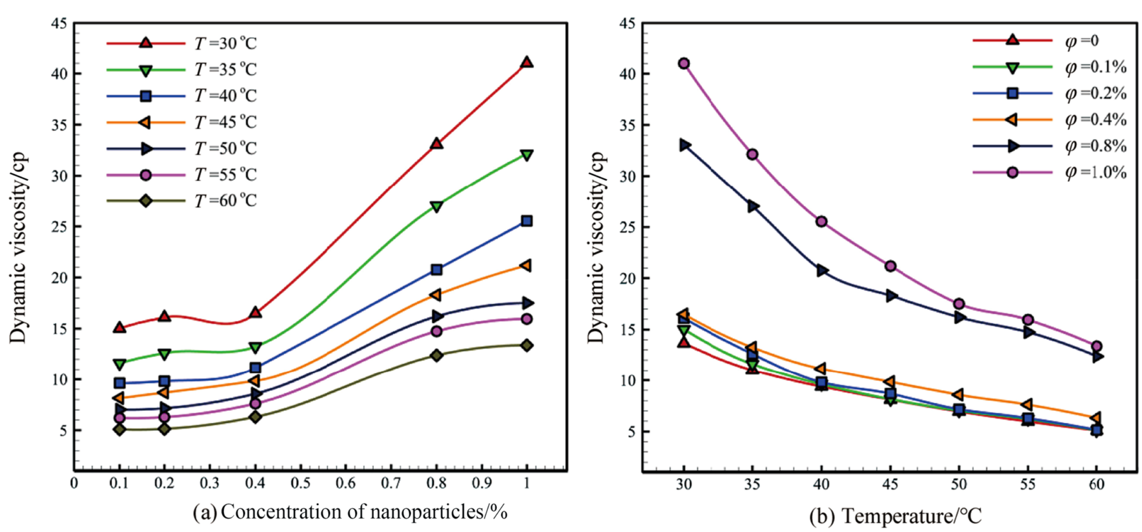

Fig. 13 Dynamics of viscosity with **a** nanoparticle concentration and **b** with temperature [129]

nanobiolubricants [130]. Asadi and Pourfattah [131] studied the effects of temperature and concentration on the viscosities of magnesium oxide (MgO) and ZnO nanobiolubricants. The viscosity increased with increasing temperature and nanoparticle concentration. At a temperature of 55 °C and a concentration of 1.5%, the viscosities of ZnO and MgO nanobiolubricants increased by more than 124% and 75%, respectively. In addition, when the temperature increased, the viscosity decreased. Esfe et al. [132] studied the viscosity of Al_2O_3 nanobiolubricants in the range 5–65 °C by using the CAP 2000+ viscometer. The viscosity decreased as the temperature increased, and was more pronounced at lower temperatures. This is because higher temperatures intensify the Brownian motion of the nanoparticles and attenuate intermolecular interactions, making the nanobiolubricants less viscous.

2.3.3 Specific heat capacity

The specific heat capacity is the heat capacity per unit mass of a substance, that is, the amount of heat absorbed or released by a unit mass of an object when it changes the temperature per unit. The specific heat of nanobiolubricants depends on the specific heat of the base fluid, nanoparticles, temperature, and concentration.

However, relatively little research has been conducted on the specific heat capacity in the manufacturing sector. There are even dialectical views in the existing studies in the field. Bertolini et al. [133] found that the addition of GR to the base oil increased the specific heat capacity. At concentrations of 0.1%, 0.5%, and 0.8%, the specific heat capacity increased by 61%, 116%, and 136%, respectively, compared to pure oil. This is because the specific surface area per unit mass of the nanoparticles increases the interfacial thermal resistance between the nanoparticles and surrounding liquid molecules. This is due to the interfacial interaction of the vibrational energy between the nanoparticle atoms and the interfacial molecules. This high interfacial thermal resistance acts as additional thermal storage and increases the specific heat. However, because of the very high specific heat value of liquids compared to that of solid particles, some studies reached the opposite conclusion. Nair et al. [134] studied the application of Al_2O_3 nanobiolubricants for heat transfer at different nanoparticle volume concentrations (0%–1% (volume fraction)) in the range of 10–50 °C. They found that, unlike the thermal conductivity and viscosity, the specific heat capacity of nanobiolubricants decreased with increasing volume. Ganeshkumar et al. [135] found that dispersing nanoparticles in a base fluid reduced the specific heat capacity of the fluid. Compared to pure oil, a specific heat capacity of 0.4% (mass fraction) nanobiolubricants is nearly 40% smaller than the specific heat capacity of the base fluid at 42 °C.

In addition, the specific heat capacity showed a decreasing trend with an increasing volume fraction of nanoparticles [136]. Pranesh et al. [137] measured the specific heat of CNTs nanofluids by using a differential scanning calorimeter. The concentration of nanoparticles increased, and the increase in the specific heat decreased. This is because of the high surface energy provided by the high surface area of the multi-walled carbon nanotubes per unit volume. However, when the concentration exceeds a certain value, a phase transition occurs in the solvent material near the CNTs, thereby increasing the thermal conductivity and density of the nanofluid. This results in a lower energy requirement at the same temperature increment, and thus a lower specific heat value.

Relatively few studies have been conducted on the effect of nanoparticle incorporation on the specific heat capacity. Therefore, the extent to which the specific heat capacity contributes to processing performance needs to be further evaluated.

3 Grinding performance of nanobiolubricants

During cutting, there are three sources of heat: the heat source generated by the elastic-plastic deformation of the material being cut, the heat source generated by chip-tool friction, and the heat source generated by workpiece-tool friction [138]. In contrast to other machining methods, grinding is more difficult to remove material and consume more energy because of the large negative angle of the abrasive grain and the large radius of the blunt circle on the cutting edge [139]. At the same time, the contact time between each grit and the workpiece is extremely short under the high-speed action of the grinding wheel, and the volume of the grinding chips produced during the grinding process is very small; thus, the heat generated is removed through the chips at a very small rate [140]. A large amount of heat accumulates in the grinding area. This reduces the life and reliability of parts, as well as the grinding performance and machining accuracy of the grinding wheel [38, 141].

The higher thermal conductivity of the nanoparticles can provide great convenience for increasing the heat transfer in the grinding zone. Moreover, various tribological mechanisms of nanoparticles act at the grinding tool-chip-workpiece interface, which further reduces energy consumption in the friction process and suppresses the generation of heat sources [142, 143]. Therefore, to improve the tribological properties and heat transfer efficiency of MQL, the grinding performance was improved by NMQL.

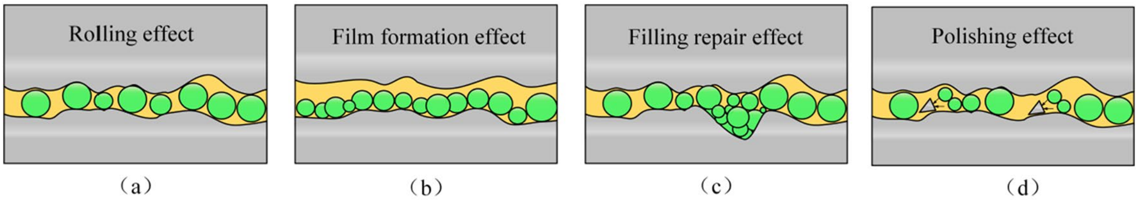

Fig. 14 Four tribological effects of nanoparticles **a** rolling effect, **b** film formation effect, **c** mending effect, **d** polishing effect

3.1 Tribological properties

As shown in Fig. 14, in recent years, scholars have carried out systematic research on the anti-wear and friction reduction and enhancement mechanisms of nanoparticles at friction contact interfaces, and obtained the following insights. (i) Nanoparticles, especially spherical nanoparticles, can play a bearing-like role in the grinding zone and transform the sliding friction between the friction pairs into rolling friction of nanoparticles, which greatly reduces the friction coefficient between the interfaces [57, 144]. (ii) The nanoparticles formed a relatively smooth and dense friction lubrication film on the tool surface. Because of the loose, flexible, and ductile nature of nanoparticles, films that peel off during sliding can be replenished and rapidly renewed by adsorption, thereby reducing friction. (iii) Nanoparticles tend to repair microdamage by filling microcracks and depositing them on friction surfaces, ultimately helping to create flatter and smoother surfaces [145]. (iv) High-hardness materials can be used for precision polishing. After nanoparticle polishing, the roughness of the friction substrate was reduced; the stress on the contact surface was reduced; and the load-bearing capacity of the lubricant was increased; that is, the nanoparticles exhibited a polishing effect.

3.1.1 Friction coefficient

During the grinding process, the tribological properties of the grinding zone directly affect the grinding accuracy and surface quality of the workpiece. The coefficient of friction is a key parameter for evaluating tribological performance. Owing to the strong adsorption properties of nanoparticles, they can penetrate the space between the contact surfaces and gradually deposit on the friction surface, forming a film on the friction surface. This physically adsorbed film was stronger and could withstand higher loads [146]. Therefore, the addition of nanoparticles can significantly reduce the coefficient of friction at the contact interface.

Most researchers attribute the superior lubricating properties of nanofluids to the deposition of nanoparticles on friction surfaces and the formation of protective films. Wu et al. [147] found that nanoparticles could easily enter sliding metal surfaces because of their small size. These nanoparticles are adsorbed or deposited on the sliding metal surface, forming a surface protection film, and thus reducing friction. Zhang et al. [56] evaluated the tribological properties of NMQL grinding. The friction coefficients of MQL, NMQL, and castable grinding were reduced by 11.22%, 29.21%, and 32.18%, respectively, compared to those of dry grinding. Wu et al. [148] conducted grinding experiments on YG8 carbides under four working conditions: dry, cast, MQL, and NMQL. The minimum friction coefficient and maximum *G*-ratio of 6.52 are obtained using NMQL grinding. As shown in Fig. 15, Wang et al. [52] compared the coefficients of sliding friction of six different nanobiolubricants for grinding nickel-based alloys, and used the flood lubrication type and pure palm oil MQL for comparison. The results show that the NMQL and flood types exhibit the best and worst lubrication performances, respectively.

Different mechanisms of friction reduction exist for nanoparticles with different properties at the friction interface. Nearly spherical nanoparticles can change the friction pattern between friction pairs, thereby reducing friction and causing a bearing effect. High-hardness nanoparticles allow precise polishing of the workpiece surface. After polishing, the roughness of the friction substrate was reduced and the contact area was increased, thus reducing the coefficient of friction. For less hard nanoparticles, a laminar lubricant film

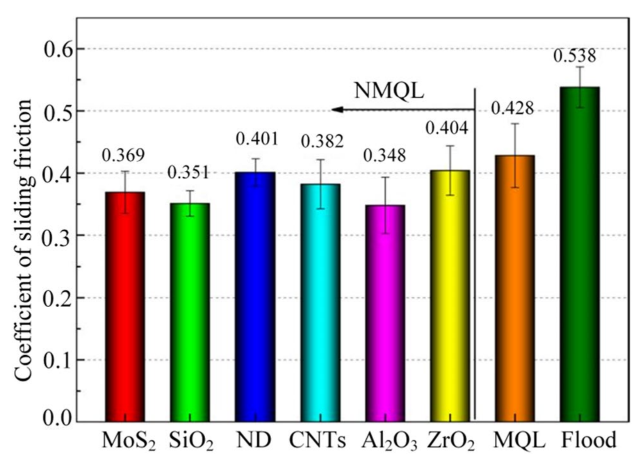

Fig. 15 Coefficient of sliding friction under different nanobiolubricants [52]

can be formed on the friction surface, thus causing a certain anti-friction effect. Influenced by the looseness, flexibility, and ductility of the nanoparticles, the films shed during the sliding process could be replenished and quickly renewed by subsequent adsorption, thereby alleviating friction. Kumar et al. [149] studied the friction and wear characteristics of Al_2O_3, hexagonal boron nitride (hBN), and WS_2 MQL grinding of Ti-6Al4V. The results showed that the Al_2O_3 nanobiolubricants exhibited excellent performance in terms of friction and wear compared with other nanobiolubricants. This is mainly due to the Al_2O_3 nanoparticles filling the uneven workpiece surface, further reducing the contact between sliding surfaces, and thus reducing friction and wear. Another role of nanoparticles is that they can act as load bearers, thus reducing direct contact between sliding surfaces and friction [150]. As hard phase nanoparticles (HR=2 700–3 000), Al_2O_3 can not only serve as a hard point support phase between friction pairs to reduce friction but also make it possible for Al_2O_3 nanoparticles to penetrate the workpiece, supporting the polishing effect. At the same time, Al_2O_3 can reach a melting point of 2 050 °C and has good resistance to high temperatures. The addition of Al_2O_3 nanoparticles improved the high-temperature stability of the lubricant film, resulting in an improved high-temperature friction performance [151].

In addition, the shape and structure of nanoparticles are important factors for improving the performance of nanobiolubricants. Studies on nanoparticle shapes have consistently concluded that spherical nanoparticles can significantly reduce friction and wear [152]. Mao et al. [153] conducted an experimental study on the nanobiolubricant grinding of AISI 52100 steel. The addition of Al_2O_3 nanoparticles to the base fluid resulted in significant anti-wear and wear reduction properties, with a 34.2% reduction in the friction coefficient. As shown in Fig. 16, Jia et al. [65] carried out experiments with Al_2O_3 and MoS_2 palm oil-based nanobiolubricants for grinding ductile iron. Although the friction coefficient of MoS_2 was slightly higher than that of Al_2O_3, the experimental results showed that the grinding performance of the laminated MoS_2 nanobiolubricants was better than that of the spherically structured Al_2O_3. This is because MoS_2 is a lamellar structure, where the layers combine with each other only by van der Waals forces, with a weak bond, and a strong Mo-S bond, while the sulfur atoms are weakly bonded between the molecular layers, creating a plane of low shear during grinding. This plane breaks along the molecular layer under intermolecular shear, creating a sliding plane that transforms the direct contact into relative sliding between the MoS_2 molecular layers. This structure provided the MoS_2 nanoparticles with a certain degree of friability, flexibility, and ductility. When grinding forces are applied, MoS_2 expands into a thin physical film in the grinding zone, thereby reducing the wear and coefficient of friction.

3.1.2 Wear

Grinding-wheel wear also has a significant impact on the surface finish of the workpiece material [154]. The grinding-wheel wear forms sharper edges, such that the contact area between the abrasive grain and the grinding material is reduced, and the coefficient of friction increases. Research has shown that the addition of nanoparticles to a base fluid significantly improves wear rate. As shown in Fig. 17a, the excellent lubrication properties of the nanobiolubricants ensured the life of the grinding wheel and the sharpness of the abrasive grains. In addition, the filler-repairing effect of nanoparticles helps to obtain better surface quality.

Virdi et al. [155] used NMQL to grind an Inconel-718 alloy and expressed the degree of wear of the grinding wheel using the *G*-ratio. As shown in Fig. 17b, the *G*-ratio is defined as the amount of work material to be removed

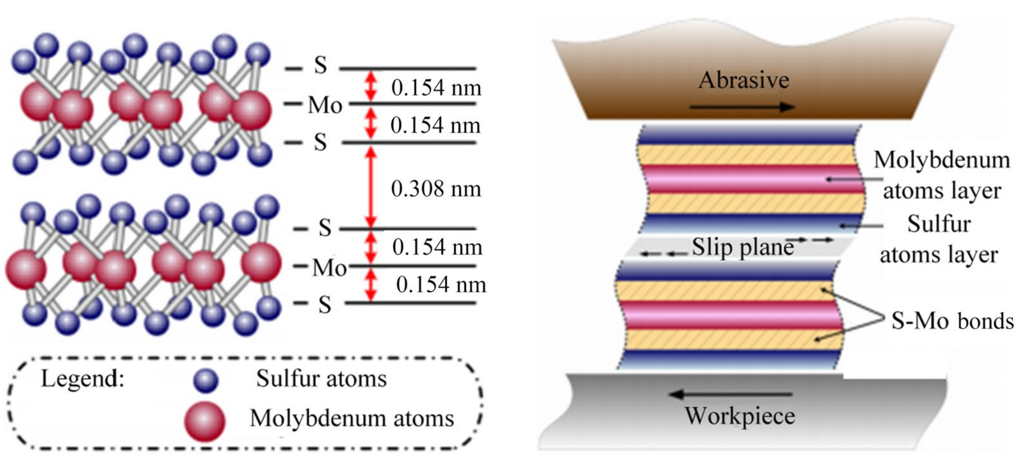

Fig. 16 Molecular structure of MoS_2 [65]

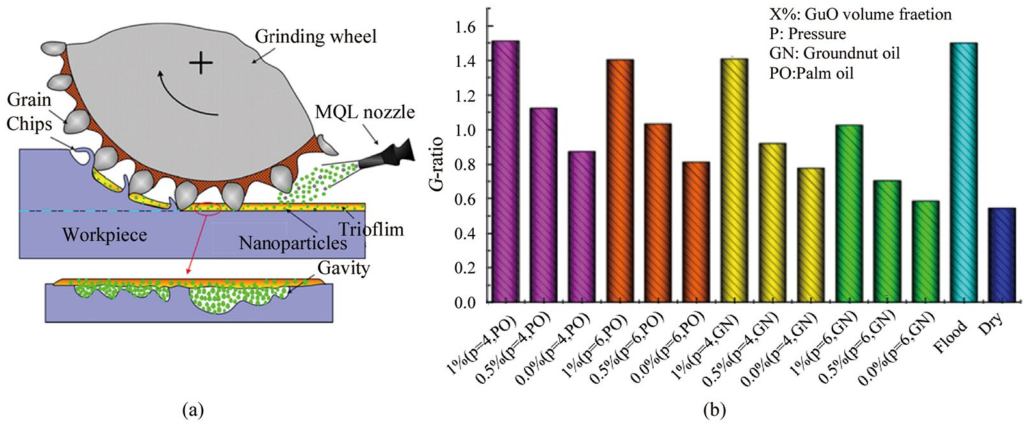

Fig. 17 **a** Anti-friction and wear reduction mechanism of nanoparticles [52], **b** *G*-ratio of grinding nickel-based alloy Inconel-718 under different lubrication conditions [155]

divided by the volume of grinding wheel wear. A high *G* ratio indicates a low grinding wheel wear rate. Their results showed that the *G*-ratios obtained with NMQL were similar to or even better than those obtained with flooding grinding under high-pressure conditions.

The nanoparticles form a separation film between the worn surfaces. This film protects the contact surfaces for a longer period, resulting in less wear and tearing [156]. Mao et al. [153] studied the role of nano-biolubricants in MQL grinding using friction and wear experiments. Compared with pure deionized water, the addition of Al_2O_3 nanoparticles to deionized water reduced the wear rate by 43.4%. This was mainly because the nanoparticles helped to separate the friction surfaces and prevent direct contact between them. This allows elastoplastic deformation caused by the shear strength to occur in the nanoparticle film rather than on the friction surface. Consequently, the adhesive wear and contact fatigue wear of the workpiece material are reduced. Setti et al. [157] compared wheel wear under different lubrication conditions. Compared to dry grinding when nanoparticles were used, the wear phenomenon was significantly controlled, and good abrasive sharpness was maintained. Under a high-pressure impact, the nanoparticles entered the pores of the grinding wheel for lubrication. This promoted the discharge of chips from the pores of the grinding wheel, which played a role in cleaning the grinding wheel.

The magnitude and direction of the cutting force affect the stress distribution and deformation of the tool, which in turn affects tool wear [158]. Nanobiolubricants significantly reduce the cutting force during material removal. Wu et al. [159] conducted grinding experiments on carbide YG8 under four operating conditions (dry, flood lubrication, MQL, and NMQL) to validate the effectiveness of nanobiolubricant grinding. The minimum specific tangential grinding force (12.47 N/mm), specific normal grinding force (2.84 N/mm), coefficient of friction, and the maximum *G* ratio (6.52) were obtained using NMQL grinding. Singh et al. [160] found that, compared to conventional flood-lubrication-type cooling, a graphene nanobiolubricant based on rapeseed oil reduced the grinding force and coefficient of friction by 22.1% and 15.1%, respectively. Pal et al. [161] compared the grinding forces of AISI 202 stainless steel under various lubrication conditions. The result showed that the minimum normal and tangential forces of 9.2 N/mm and 0.76 N/mm were reduced by 56.19% and 66.22% respectively, and the wheel wear was reduced by 40.2% under trace lubrication of MoS_2 nanobiolubricant as compared to the dry grinding condition.

The concentration and particle size of the nanoparticles are two important parameters that influence wear. Arrabiyeh et al. [162] studied the effects of different concentrations of Al_2O_3 nano-biolubricants on the tribological properties of Ti-6Al-4V MQL grinding. As the Al_2O_3 concentration increased, less wear was observed. This was mainly due to the increase in the number of particles involved in the exposure as the concentration increased. This increased the void area near the particles and reduced the actual contact area. However, the effect of the nanoparticles on wear and friction was saturated at certain concentrations. As the nanoparticle concentration increased, the viscosity increased. The higher viscosity not only hinders the flow properties but also reduces the wetting capabilities, which reduces the effective migration distance of the lubricant, thus reducing the lubrication capability in the grinding zone. However, high concentrations of nanobiolubricants are prone to clustering and lead to clogging of grinding wheels [163]. Talib et al. [117] found that at low concentrations, the presence of hexagonal boron nitride (hBN) particles improved lubrication and enabled relatively easy sliding. At the same time, the hBN particles fill the microcracks at the contact interface, forming a lubricating film that reduces friction and prevents wear. However, as the concentration of hBN increased, the movement of nearby particles was restricted, creating a greater force. Compared to 0.05 % (mass fraction), hBN particles at 0.1% (mass fraction) and 0.5% (mass fraction) produce more areas of damage when sliding along the contact surface, leading to abrasive wear.

The current research on the effects of particle size is contradictory. Su et al. [164] found that, at the same volume fraction, the smaller the particle size, the smaller the friction coefficient and wear volume. This is mainly because the smaller the particle size, the better the contact area penetration, the higher the load resistance and the more effective the friction reduction [165]. However, Lee et al. [130] came at the opposite conclusion. They experimented with Ti-6Al-4V by using ND nanobiolubricants. A larger particle size (80 nm) was more conducive to improving the grinding performance of the nanofluid than a smaller particle size (35 nm) of diamond nanoparticles. Because of the high surface roughness of the workpiece, small nanoparticles may not be able to effectively penetrate the contact area between the workpiece and abrasive particles. Consequently, the tribological behavior of the contact area did not significantly improve. To fully investigate the relationship between the grinding performance and the presence of nanoparticles. Yuan et al. [166] demonstrated that larger nanoparticles could achieve lower cutting forces, but poorer surface quality. To attenuate the unfavorable size effect of nanoparticles in the MQL process of nanolubricants, it is recommended to choose a base fluid with a high viscosity to work with larger nanoparticles. There are also differences in the action mechanisms of nanoparticles of different sizes at the friction interface, and the scale of the friction interface roughness peak must be considered. The processing results must be evaluated before selecting the size of the nanoparticles. Gao et al. [167] suggested that larger nanoparticles should be considered when process parameters, such as cutting forces, must be reduced for larger cutting parameters. Smaller nanoparticles are recommended for finishing applications in which surface integrity and tool life are required.

In addition, during material removal at high temperatures and pressures, the nanoparticles and base fluid reacted with the workpiece surface to form a friction film, which affected the wear. Sun et al. [168] evaluated the anti-wear and friction-reduction performances of pure palm oil and SiO_2 nanobiolubricant grinding of nickel-based alloy 718, and found that palm oil contained a large amount of fatty acids and polar groups. The polar groups in palm oil were prone to saponification reactions with metals, thereby tightly adsorbing onto the surface of the workpiece material to improve the friction and wear performance. Owing to the surface effect of the nanoparticles, under the high pressure of the grinding process, the vacancy bonds of the atoms on the surface of the nanoparticles can easily chemically bond with the polar molecules in palm oil (e.g., hydroxyl groups), forming a chemical friction film on the surface of the workpiece. The friction film effectively isolates the direct contact between the grinding grains and workpiece friction substrate, resulting in a significant reduction in the wear of the grinding wheel. Kalita et al. [169] conducted surface grinding tests on ductile iron workpieces using MoS_2 nanofluid and pure paraffin oil, and showed a 48%–55% reduction in grinding wheel wear with the addition of nanoparticles to the base fluid. They found that organic molecules embedded in nanoparticles were encapsulated in porous abrasives during grinding, forming a tribochemical film of Mo-S-P chemical complexes on the friction surface. This film reduces the wear of the grinding wheel.

Unlike physically adsorbed films, chemically reactive boundary lubrication films are stable in the grinding zone at higher temperatures. If the chemical film is broken or peeled off during the machining process, it is immediately replenished with a new chemical film on the emerging workpiece surface, thereby ensuring that there is a sufficient reactive lubricating film in the grinding zone. In addition, the addition of nanoparticles enhanced the heat-transfer performance of the base oil. This reduced the temperature and avoided heat damage, which improved the machining quality of the workpiece.

3.2 Enhanced heat transfer properties

Good heat transfer is crucial for improving grinding performance and extending tool life. Many researchers have confirmed that after adding nanoparticles, the heat transfer rate of a mixed fluid is higher than that of a pure base fluid [170–174].

The enhanced heat transfer mechanism of nanobiolubricants is shown in Fig. 18a. After the addition of nanoparticles, Brownian motion forces the nanoparticles to impact the workpiece, and heat is transferred from the workpiece to the nanoparticles. Plant oil molecules form adsorption layers on the outer surfaces of nanoparticles owing to their high surface energies. When these layers come in contact with each other, heat transfer channels are formed through which excess heat is effectively transferred to areas away from the grinding zone [175]. These findings were confirmed by grinding cemented carbide. Sui et al. [176] studied the grinding temperature of cemented carbide YGB under different working conditions, and their results indicated that the NMQL grinding temperature was lower than that of dry grinding. As shown in Fig. 18b, Xu et al. [177] compared the machining temperatures of dry grinding, casting, MQL, and NMQL using the same parameters. The casting method exhibited the best cooling performance, followed by NMQL. Although heat transfer was not as effective as casting, the

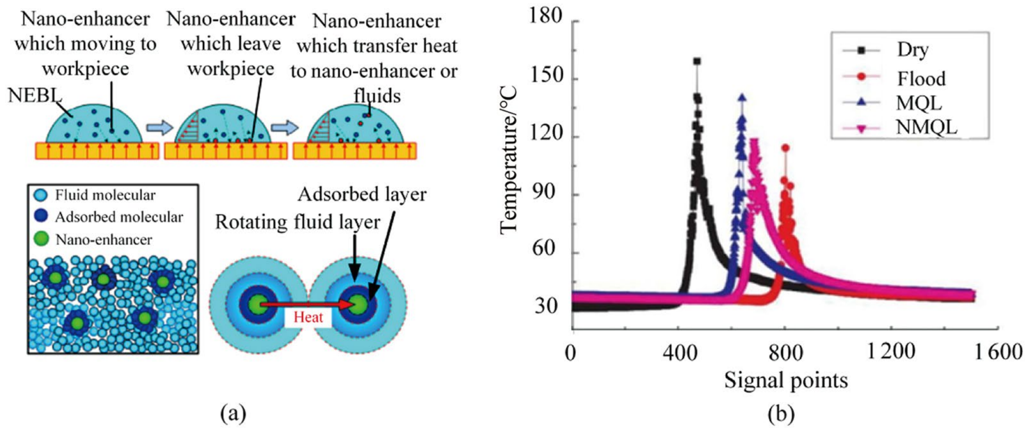

Fig. 18 **a** Heat transfer performance of nanofluid and enhanced heat transfer mechanism [175], **b** processing temperature under different cooling and lubrication conditions [177]

addition of nanoparticles enhanced the heat transfer performance in the cutting area to a certain extent.

3.2.1 Energy ratio coefficient of the incoming workpiece

The proportional coefficient of the energy transferred to the workpiece is an important parameter for determining the grinding temperature transfer and the cooling effect of the grinding fluid. The higher the energy transferred to the workpiece, the higher is its temperature. When the temperature of a workpiece reaches a certain threshold, it can cause damage including surface burns. The use of grinding fluids with high heat transfer efficiency not only improves the surface quality, but also increases the life of the grinding wheel and reduces adhesion, thereby ensuring machining accuracy.

Li et al. [124] compared the energy-scaling factors for different NMQL grinding methods. The results are shown in Fig. 19, where the CNTs nanobiolubricant transferred heat to the workpiece with an energy ratio factor of 40.1% and achieved the lowest grinding temperature. This implies that approximately 60% of the heat generated by the CNTs nanoparticles was not transferred to the workpiece. In addition, they developed a mathematical model of the convective heat transfer coefficient based on boundary layer theory. The model calculations show that the CNTs nanobiolubricant has the highest heat transfer coefficient of 1.3×10^4 W/($m^2\cdot$K), explaining the excellent heat transfer performance of the CNTs nanobiolubricant.

3.2.2 Viscosity

Viscosity mainly affects the lubrication effect of the grinding fluid on the grit-workpiece interface and heat exchange at the grit-chip interface. The excellent lubricating properties of the high-viscosity base oil reduced the level of friction in the

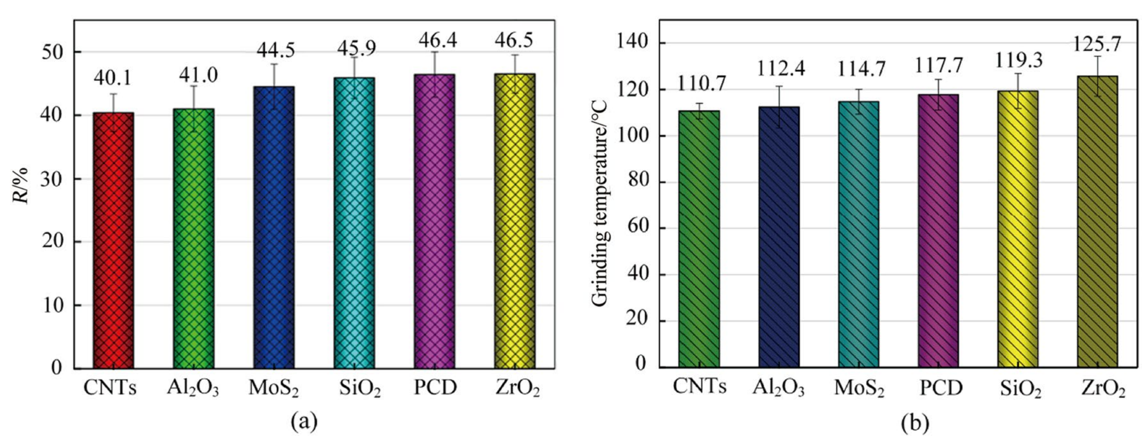

Fig. 19 Different nanobiolubricants **a** proportional coefficient of energy imparted to the workpiece, **b** grinding temperature [124]

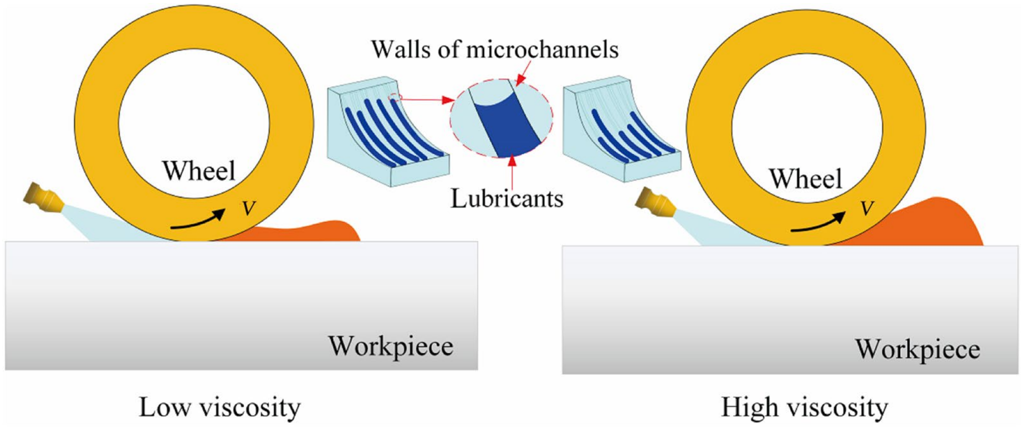

Fig. 20 Effect of viscosity on heat transfer

grinding area and, to a certain extent, the grinding temperature. However, as shown in Fig. 20, a higher viscosity leads to poor fluidity of the grinding fluid and hinders the wetting effect of the grinding fluid in the capillary microchannel, which reduces the permeability of the droplets. The permeability of the droplets affects the heat exchange efficiency, and thus the heat exchange capacity of the grinding fluid [178–180].

Zhang et al. [63] found that although castor oil had a better lubrication effect than palm oil; the high viscosity of castor oil caused an atomization effect and mobility during grinding; and the grinding heat could not be transferred out in time, affecting the quality and accuracy of the workpiece. Li et al. [181] determined the grinding temperatures of seven different vegetable oils on Ni-based alloys using clip-type thermocouples. The highest grinding temperatures as shown in Fig. 20a, the highest grinding temperatures were obtained with castor oil. Conversely, vegetable oils with lower viscosity (such as palm oil and soybean oil) have good heat transfer properties, as they can be quickly flushed out of the grinding zone by high-pressure air, thus preventing the build-up of heat in the grinding zone. As shown in Fig. 21b, the main mechanism of heat transfer from the droplets in the cutting zone can be analyzed in terms of viscous hydrodynamics. The velocity boundary layer is thinner for more viscous nanofluids, resulting in weaker momentum diffusion and mobility. The thicker temperature boundary layer has a higher heat diffusion capacity and, therefore, accumulates more heat in the grinding zone than the less viscous nanobiolubricants, thereby reducing the heat transfer coefficient of the nanobiolubricants and weakening their enhanced heat transfer performance. Conversely, the lower viscosity nanobiolubricant has a velocity boundary layer that is the same thickness as or slightly lower than the temperature boundary layer, resulting in a better heat transfer capacity.

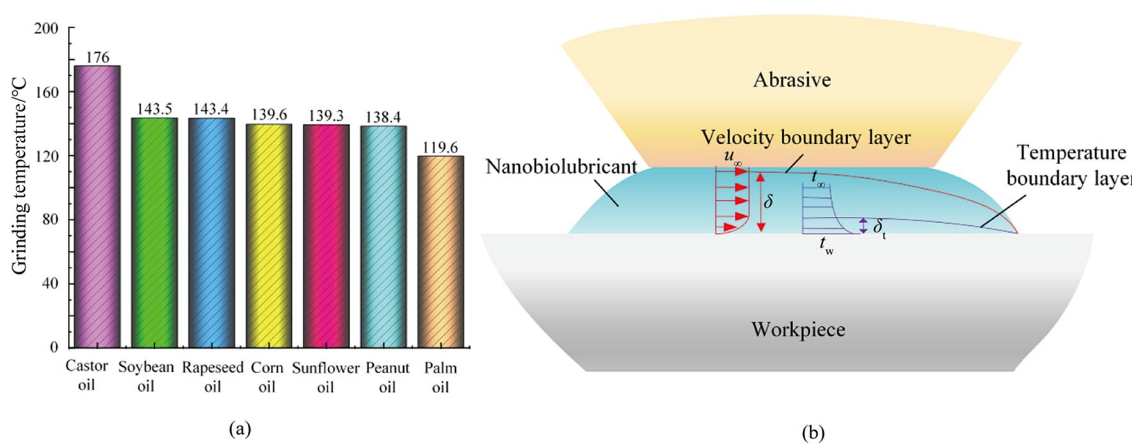

Fig. 21 **a** Grinding temperatures of vegetable oils of different viscosities, **b** schematic diagram of the nanobiolubricants boundary layer in the grinding zone [181]

Viscosity also exerts a certain influences on the formation of the lubricant film. Gu et al. [182] compared the grinding performance of 45 steel grindings under various working conditions. Lubricants with low viscosities had difficulty forming thick and strong lubricant films on high-temperature frictional surfaces. Because of its low strength and thickness, this lubricant film has a low load-bearing capacity and can be easily damaged, thereby reducing the lubrication effect. Therefore, studying the effect of viscosity on processing properties is important for the positive selection of nanobiolubricants.

The incorporation of nanoparticles with high heat-transfer coefficients and tribological properties can effectively solve these problems. This is because solids generally have better thermal conductivity and convective heat transfer capabilities than liquids in terms of cooling performance [183, 184]. However, the addition of nanoparticles to the base fluid not only improves the heat transfer properties of the base fluid but also increases viscosity. Considering that the addition of nanoparticles increases the viscosity of the base solution, Arafat et al. [73] conducted tapping torque tests on nanofluids with different viscosities and glycerol fluids without nanoparticles. The presence of nanoparticles had a much greater impact than an increase in viscosity. Zhang et al. [63] chosed the lowest-viscosity soybean oil as the base oil for grinding experiments on 45 steel workpieces with a MoS_2 nanobiolubricant. As the mass fraction of MoS_2 in the soybean-oil-based nanobiolubricant increased, the viscosity increased, and good lubrication and cooling properties were obtained. Nwoguh et al. [185] used Al_2O_3, MoS_2 and TiO_2 nanoparticles in order to enhance the viscosity and thermal conductivity of highly oleic soybean oil. The viscosity of soybean oil increased with increasing nanoparticles concentration. They found that, as the viscosity increased, lower oil flow rates could be applied for optimum processing performance, reduced power consumption, and less negative environmental impact. Li et al. [124] further explored the influence of the volume fraction of nanoparticles on the grinding temperature of Ni-based alloys with soybean and castor oil mixtures as the base oils. At concentration of 2%–8% (mass fraction), the viscosity of the base oil did not increase significantly. This is because the nanoparticles are highly reactive and, therefore, do not have much influence on the mobility. However, at the concentration of 10% (mass fraction), the nanoparticles form aggregation. Aggregation can scratch the oil film and disrupt its continuity. Therefore, the heat transfer ability is significantly reduced.

3.2.3 Surface tension and contact angle

Surface tension controls the contact angle after spreading. The lower the surface tension, the lower the gravitational force of the molecules inside the droplet on the surface molecules and the tendency of the droplet to spread to the surface as much as possible, resulting in a lower contact angle.

The surface tension of nanobiolubricants is negatively correlated with boiling heat exchange. This is particularly true during the formation, expansion, separation, and movement of bubbles. Nanobiolubricants have a low surface tension and are weakly bound to bubble formation and expansion. It is characterized by the presence of many bubbles and high boiling heat transfer activity [186]. The presence of a large number of bubbles and the high activity of boiling heat transfer facilitate the achievement of excellent properties such as lower temperatures in the grinding zone, avoidance of workpiece burns, and improved workpiece quality.

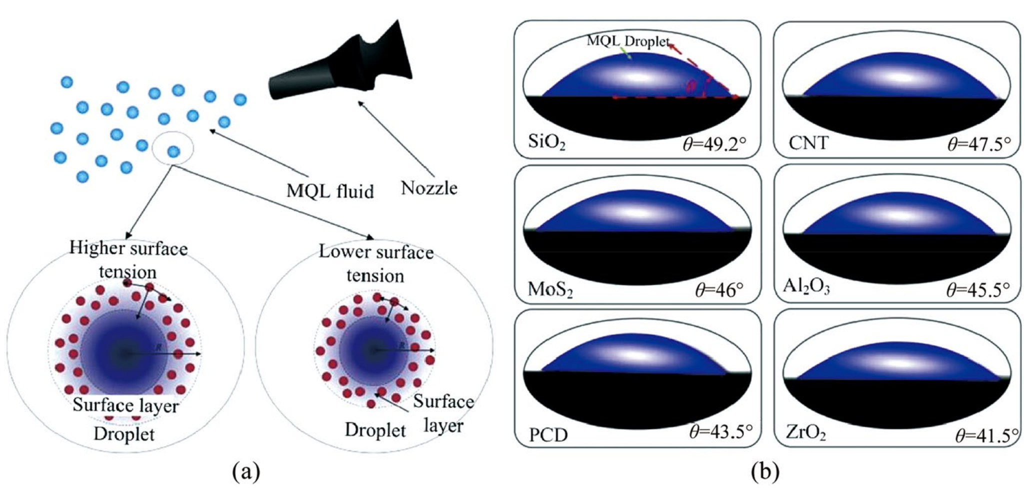

Fig. 22 **a** Effect of surface tension on droplet size [63], **b** contact angle and grinding temperature for six different nanoparticles [124]

In addition, as shown in Fig. 22a, the nanobiolubricant was ejected from the nozzle and entered the grinding zone between the workpiece and the grinding wheel as droplets for cooling and lubrication during the MQL grinding process. Therefore, the lower the surface tension of the nanobiolubricant, the better the droplet breaking and atomization effect. The smaller the space created by the grinding wheel when grinding the workpiece, the easier it is for the droplets to enter the grinding wheel-workpiece interface and the better the lubrication and cooling effects [187]. In addition, because the mist droplets remain in the grinding zone for a short time, they are carried out using a grinding wheel. According to the thermal convection theory, droplets during thermal convection can be divided into a thermal boundary layer and a mainstream zone. The thickness of the thermal boundary layer remained constant. However, the grinding fluid in the main stream area rapidly flowed from the grinding zone before sufficient heat was absorbed. In other words, the grinding fluid in the main stream area did not provide a satisfactory heat exchange effect. However, when the contact angle decreased, the thermal boundary layer expanded, and the proportion of the grinding fluid in the mainstream zone decreased. Therefore, MQL droplets with smaller contact angles exhibit a high cooling efficiency.

Zhang et al. [56] studied the effect of contact angle on the lubrication effect of MQL grinding, and the smaller the contact angle of the mist droplets during grinding, the better the cooling and lubrication effects. This is because a reduced contact angle results in thinner droplets and a larger contact area, producing a better cooling and lubrication effect. Zarrag et al. [188] found that evaporation would not occur effectively with a high surface tension; convective heat transfer would be reduced; and the addition of nanoparticles to the base fluid could reduce its surface tension of the base fluid. As shown in Fig. 22b, Li et al. [124] compared the contact angles of different nanobiolubricants with those of the surfaces of nickel-based alloy workpieces. Based on the above conclusions, ZrO_2 had the smallest contact angle and the best heat transfer performance. However, the grinding temperature shows that the CNTs obtains the lowest grinding temperature. This is because the relationship between the convective heat transfer coefficient and the contact angle can be expressed as $h \propto (1—\cos\theta)$, CNTs convective heat transfer coefficient is higher than that of ZrO_2. This is also consistent with the results for the proportionality factor of the energy imparted to the workpiece. This indicates that the excellent heat transfer performance is caused by a combination of factors.

3.3 Surface integrity

The integrity of the machined surface is the most important indicator of the effectiveness of the process, and is considered to be the result of a combination of tribological and thermal properties. In general, surface integrity includes the surface morphology (e.g., surface defects and surface roughness), surface organization (e.g., subsurface structure and metamorphic layer), and mechanical properties (e.g., residual stress and microhardness).

Silva et al. [189] found a significant improvement in surface roughness, radial wear, and residual stresses using NMQL grinding compared to flooding. Shabgard et al. [190] conducted grinding experiments on AISI 1045 steel by dispersing rapeseed oil containing different concentrations of CuO nanoparticles. The nanobiolubricant has a smoother surface than the cast type. Zhang et al. [63] reached similar conclusions from a grinding experiment conducted on 45 steels. This study showed that adding nanoparticles to vegetable oil could effectively improve its surface quality. This is because the nanoparticles are released into the tool-chip interface together with the nanobiolubricant, which plays an active role in further reducing the surface roughness through different tribological mechanisms that occur during the grinding process. Seyedzavvar et al. [191] prepared a CuO nanobiolubricant using palm oil as the base oil to conduct grinding experiments on nickel-based alloys under trace lubrication and nanobiolubricant trace lubrication conditions using surface roughness as the evaluation index. The results showed a 30% reduction in the surface roughness in the NMQL condition compared to that in the MQL condition. SEM analysis revealed that the lubrication mechanism of the nanobiolubricants was attributed to the rolling and repair effects of the CuO nanoparticles.

It is worth noting that the surface qualities of different nanoparticle-processed surfaces are not the same. Pal et al. [192] showed that the rolling or ball-bearing effect of Al_2O_3 nanoparticles resulted in an improved machining performance. The experimental results of Virdi et al. [193] for Inconel-718 grinding also confirmed this conclusion. Tang et al. [41] studied the grinding performance of Ni-based alloys under various working conditions. Under the same grinding parameters, the grinding temperature obtained with the Al_2O_3 nanofluid was reduced by approximately 10.5%, the surface roughness by 22.4%, and the residual stress by 11.88% compared to pure soybean oil MQL grinding. Wang et al. [52] conducted grinding experiments on nickel-based alloy 718 based on different nanoparticles. As shown in Fig. 23, compared with the flood lubrication method, the NMQL made the surface of the abrasive debris smoother, with longer and thinner shapes, resulting in lower surface roughness and smoother surfaces. And Al_2O_3 obtained the best surface roughness, followed by SiO_2 and diamond. Better surface morphologies were obtained for Al_2O_3 and MoS_2. The CNTs, which were mentioned in the previous section as having the best heat-transfer performance, did not exhibit very good surface quality. This is mainly related

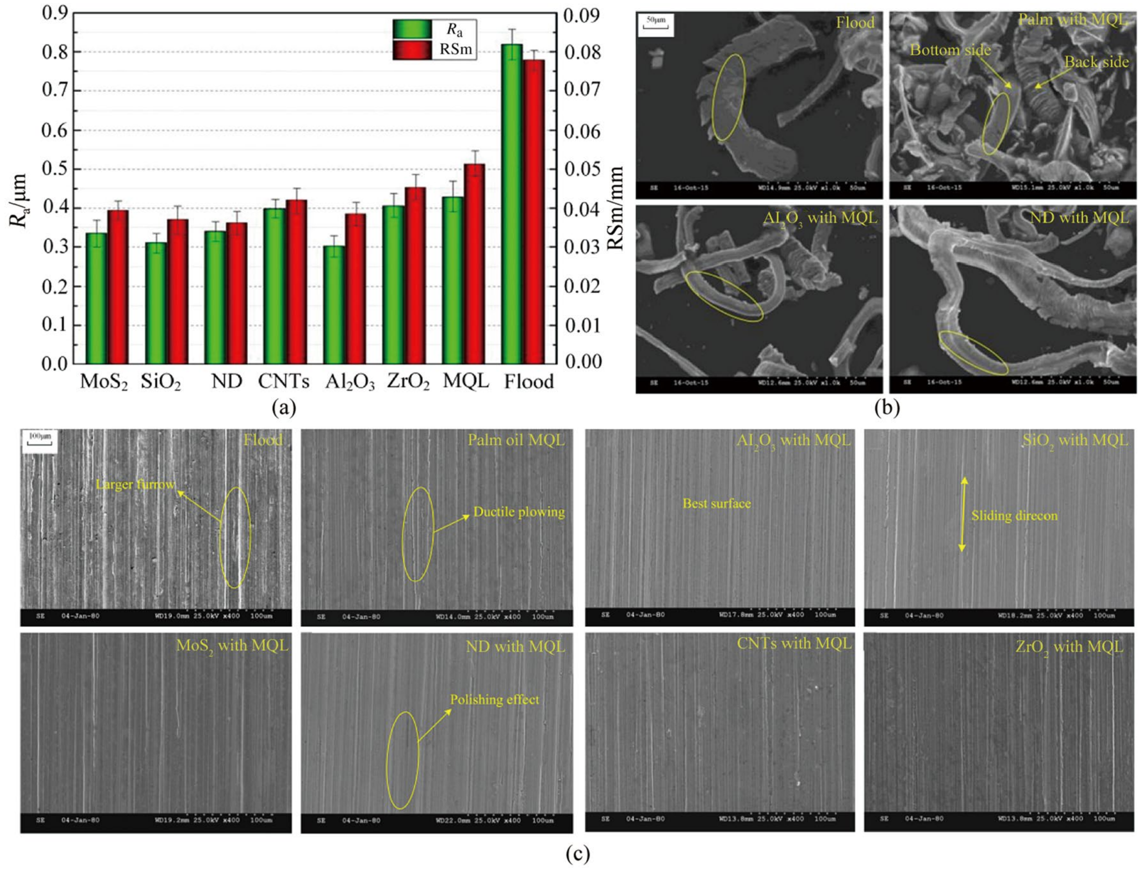

Fig. 23 **a** Surface roughness of different types of nanoparticles, **b** abrasive chip microstructure, **c** surface morphology [52]

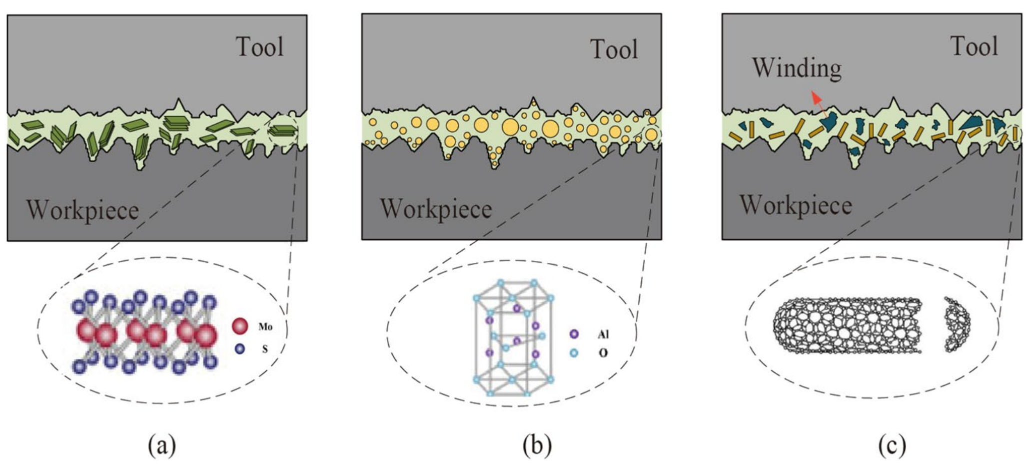

Fig. 24 Physical properties of nanoparticles **a** MoS_2, **b** Al_2O_3, **c** CNTs

to the physical properties of the nanoparticles. The structures, sizes, and shapes of different nanoparticles produce different physical effects. As shown in Fig. 24, spherical Al_2O_3 nanoparticles can significantly reduce the coefficient of sliding friction and move easily under the pressure of the lubricating oil to form a self-adhesive film in the wear area to achieve repair and micropolishing effects, thereby reducing the surface roughness and obtaining better surface quality [145]. The ND exhibited a cubic structure with spherical or ellipsoidal particles. It has very high hardness (98 GPa)

Table 4 Processing properties of different types of nanoparticles

Researchers	Types of nano-biolubricants	Workpiece material	Results
Rahman et al. [195]	Al_2O_3 MoS_2 TiO_2	Ti-6Al-4V	The Al_2O_3 nanofluid with a volume fraction of 0.5% suppresses surface defects and gives the smoothest surface
Sharma et al. [126]	Al_2O_3 MoS_2 TiO_2 CNTs ND ZrO_2	Nickel-based alloys	The best surface roughness and surface topography were obtained for Al_2O_3
Li et al. [124]	CNTs Al_2O_3 MoS_2 SiO_2 ZrO_2	Nickel-based alloys	The CNTs obtained the lowest grinding temperature, while the best surface quality was obtained for Al_2O_3
Hosseini et al. [196]	Al_2O_3	45 steel	Better surface morphology, lower force ratios and grinding specific energies and higher *G*-ratios were obtained with MoS_2 than with Al_2O_3
	MoS_2		Better surface roughness was obtained with MoS_2
Jia et al. [197]	Al_2O_3 MoS_2	Ductile cast iron	MoS_2 is most effective, with shallow and narrow furrows on the surface of the workpiece and the disappearance of adhesion and plastic build-up.
Chetan et al. [198]	Al_2O_3 Ag	Nimonic 90	For all concentrations, the lowest contact angles, surface tension and tool wear were obtained for Al_2O_3

and modulus of elasticity (980 GPa). At the start of grinding, the gap between the grinding wheel and workpiece was very small, and the diamond nanoparticles entered the grinding area and were pressed into and embedded in the depressions of the grinding wheel surface. The micro-removal of the workpiece was completed at the wheel-workpiece interface, resulting in a good surface profile and surface roughness. The strong van der Waals forces and high aspect ratios between CNTs make them prone to tangling and agglomeration, thereby forming irregular tube clusters that damage the lubricating oil film on the friction surface. This results in an incomplete oil film, which prevents the timely discharge of abrasive chips and the appearance of plow grooves on the machined surface [194].

As shown in Table 4, machining characteristics such as grinding temperature, *G*-ratio, and surface roughness were significantly affected by the different nanobiolubricant MQL grinding of different materials [124, 126, 195–198]. To select nanobiolubricants, Wang et al. [199] studied the machining characteristics of different vegetable-oil-based NMQL for grinding various workpiece materials. By evaluating the morphology of the workpiece surface and abrasive chips, they found that Al_2O_3 nanoparticles were more suitable for machining materials with high strength and hardness, such as nickel-based alloys. In addition, different workpiece materials exhibited different removal mechanisms. 45 steel has a long, curly streak of abrasive chips owing to its plastic removal mechanism. Simultaneously, a large amount of energy is consumed during the removal process. The unique lamellar structure of MoS_2 nanoparticles, excellent film-forming properties, and high *G*-ratio make them more suitable for processing soft medium-carbon steels such as 45 steel. Yang et al. [128] studied the grinding performance of nanofluids with different physicochemical properties for grinding high-strength steels, and with an increase in tensile strength, difficulties in chip breakage, grinding-wheel clogging, and high grinding temperatures occurred. Al_2O_3 nanoparticles with high hardness and spherical properties, together with low-viscosity vegetable oils (e.g., rapeseed and sunflower oils) with improved cleaning properties, are a better choice. The *G*-ratio increased from 0.688 to 1.532 compared to flood lubrication.

Therefore, the boundary conditions of the process must be considered, and nanoparticles with an excellent heat transfer medium and high hardness are recommended for use under severe friction conditions. At non-strenuous contact interfaces, nanoparticles with a multilayer structure that can effectively transfer the friction state of friction interface parts are recommended.

Some nanoparticles may have good heat-transfer properties but poor lubrication, and vice versa. Lyered MoS_2 nanoparticles can improve the lubricating properties of the grinding fluid; however, their low thermal conductivity does not allow for a simultaneous improvement in heat transfer. In contrast, CNTs have high thermal conductivity but do not improve the lubricating properties of the grinding fluid. Therefore, there appears to be a contradiction between the cooling and lubricating properties when selecting nanoparticles. Much of the current research focuses on the application of individual nanoparticles, which have limitations in terms of the coexistence of cooling and lubrication. If the cooling properties are the main concern, CNTs with a high heat-transfer capacity can be chosen. If the lubricating properties are the main concern, Al_2O_3 and MoS_2 nanoparticles can be chosen. If the cooling and lubricating properties are the main concerns, layered graphene will be an ideal choice. The laminar structure of graphene facilitates lubrication, while having a high thermal conductivity (higher than that of CNTs), which facilitates heat transfer. Attempts have been made to investigate the use of graphene-based nanobiolubricants in MQL to achieve better processing properties [200]. However, the high price of graphene limits its application in processing [201]. Additional regulatory strategies are required to address this issue.

3.4 Regulation strategies

3.4.1 Hybrid nanobiolubricants

The practice of mixing different types of nanoparticles has emerged as a cost-effective method to combine cooling and lubricating properties. Numerous exploratory studies on hybrid nanobiolubricants have been conducted. Zhang et al. [202] proposed a novel method of mixing high lubricating performance MoS_2 nanoparticles with CNTs and studied the physical synergy of MoS_2/CNTs mixed nanobiolubricants. As shown in Fig. 25, the adsorption of MoS_2 on carbon nanotubes improves the characteristics of the CNTs nanoparticles, which are prone to entanglement clustering. Furthermore, the high strength and hardness of CNTs, the fact that they do not wear into a hard film under high loads, and their excellent heat transfer properties improve the disadvantages of lubrication failure under the high temperatures and pressures of MoS_2. And it was found that the mass fraction of CNTs in the MQL grinding fluid increased accordingly with the increase in the proportion of CNTs. CNTs nanoparticles are governed by van der Waals forces between them and agglomerate to varying degrees, thereby weakening the lubrication effect. Compared to pure MoS_2 and CNTs nanobiolubricants, the mixed nanobiolubricants showed a 13.1% and 38.9% reduction in the friction coefficient and a 13% and 38.9% reduction in surface roughness for grinding nickel-based alloys with MoS_2/CNTs (2:1), respectively. Zhang et al. [63] studied the grinding performance of Al_2O_3/SiC hybrid nanobiolubricants for grinding nickel-based alloys, and Al_2O_3 nanoparticles had good adsorption properties, making them better adsorbed on the surface of SiC nanoparticles. Al_2O_3 nanoparticles physically modified SiC, improving its dispersion and stability of SiC nanoparticles in nanobiolubricants. A bearing-like effect is observed. Owing to this physical synergistic effect, the hybrid nanobiolubricant composed of Al_2O_3 and SiC had the lowest specific grinding energy, obtaining the lowest grinding temperature and surface roughness value, and exhibiting good lubrication and cooling performance.

Hybrid nanobiolubricants often exhibit better heat transfer and lubrication properties owing to their synergistic physical effects. Thus, they are suitable for working conditions in which high lubrication and cooling performances are required. The properties and mechanisms of action of different combinations and ratios of hybrid nanobiolubricants were extensively studied to characterize their suitability of various hybrid nanobiolubricants for various material-removal processing methods. However, because there are many possibilities for nanoparticle mixing, it is difficult to predict the best mixing solution from the

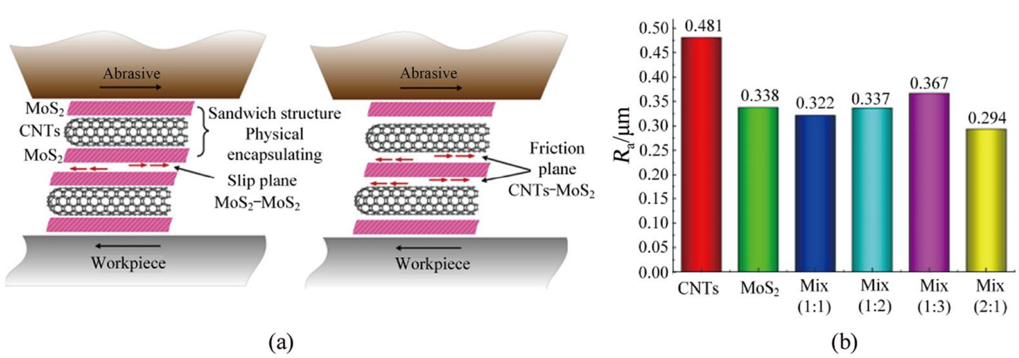

Fig. 25 **a** Physical synergy of hybrid nanobiolubricants, **b** surface roughness for different nanoparticle ratios [202]

limited literature. For machining conditions where high lubrication and cooling properties are required, such as when processing difficult materials in aerospace machining, the process can be further tuned by multi-field empowerment in addition to the use of hybrid nanobiolubricants.

3.4.2 Multi-field empowerment regulation strategy

Although as a highly efficient lubrication technology, it significantly improves the friction and heat transfer during grinding. However, it is necessary to take measures to further improve the grinding performance of difficult-to-machine materials under continuous high-temperature and high-pressure boundary conditions. Multi-energy field-enabling techniques (such as ultrasound and magnetic fields) are effective in addressing mechanical and thermal damage to workpieces.

3.4.2.1 Ultrasonic vibration-assisted grinding Ultrasonic vibration-assisted grinding superimposes high-frequency microamplitude ultrasonic vibrations onto conventional grinding. From a processing perspective, ultrasonic vibration and the superposition of the trajectory of the abrasive grain, such that the relative motion between the abrasive grain and the workpiece shows short contact and long separation, reduce the actual grinding time of the abrasive grain. In addition, the "contact-separation-contact-separation" cycle of intermittent grinding between the abrasive grits and the workpiece allows the coolant to effectively enter the grinding area, improve the heat transfer efficiency of the coolant and reduce the grinding temperature. It has the advantages of high cooling and heat transfer efficiencies, low grinding temperature, and high surface quality of the workpiece obtained. For NMQL, the penetration of the grinding fluid is hindered by the narrow gap at the tool-chip interface. Ultrasonic vibrations allow the grinding wheel to be separated from the grinding chips, providing a microspace for the lubricating medium to enter the grinding area. The grinding fluid was drawn into the space where the grinding chips were separated because of the pumping action of the transient vacuum, giving full play to its lubricating effect [102]. The ultrasonic vibration-assisted grinding device is shown in Fig. 26a, where (1) indicates the piezo actuator and transducer, (2) the horn and booster, (3) the work fixture (main plate) with the flexible joint, (4) the workpiece, (5) the MQL nozzle, (6) the grinding wheel, and (7) the force.

Elcioglu and Murshed [203] found that ZnO nanobiolubricant droplets in the presence of ultrasonic vibrations could explode into a microspray of smaller droplets and form a stable capillary wave, which enhanced the infiltration properties of the droplets. Yan et al. [204] found that under the radial ultrasonic vibration MQL process, the lubricating medium could enter the chip-tool contact interface more effectively and affect the friction under tool vibration. Yan et al. [204] applied ultrasonically empowered nanofluidic microlubrication for the microgrinding of biological bone materials. The grinding temperature was reduced by 33.5% and 10.0% compared to ultrasonic vibration alone and NMQL, respectively. Rabiei et al. [205] studied the cooling effect of an Al_2O_3 NMQL in tangential ultrasonic vibration-assisted grinding. A temperature reduction of up to 48% in the grinding zone compared to dry grinding, a glossy surface was obtained, and thermal damage was effectively avoided. Molaie et al. [206] compared the surface quality of the MoS_2 nanobiolubricant MQL grinding before and after the application of horizontal ultrasonic vibrations. The results are shown in Fig. 26b, which shows that the use of ultrasound together with the nanobiolubricant MQL significantly improved the surface roughness. This is partly because the nanoparticles penetrate the grinding zone more easily when vibration is superimposed and partly because the low frictional grain movement in horizontal vibration creates a higher chance of cutting surface burrs, resulting in an increase in surface integrity. Duan et al. [84] studied the machined surface of a Ti-6Al-4V titanium alloy with ultrasonic vibration-assisted nanobiolubricant grinding. The axial motion generated by the ultrasonic vibration created sinusoidal grinding marks on the surface of the workpiece, which reduced the adhesion

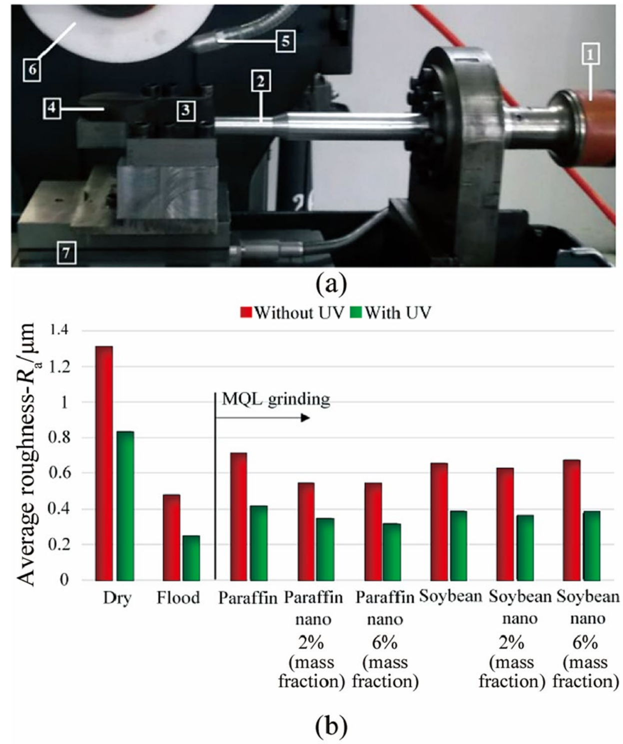

Fig. 26 **a** Ultrasonic-assisted grinding device, **b** surface roughness under different grinding conditions [206]

phenomenon in the grinding of titanium alloys. Thus, slip and plowing during grinding were reduced, and the grinding temperature was reduced by 15.7%, thereby improving the quality of the machined surface.

The technological advantages of ultrasound-enabled MQL are even more significant for the machining of hard and brittle materials. Gao et al. [207] studied the material removal mechanism of ultrasonic vibration-assisted CNTs nanobiolubricant grinding of a carbon fiber-reinforced polymer (CFRP). The ultrasonic vibration-assisted treatment reduced the brittle fracture of the material and achieved the lowest grinding force and optimal surface quality compared with the pure nanobiolubricant. Wdowik et al. [208] examined the surface quality of ZrO_2 ceramics after ultrasonic-assisted and ordinary grinding. It was found that ultrasonic vibrations could significantly promote plastic material removal and form a special weave on the surface of the workpiece. Xu et al. [177] found that ultrasonic vibration-assisted grinding of CFRP composites effectively suppressed the formation of damage and obtained lower grinding forces and better surface morphology compared with conventional grinding. Liang et al. [209] found that ultrasonic vibration was effective in reducing the generation of scratches when grinding CFRP composites. The main reason for this is because axial ultrasonic vibration effectively increases the length of the grinding arc, and the superimposition between the trajectories of the grinding grains plays a reciprocal role in ironing the surface of the workpiece. In addition, based on ultrasonic cavitation, the rapid expansion and closure of the bubble generates a large pressure around the solid-liquid interface to produce repeated impacts and break down the surface residue of the workpiece and flake it off, which can have an ultrasonic cleaning effect on the surface of the workpiece to improve the quality of the processed surface [210].

In summary, the combination of ultrasonic assistance and NMQL changed the material removal mechanism and significantly improved the grinding performance. Simultaneously, by enhancing droplet wettability, ultrasonic-assisted grinding improved the cooling heat transfer performance and effectively reduced the grinding temperature.

3.4.2.2 Magnetic field empowerment Magnetic field empowerment involves the modulation of the processing properties using magnetic fields in conjunction with magnetic nanofluids. Nanoparticles exhibit a magnetic response to an applied magnetic field and can change their morphology and movement in response to changes in the magnetic field, such as alignment, aggregation, and dispersion. This enables the adsorption, separation, and manipulation of other substances using nanoparticles. Consequently, magnetic nanoparticles are more likely to adsorb onto the friction interface under the influence of a magnetic field, filling and repairing them and significantly improving their tribological properties [211]. As shown in Fig. 27, the magnetic field exerts an additional adsorption force on the lubricant compared to the conventional NMQL, which is much higher than the viscous force and gravity. The nanofluid can be stored and transported in the pores of the wheel, significantly improving its permeability [212]. In addition, by influencing the surface energy of the magnetic droplets, the magnetic field can reduce the contact angle of the droplets and improve heat transfer. Consequently, magnetic nanofluids under the influence of a magnetic field exhibit better friction and heat transfer capabilities, which reduce the surface roughness of the machined workpiece and improve the grinding performance.

Wang et al. [213] found that as the strength of the magnetic field increased; particles in the heat transfer

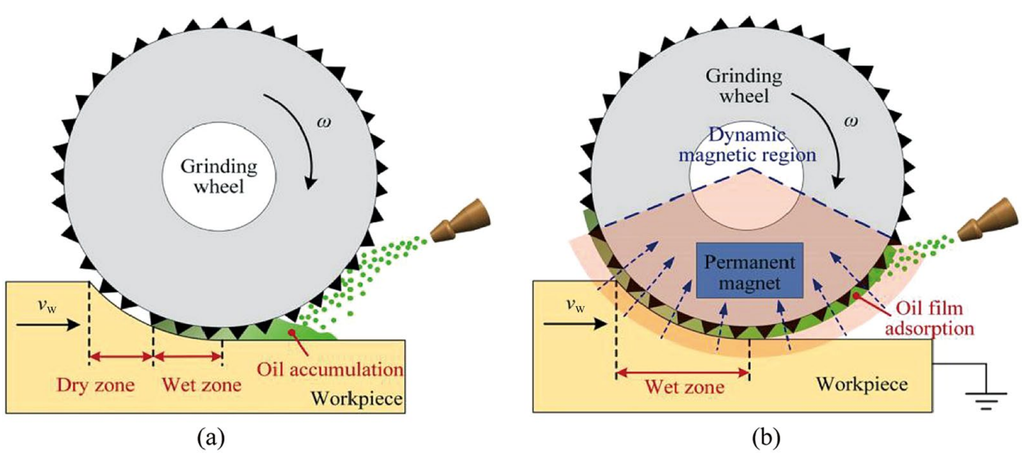

Fig. 27 Permeation mechanisms of nanobiolubricant under different operating conditions **a** minimum quantify lubrication, **b** magnetic field empowerment [212]

channel aggregated; the degree of fluid movement increased, thereby improving the heat transfer performance. The heat transfer performance of the Fe_3O_4 nanofluid improved by 17.62% compared to that of pure water. Cui et al. [212] compared the grinding performances of graphene and Fe_3O_4 for grinding a Ti-6Al-4V alloy. They found that the permeability of Fe_3O_4 was enhanced by magnetic field adsorption and traction. Compared with graphene nanoparticles with high thermal conductivity, the grinding temperature was reduced by 13.8%. Lv et al. [214] found that the contact angle of a droplet decreased under the influence of a magnetic field. This not only improves the permeability of the Fe_3O_4 nanofluid but also increases the diffusion area of the droplet once it reaches the heat transfer surface, resulting in an increase in the evaporative heat transfer efficiency of the droplet and enhancing its lubrication and cooling efficiency. The magnetic-field-assisted Fe_3O_4 nanobiolubricant MQL had a 35.5% reduction in cutting temperature compared with the conventional vegetable oil nanofluid MQL. Gao et al. [207] found that the addition of an external magnetic field could guide Fe_3O_4 nanoparticles to penetrate the tool-chip interface, resulting in better friction reduction and improved machining performance. The surface roughness was reduced by 25.6% compared with that of pure NMQL.

In addition, scholars have studied the coupling between magnetic nanofluids and textured tools. The directional transport of magnetic nanofluids in the presence of a magnetic field allows magnetic nanoparticles to be concentrated in the grooves of textured tools, facilitating the formation of a lubrication layer between the workpiece and tool. The texture of the tool surface, on the other hand, holds the cutting fluid and further facilitates the penetration of the lubricating fluid, while also storing some of the abrasive chips and preventing them from scratching the substrate surface. Thus, coupling magnetic nanofluids and textured tools under the influence of a magnetic field can effectively improve tribological properties and surface quality. Guo et al. [215] revealed the coupling mechanism between textured tools and magnetic nanofluids in the presence of magnetic fields. The best performance was exhibited when the magnetic field direction was parallel to the groove direction, with a 19.4% reduction in the surface roughness compared with no magnetic field. Zhang et al. [216] studied the coupling of magnetic nanofluids and textured tools in a magnetic field. The surface roughness of the workpiece under the new process conditions was reduced by 49.1% compared with that under conventional lubrication.

In summary, magnetic field empowerment improves the frictional and heat transfer properties of nanofluids, and the enhancement of the processing performance has been widely demonstrated. However, the current selection of magnetic nanoparticle types is homogeneous. Therefore, different types of magnetic nanoparticles must be compared.

Their lower coefficient of friction, high antiwear properties, and high heat transfer properties make nanobiolubricants promising candidates for a wide range of grinding applications. The high temperature and pressure generated during the grinding process lead to friction and wear, thereby reducing machining quality and tool life. Nanobiolubricants reduce friction and wear by forming a nano-lubrication film on the grinding interface, which can be automatically repaired during the grinding process, thereby extending tool life and improving machining quality. Based on the physical and chemical properties of different nanoparticles, nanoparticles with an excellent heat exchange medium and high hardness are recommended under the condition of intense friction during the grinding of cemented carbide. In the grinding of soft medium-carbon steel, nanoparticles with multi-layer structures are recommended to effectively transfer the friction state of friction interface parts. Facing the boundary conditions of high temperature and high pressure during the grinding of difficult-to-machine materials, hybrid nano-biolubricants and multi-field empowerment modulation are effective methods to solve the problems of mechanical and thermal damage to workpieces.

4 Sustainability assessment in nanobiolubricant minimum quantity lubrication processing

In recent years, the concept of sustainability in the field of cutting has attracted considerable interest from researchers owing to the strict regulations imposed by government agencies [217, 218]. In recent years, nanobiolubricants have received increasing attention from researchers owing to their ability to increase productivity in the processing industry and improve processing performance while protecting the environment [219–223]. Hegab et al. [224] systematically evaluated the sustainability of NMQL in terms of energy consumption, tool wear, environmental impact, and personal health and safety. The nanoadditives improved the cooling efficiency and friction performance and reduced the thermal softening of the cutting tool compared with conventional MQL. Sustainability was significantly improved by reducing tool wear and power consumption. In terms of specific energy, research showed that NMQL conditions could be reduced by 40%–42%, 25%–30%, and 17%–19% at relatively low combined friction and heat flux densities compared to dry, flood, and MQL conditions, respectively [225]. These trends suggest that NMQL is an efficient and sustainable processing method.

4.1 Models

Deiab et al. [226] conducted an experiment to process a Ti-6Al-4V alloy using six different lubrication and cooling techniques. NMQL consumed the least amount of energy compared to the other methods. However, the energy consumption assessment is not sufficiently representative of the sustainability of the process. Khan et al. [227] measured sustainability indicators such as energy and carbon monoxide to assess the sustainability of NMQL. Ic et al. [228] further considered in their model the energy required for processing, carbon emissions from raw material production, and material removal. Priarone et al. [229] developed a holistic model of energy, cost, and carbon emissions for a conventional cooling-assisted machining process. The authors not only considered the resources used but also determined the optimum machining conditions to achieve environmental and economic goals. Yi et al. [230] developed an empirical model to assess carbon emissions during the processing of AISI 1045 steel. The process model includes not only the carbon emissions generated during the processing phase, but also the environmental burden of the resources used.

4.2 Energy consumption and carbon emissions

Carbon emissions are directly proportional to the energy consumption [231]. As the demand for product quality increases, energy consumption also increases. Higher energy use leads to higher CO_2 emissions. Especially in manufacturing, improving manufacturing efficiency to reduce material and energy consumption and industrial pollution, and thus achieving sustainable performance in machining processes, is a strong concern.

Khan et al. [232] found that NMQL not only significantly improved the surface quality compared to flood lubrication, but also reduced CO_2 emissions. Because NMQL uses the smallest amount of lubricant, there is less need for cleaning parts, recycling, and disposal, thereby reducing costs. This was due to the ability of the nanoparticles to form a protective layer between the friction surfaces, thus reducing friction. The high thermal conductivity of nanoparticles also makes it easy to release the heat generated in the cutting or grinding zone, thus slowing down the tool wear mechanism. This maintains the sharpness of the cutting edge or grinding grains, and therefore requires less energy [233]. Padhan et al. [234] found that dry machining increased friction and wear owing to the lack of lubrication, which led to higher power requirements. After using nanobiolubricants, the energy consumption of the machine tool decreased by 47%. Assuming that each machine works 350 h per year, NMQL can reduce carbon emissions by 88.78 kg. As shown in Fig. 28, they assessed the sustainability of dry and NMQL by considering different factors such as worker safety, power consumption, surface finish, environmental impact, coolant costs, coolant recycling and disposal, noise, and part cleanliness. It was concluded that the use of NMQL cooling and lubrication conditions for machining was economically efficient and socio-technically beneficial because of

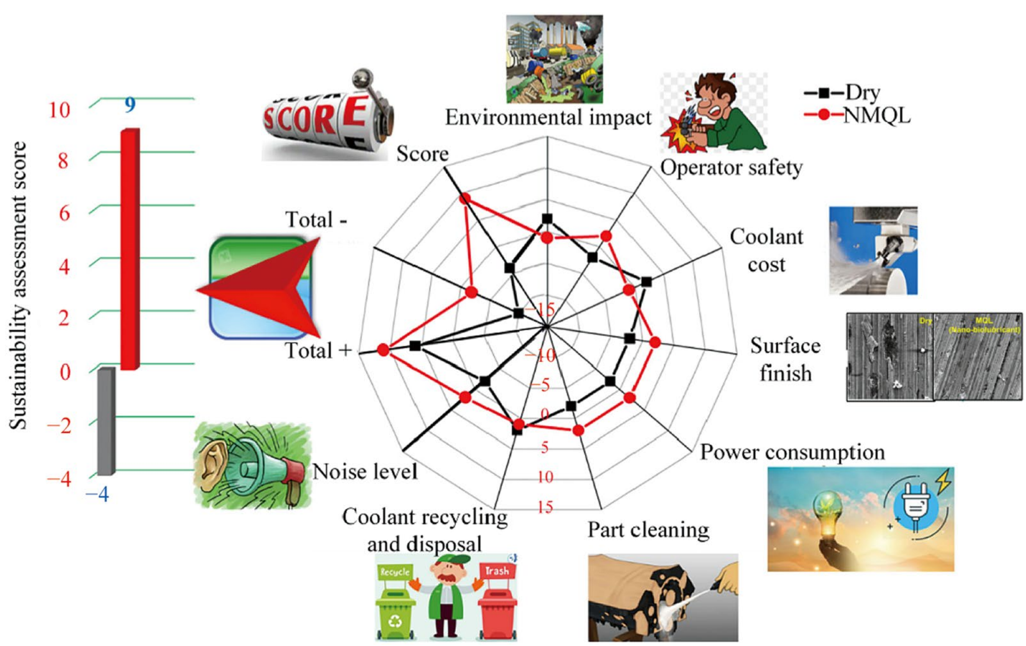

Fig. 28 Sustainability assessment results for dry and NMQL [234]

the excellent tribological and thermodynamic properties of nanobiolubricants.

Because of the reduction in the use of cutting fluid, MQL and NBL not only reduces the environmental load caused by waste liquid treatment, but also reduces the purchase and maintenance costs of cutting fluid-related equipment (e.g., high-pressure pumps and filtration systems). However, the preparation of nanoparticles may result in additional energy consumption. However, studies have shown that the use of natural materials such as silica, alumina, and iron oxide has a much lower environmental impact. This is because no synthesis is required to produce these particles. Natural nanoparticles are usually non-toxic, which further reduces the potential toxicity of nanofluids during application and when discharged into the environment [235].

In recent years, the use of vegetable oils has provided favorable results in terms of environmental issues. This minimizes the health problems caused by mineral oils, allowing for high-performance machining and good environmental compatibility [236]. Future research should focus on solutions to overcome the disadvantages of vegetable oils such as their low heat and oxidative stability.

5 Conclusions and prospect

5.1 Conclusions

The excellent film formation and heat transfer properties of nanobiolubricants can be used to improve the grinding temperature and surface quality of machined parts. In industrial applications, the above-mentioned implications of increased machining efficiency and reduced grinding fluid use can help traditional manufacturing industries become sustainable while ensuring machining accuracy. The preparation, dispersion, and thermophysical properties of nanobiolubricants are reviewed. In addition, the grinding properties of the nanobiolubricants were analyzed under different boundary conditions. The sustainability was also evaluated. The main conclusions are as follows.

(i) Nanobiolubricants with excellent lubrication and cooling properties can be used as high-performance cooling and lubrication media. Owing to the high production costs and difficulty of handling the one-step process, the two-step method is preferred for the preparation of nanobiolubricants. Dispersion stability is a key factor in the performance of nanobiolubricants, and the dispersion should be regulated by mechanical or chemical means prior to use.

(ii) The application of nanobiolubricants in MQL is an effective and clean machining technology. The addition of nanoparticles not only improves the heat transfer performance of the base liquid but also changes the friction state of the tool-workpiece interface. Compared to MQL, the grinding temperatures were reduced by approximately 6.6%–36.9%, and the surface roughness was reduced by approximately 6.9%–30%. Multiple fields such as magnetic and ultrasonic fields have improved the wetting performance of nanobiolubricant droplets, effectively avoiding thermal damage and enabling the replacement of flood lubrication.

(iii) The excellent tribological and thermodynamic properties of NMQL result in lower noise levels, controlled power consumption, lower lubricant usage, recycling disposal costs, lower equipment maintenance costs, and lower environmental impact than other lubrication methods. This study provides novel ideas for green manufacturing and clean production.

5.2 Prospect

(i) Vegetable oil is processed using an environmentally conscious method that allows for high-performance processing and environmental compatibility. The chemical modification of the C=C bond is expected to be an effective method for improving the oxidative stability of vegetable oils. In addition, the complementary effect of blending vegetable oils with different physicochemical properties is another way to improve their antioxidant and extreme-pressure properties of vegetable oils. However, the proportion of vegetable oils to be blended is unknown.

(ii) The dispersion stability of nanofluids remains a key factor affecting the performance of nanobiolubricants, and the addition of surfactants is a common method for improving the dispersion stability of nanobiolubricants. However, the biodegradability of commonly used surfactants such as GA, SDBS, and SDS has not yet been discovered; therefore, the development of new and efficient dispersants is necessary.

(iii) For new materials with high machining quality requirements, ultrasound and magnetic field empowerment have emerged as novel methods to improve the properties of nanolubricants. However, the influence of changes in the physical and chemical properties caused by ultrasonic vibration (such as ultrasonic softening and the ultrasonic cavitation effect) on the machining performance needs to be further investigated. Currently, the types of magnetic nanoparticles are limited. In the future, it will be possible to explore the combination of magnetic and other nanoparticles to prepare magnetic composite nanoparticles with better performance.

(iv) Based on the mechanism of action of different nanoparticles during processing, hybrid nanobiolubricants can achieve multifunctional requirements. Nanobiolubricants (specifically, hybrid nanobiolubricants) must be tailored to specific processes. Depending on the machining results, a series of systems with different cutting temperatures can be fabricated using the hybrid nanobiolubricants. Therefore, the demand for processing orientation should be better summarized, and the synergistic effects between different nanoparticles should be further explored. In future research, it will be necessary to provide more knowledge about the performance of process structures.

(v) The evaluation criteria for sustainable machining are not well developed, and existing models do not consider human health and tool wear costs. The effect of NMQL on the necessary peripheral elements (e.g., exhaust air systems and high-pressure pump filtration systems) has not yet been studied. In the future, relevant research associations should be created to explore the potential of NMQL under different processing conditions to achieve optimal sustainability indicators.

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