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A review on potentials and challenges of nanolubricants as promising lubricants for electric vehicles

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Abstract

The most remarkable difference between electric vehicles (EVs) and conventional ones is the fuel burning dependency of the internal combustion engine, while the emerging EVs operate on electric motors. These alternations create staggering shifts in both lubricants' market demand and performance specifications. Lubricants for electrical powertrain constitutes greases, transmission oils, and lubricants for auxiliary systems and do not rely on engine oils as internal combustion vehicles. The new standards will be more focused on lubricants' electrical properties such as breakage voltage and conductivity, coupled with tribological performance under high rpm, corrosion resistance and thermal management benchmarks. This paper thematically reviews the different studies performed with nanolubricants, and how they match EVs' operational requirements. Conclusions from this study can be considered as guidelines for the potential application of nanolubricants in EVs and possible future research that can be accomplished on the topic.

KEYWORDS

copper corrosion performance, electrical compatibility, nanolubricants, nanoparticles performance in greases, oxidation performance, thermal management

1 | INTRODUCTION

In recent times, electric vehicles (EVs), including battery electric vehicles (BEV), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV) and fuel cell electric vehicles (FCEV), have become more prevalent in the transport sector. This shift in transportation is intended to replace the internal combustion engine (ICE) vehicles in the future.[1] One example of such dramatic change is seen in the United Kingdom as by 2030, the government has decided to ban new fossil fuel vehicle production. [2] Accordingly, this would help reduce car emissions to the equivalent of 46 million tons of CO_2 in the United Kingdom alone. CO_2 global emissions from combustion engine vehicles are 4.5 times higher than electric cars when the electricity is supplied from renewable energy sources. Worldwide sales are on the rise due to subsidies from governments and car producers for EVs to offset the extra battery costs. These incentives and public environmental awareness have reflected on car purchasing habits, particularly in the EU countries, in contrast to ICE vehicles (Figure 1). Additionally, around 7.5 million

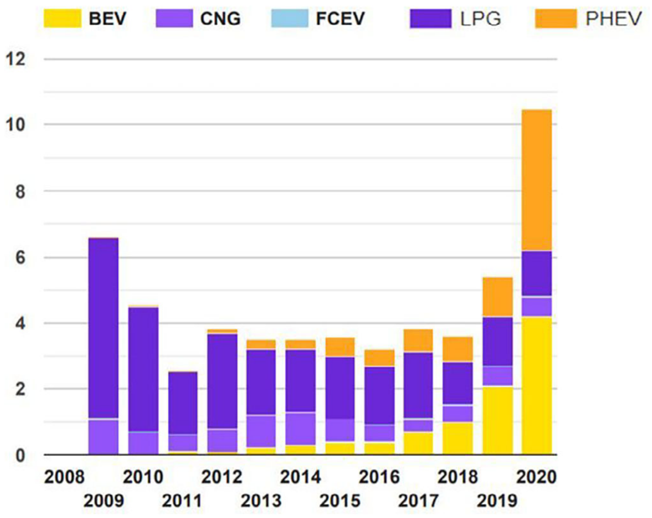

FIGURE 1 Newly registered alternative fuel vehicles (in %), data collected by the European AF Observatory, contractually commissioned by the European Commission, reproduced from open access data Ref. 221. BEV, battery electric vehicles; CNG, compressed natural gas; FCEV, fuel cell electric; LPG, liquefied petroleum gas; PHEV, Plug-in hybrid electric vehicles

BEVs/PHEVs already operated worldwide at the end of 2019.[3]

The current global industry demands enhanced lubricants performance to improve energy efficiency, sustainability and cost reduction.[4,5] This need also holds for EVs as about 57% of the energy supplied to an EV is used to overcome friction, including 41% to rolling resistance and 19% is dedicated to acceleration and braking inertia.[6] However, with this conversion pace, the automotive industry sees unknown technological changes as electric motors and electric vehicles (EVs) are becoming more prominent. Over decades of joint development efforts, lubricants have been optimised for vehicles with ICE and now they have to overcome these new challenges of electric mobility. Compared with the conditions in a traditional ICE vehicle, the mechanical parts of EVs have higher speeds, loads, elevated temperatures and electrical currents. Today's available practical solution to mitigate these challenges includes applying reduced oil viscosities to counter the high electric motor speeds. Hydro-lubes, a mixture of polyalkylene glycol (PAG) and thickened water, allow simultaneous battery cooling and gear lubrication. However, these solutions can not withstand the evolving industry as harsh conditions are pushed even further by manufacturers to improve EV's range and performance.[7] Therefore, to overcome these propagating hurdles, the development of new lubricant formulations is a must. Nanolubricants, a nanofluid class dedicated to lubrication, have shown success in reducing the wear and coefficient of friction in conventional ICE lubricants.[8–13] However, their performance has never been discussed and reviewed in terms of EVs' tribological conditions. This study explores the behaviour of various nanolubricants combinations composed of single or several types of nanoparticles (NPs). The theme in which nanolubricants are evaluated is their performance in greases, electrical compatibility, thermal management, low-viscosity lubricants, lubricants oxidation stability and copper corrosion. Regarding low-viscosity lubricants, the discussion will focus on polyalphaolefins (PAO) and hydro lubricants due to their inherently low-viscosity nature compared to other types of lubricants. These areas are selected as they are considered central assessment criteria when applying a lubricant to an EV.

2 | NPS ABILITY TO ENHANCE GREASE PERFORMANCE

2.1 | Greases challenges in EVs

Grease is described as a solid to a semi-fluid substance or a thickening agent dispersion into a liquid lubricant.[14] Lubrication greases are categorised according to their type of thickener (such as fatty acid soaps), which constitutes between 10% and 15% of the grease.[15] These thickeners are fibrous in shape, with lengths that approximately range from 1 to 100 μm while its length is one order of magnitude greater than its diameter, whereas this dimension ratio is associated with the consistency of the grease for a given thickener concentration.[16] Lubricating oil that may be either mineral or synthetic makes up the most significant portion of the grease formula. It is mostly the thickener that specifies the operating temperature range. The tribo-performance of conventional greases is determined predominantly by the base oil and additives.[15]

About 80%–90% of rolling bearings, in general, are lubricated with grease.[15] This dominance is due to the significant lead of greases over oils in durability and maintaining properties under shear and wide temperature range. Besides, greases acts against moisture and contamination as a sealing agent. The trend in grease lubricant consumption is on the rise as fully EVs and hybrid electric vehicles (HEVs) consume a higher amount of bearing grease than traditional vehicles and the number of these vehicles is estimated to be more than double between now and 2035.[17] The use of greases in many parts or systems within an EV includes powertrain, wheel bearings, chassis and other parts.[18] However, when considering the most significant role of greases is within bearings, it directly impacts the friction, which reflects in vehicle performance, and it is crucial in determining the mileage that an EV can run. Therefore, to improve EVs' efficiency, the improvement of greases' performance in rolling element bearings is vital to ensure their reliability.

EVs mechanical configuration establishes novel challenges for grease usage in bearings. These challenges are due to the extreme lubrication environment that greases undergo sealed in motors at high speeds and elevated temperatures, which poses long-term efficiency complications. This is evident as the most frequent failure inside an electric motor is the greased bearings elements[19]; thus, new kinds of lubricating greases need to be created.

The historical track for enhanced commercial greases formulation started with aluminium and sodium soaps greases as they have better capabilities to cope with higher temperatures than the previously invented calcium greases. Following this, new barium, lithium and calcium-based greases were created with even superior properties compared to the previous era.[20] Polymer grease is considered one of the latest technological advances with chemical inertness properties. [21] However, due to their many beneficial properties such as high dropping point, corrosion protection, pleiotropic efficiency and moisture resistance, lithium greases have ubiquitously been used as lubricants for ICE automobiles.[22,23]

However, an electric motor requires dedicated greases to meet specific requirements, such as lower noise levels. Besides, tribo-contact points are affected by electrical fields and currents produced by magnetic fields.[24] Furthermore, a significant challenge for greases is EVs' torque characteristics; an EV motor produces higher torque, in contrast to ICE, and can provide the maximum power over an extensive speed range, even at slow speeds. The latter fact indicates the possibility of extreme boundary lubrication conditions. Moreover, when dealing with higher rotational speeds, which can reach up to 20 000 rpm,[25] air may penetrate the components and causes the fluids to foam, leading to extreme stress on the motor. Therefore, low-viscosity greases are more fitting for reducing torque, as the friction losses caused by rolling resistance can diminish considerably.

Nonetheless, it accelerates the decline in bearing life due to the thinning in lubricant film and the realisation of heavy wear.[15] In such cases, Nanolubricants can play a significant role due to their anti-vibration damping effect, coupled with anti-wear (AW), anti-frictional (AF) and even extreme pressure (EP) superior performance. Most conventional friction modifiers have fatty acid chain lengths similar to the grease thickener and are thus trapped by the thickener and do not reach the surface to form low friction layers.[15] Knowing this merit of NPs paired with classical additives' significant drawbacks, NPs will perform better in EVs conditions.

2.2 | NPs tribological role in greases form EVs lubrication perspective

Since the revolutionary formulation of nanolubricants composed of WS_2 NPs with closed-cage structure (fullerene-like IF) conducted by Professor Tenne's group, nanolubricants have been considered a game-changer in the field of tribology.[26] However, most of the studies in nanolubrication focus on enhancing oil properties rather than grease since the latter composition can be created in many formulations and properties,[27] magnifying its analysis complexity. However, the relatively few studies on lubricating greases indicate that nanomaterials have many advantages that manifest on the friction pair.[28]

NPs can be categorised according to their chemical nature into metallics, metal oxides, sulphides, clays, carbon-based, rare-earth and others. In the following section, as indicated in Table 1, a literature scan is performed on utilising several types of NPs as additives in greases, with critical discussion on its tribological action.

These results listed in Table 1 are ample evidence that the addition of NPs to greases would significantly enhance its tribological performance. Although these findings are not performed under the same experimental conditions or on similar surface materials and roughness, it is apparent that the size, morphology, crystal structure and compatibility with lubricating base oil influence the NP's tribo-performance.

Considering the NP size, the smaller the NP is during loading and shearing of the surfaces, the better its ability to penetrate the contact region, offering a mending effect by filling the surface roughness.[29–31] Furthermore, the size of NPs must be equivalent to that of the surface's asperities and valleys, as if the NP is too large, they can easily escape and not conform to the rubbing zone, resulting in insufficient lubrication.[32] Additionally, it is worth noting that NPs melting points drop dramatically with their decreasing size,[33–36] affecting the anti-wear mechanism of NPs that depends on welding and melting (sintering) between the moving surfaces.[37]

In the literature, various shapes have been reported: spherical, semi-spherical, sheets, tubes and onion-shaped NPs. Different particle forms have unique effects on the tribological mechanism. Several studies indicated that NPs' spherical morphology provides an effective rolling mechanism, mainly when the NP diameter is equivalent to that of the film thickness,[36,38,39] while plate NPs tend to slide.[40–43] The crystalline structure can be strongly intertwined with the lamellar-shaped particle similar to that of graphite, as weak Van der Waals forces bond adjacent layers resulting in simple slippage or breakage by simply "pull off" layers.[44] This behaviour was confirmed by Sarno et al. as graphene oxide NPs dispersion in oil resulted in

TABLE 1 Literature scan on the ability of NPs in reducing wear scar diameter (WSD) and friction coefficient (COF) in different grease bases

Type of NPs	Size	Type of grease base	Reduction		Mechanism	References
			CoF	WSD		
TiO_2 CNTs	21 nm D (10-12 nm), L (1-20 μm)	Calcium	72.3%	60%	Protective film	57
ZnO Si_3N_4	60 nm 100 nm	Lithium	34.3%	8.3%	Sintering and mending	58
G MWCNTs	10-20 nm D (10-20 nm), L (5-10 μm)	Lithium	66%	91%	Protective film	51
G Cu	NA 20-50 nm	Lithium	15%	85%	Protective film	223
BN MoS_2	NA NA	Lithium	46%	75%	Sliding (Ability to change adhesive wear to abrasive)	44
MoS_2	50–150 nm	Lithium	42%	61%	Protective film	224
TiO_2	20 nm	Water-Glycerol	49.5%	97.8%	Rolling and mending	225
CeO_2	500 nm	Lithium	28%	13%	Polishing	40
rGO	500 nm	Lithium	60%	35%	Protective film	65
αAl_2O_3	40 nm	Lithium	Negative effect		Abrasion	
$CaCo_3$	50 nm	Lithium	33%	20%	Protective film	
$CaCO_3$	45 nm	Lithium	7.5%	12%	Protective film	226
CNTs	D (5 nm), L (5 μm)	Lithium	81.5%	63%	Protective film	50
CaF_2	60 nm	Lithium	19%	29%	Protective film	227
G	NA	Lithium	50%	50%	Protective film	228
$Ca_3(BO_3)_2$	70 nm	Lithium	10%	33%	Tribochemical reaction and protective film	229
TiO_2	35 nm	PTEF	14%	3%	Protective film	94
SiO_2	30 nm	PTEF	14%	Negative effect	Protective film	
SnO_2	20 nm	PTEF	Negative effect		Deterioration of grease's mechanical properties	
NGT	2–6 μm	Lithium	No effect		No action	230
		Titanium	14.6–12.9%	2–2.3%	Tribochemical reaction and protective film	
TiO_2	40–60 nm	Lithium	40%	50%	Protective film	231
CuO	90–110 nm	Lithium	20%	60%	Protective film	
CuO	15–530 nm	Lithium	30%	13%	Polishing and mending	232
ZrO_2	12.7 nm	Lithium	48.8%	46.5%	Sintering	233
SiO2	>100 nm	Lithium	26%	7%	Protective film	234
CS	>600 nm	Lithium	20%	40%	Rolling	235
Bi	10-30 nm	Lithium	13.4%	19.2%	Mending	236
BN	255-955 nm	Lithium	20%	10%	Protective film and sliding	237

Note: Besides, an indication of the different tribological mechanisms played by NPs. The blue highlighted rows signify the utilisation of NPs as mixtures to form composites.

Abbreviations: CNTs, carbon nanotubes; CS, carbon spheres; G, graphene; MWCNTs, multi-wall carbon nanotubes; NGT, nanographite; rGO, reduced graphene oxide; rGO, reduced graphene oxide.

friction reduction and anti-wear properties caused by the small and fragile laminated NPs structure, which offer lower shear stress and prevent interaction between metal interfaces.[45] Furthermore, it was highlighted in a previous study by Dassenoy that hallow metal disulphide NPs exfoliate more easily than well-crystallised ones.[13] Therefore, the optimum tribological result is accomplished with small hollow NPs. Additionally, NPs may share some compressive stress under mixed or boundary lubricating conditions and consequently form a solid self-laminating protective film or micro-polish the friction surface and self-mend it.[40,46,47]

In grease, NPs exhibits several of the mechanisms mentioned above, such as rolling, protective film formation, mending, sliding, sintering onto surfaces and polishing, as depicted in Figure 2. However, the most dominant mechanism was the protective film formation, as Table 1 reveals.

Moreover, NPs addition to greases would significantly enhance its load-carrying capacity and extreme-pressure performance. In particular, carbon-based NPs have superior abilities to improve the load-carrying capacity due to their excellent mechanical properties.[48,49] Mohamed et al. revealed that lithium-based greases' load-carrying capacity could rise to 52% with just 1%wt of CNTs.[50] In another study, Ashour et al. showed that the overall maximum seizure pressure increased by 75% when 1 wt% of multilayered nanographene was incorporated into lithium grease.[51]

Composites typically exhibit superior performance compared to individual NPs due to the synergetic effect of more than one type of NP.[52,53] According to Kumara et al. Ag and Pd NPs modified by Dodecanethiol can interact actively, modifying their sizes, forms and electronic structures. A mixture of these two quasi-spherical ultra-small sizes (2–6 nm) NPs could form a stable suspension and effectively increase tribological efficiency in the 0.1%–1% concentration range in lubricating fluid. In contrast to either NP alone at the same overall NP concentration, the Ag-Pd NP combination further decreased friction and wear by >30% and >80%, respectively. The superior lubricating activity was due to the formation of two forms of ultra-thick tribo-film (up to 3 μm), caused by the Ag-Pd combination's electron donation capacity.[54] Also, granular Ag NPs can be used with other nanolaminar particles such as MoS_2 or graphene to boost lubrication efficiency by acting against the nanosheets' shear restacking.[55,56] Besides, Ag NPs enhanced the MoS_2's ultra-high temperature (>450°C) lubrication efficiency.[56] This composite feature can significantly benefit from the elevated temperatures during electric motor bearing operations. Only a few studies have been

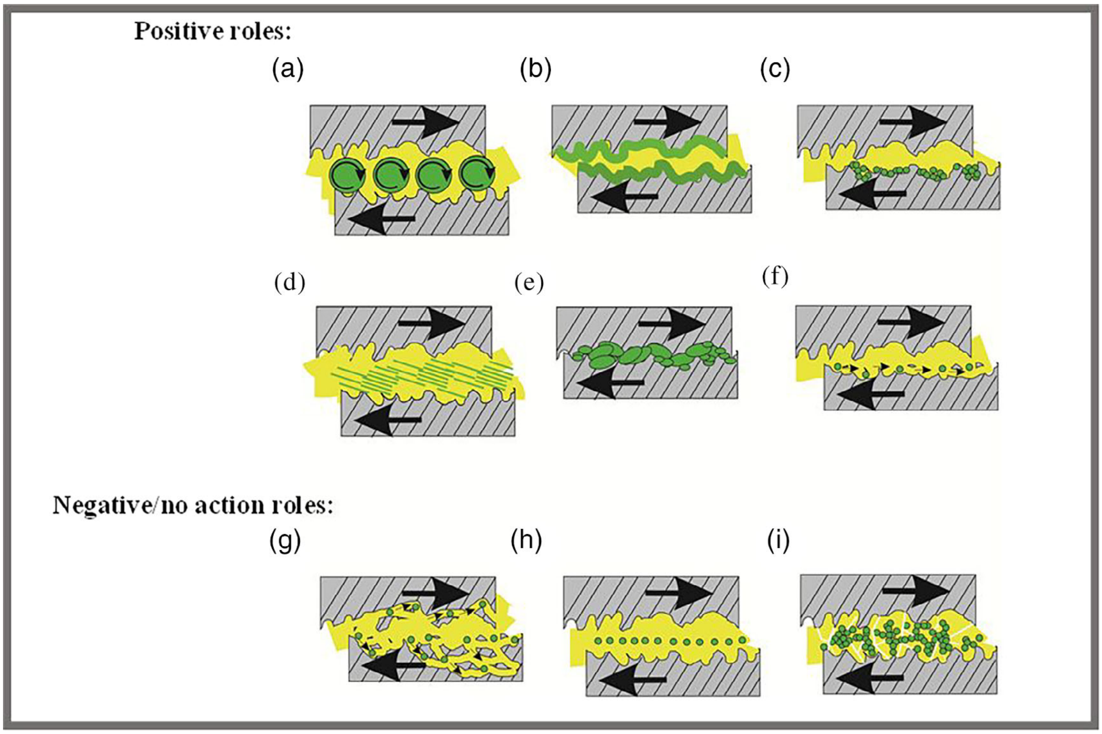

FIGURE 2 Schematic depiction of tribological roles for NPs in lubrication greases, conceptualised from literature results: (a) rolling, (b) protective film formation, (c) mending, (d) sliding and shearing, (e) sintering onto surfaces, (f) polishing and smoothing, (g) heavy abrasion on the surface, (h) no tribo-interaction, (i) NPs agglomeration at high concentrations and the destruction of grease's structure

presented in investigating the use of nanocomposites in greases.[44,51,57] For instance, He et al. demonstrated that composite grease based on ZnO-Si_3N_4 NPs has excellent potential for vibration reduction and temperature rise in high-speed bearings (55 000 rpm), coupled with excellent properties of lubrication and antifriction.[58]

Another aspect of incorporating NPs as additives is their impact on grease's microstructure and rheological behaviour, but firstly, it is better to classify grease lubrication phases to comprehend the possible role of NPs. It is possible to classify the grease lubricating phases into two stages, based on the film thickness.[59] The initial phase, referred to as the "churning" phase, is a lubricant redistribution phase that relies primarily on the grease rheology and bearing geometry and characteristics. The churning phase is a fully flooded state where the dominant phenomenon is frictional viscous heating. Churning is the shortest phase compared to the second phase of bearing operation since the quantity of grease in the bearing raceways would be decreased due to the grease shift to the sides of the raceway.[15] The second phase, recognised as "bleeding," is accountable for most of the lubrication during the lifetime of the bearing and is characterised by the discharge of base oil from the thickener structure so that the mixture of base oil and thickener perform its action in the rubbing zone.[60] NPs role in the churning phase can be considered on the downside, as NPs tends to increase the viscosity of the grease with considerable proportions that can be equal to or greater than 50%,[57,61] contribute to the power losses in the friction drag and magnification in the friction torque required for rotation.

In the bleeding phase, the lubrication mechanism is governed by starvation, which indicates the balance between supply and loss processes of the lubricant in the contact zone that will govern the thickness of the Elasto-Hydrodynamic Lubrication (EHL) film. However, with the prolonged operation, the thickness of the EHL film and the lubricant loss becomes so extreme at some point in time that the boundary regime dominates and metal-to-metal contact can occur, leading to bearing failure.[62] The degradation rate of EHL film could accelerate within EVs lubrication conditions and in this case, NPs positive contribution to viscosity and shear stress can extend the EHL operation. Furthermore, NPs can interact with the grease's microstructure and elevate its dropping point,[61] resulting in a significant gain during these conditions. Nevertheless, the presence of NPs in relatively high concentrations can cause the bonds between grease fibres to break due to NPs agglomeration, resulting in deterioration in the grease's performance (Figure 2a).[51] This effect is highly probable as a combination of Van der Waals and capillary forces holds up the base oil within the thickener structure,[63] and the presence of NPs that usually contain active functional groups can interfere with these bonding forces' effectiveness. This effect is not only limited to NPs; according to Gow, 90% of all conventional AW and EP additives disrupt the thickener structure of grease because they are mainly formalised from surface-active materials, contributing to what is widely referred to as the mayonnaise effect (softening and de-colouring).[64] He also indicates that the remaining 10% do not perform well as AW and EP due to the polar nature of additives, which will adhere to the polar (metallic soaps) soap structure rather than to the metal surface.[20]

On the other extreme, at the prevalence of boundary conditions, NPs can demonstrate direct tribo-role as discussed earlier, since its effectiveness to act as AW, AF and even extreme EP additives rely on the presence of boundary lubrication. Nevertheless, care must be taken as excessive concentration and or non- surface-compatible NPs can result in heavy abrasive action (Figure 2g).[65]

EVs have short-range mileage, which makes them the ideal vehicle to use in urban areas. However, urban driving requires slow or medium speed operation, and these ranges require a great deal of torque that can reach up to 125 Nm.[66] Additionally, EV's electric motor can provide constant maximum torque from zero to base.[67] Therefore, it is safe to postulate that EVs lubrication conditions will always suffer from harsher conditions than ICE, and NPs can play a considerable beneficial role.

3 | NPS ELECTRICAL COMPONENTS COMPATIBILITY

3.1 | Lubrication challenges in the electrical environment

In addition to friction-reducing and anti-wear function, lubricants play a crucial role in electro-mechanical system operation, such as preventing corona discharge and arc absorbance, making the lubricant's electrical properties of particular importance.[68,69] In a number of EVs' components such as bearings, seals, pads and gears, the induced shaft voltages and currents can cause premature failure problems and can also cause electromagnetic interference (EMI) and radio frequency interference problems that make the motor unstable.[70–72] These complications can lead to bearing instability, vibration, noise and more extreme mechanical failures.[73,74] Additionally, studies have shown that the use of frequency inverters to control inverter-fed electrical motors and generators of variable speed creates harm to the rolling bearings as bearing currents can cause a detrimental effect.[24,75] Dependent on the composition and electrical and rheological properties of the lubricant, these currents that arise show different characteristics on the smoothness of operation.[76] These currents discharge happen through the bearing balls and raceways, causing significant energy dispersion and electrical wear within a split second.

Electrical wear or electrical tribo-failure stem from a dissymmetrical effect when voltage differences are created between the shaft and the bearing housing, current passes through the fragile lubricating film. The current causes sparks, arcing and melting of the bearing.[77] According to these currents' intensity, frequency and duration, frequent electrical wear is classified into surface frosting, fluting, pitting, spark tracks and welding.[78–80]

However, electro-lubricants interactions must be considered as an additional cause for tribo-failure. While nonpolar oil-based lubricants are generally chemically inert, the potential and energy needed for their chemical reactions is given by shaft voltage and bearing current, accelerating the oil degradation process.[81] This process occurs when the free radicals formed in oil by electrical excitation react to form peroxide groups with oxygen, which in turn will cause the formation of new radical groups and such a chain reaction will gradually form products containing carboxyl.[82] The final degraded oil lubricant will be in the form of highly viscous and acidic degradation products and additive agglomeration, in which case oil lubricity is lost.[81] Moreover, the electric field induces interfacial stress in the case of polar lubricants, such as water-based lubricants, confined between two metallic surfaces affecting its wetting properties, which may result in an alternation in its lubrication action.[83] Furthermore, electrostatic forces on interfacial tension of microbubbles in polar lubricants are affected and can transform to vulnerable points for electrical breakdown.[84] Besides, the evaporation of the lubricant component, which is believed to be the key reason for the grease failure of cylindrical roller bearings, may also have been induced by the thermal effect of the undesired electrical discharge process.[85] Additionally, an assumption can be made on the occurrence of lubricant's additives (AF, AW and EP) chemo-physical surface absorption and reaction shifts under the influence of an external electric field, resulting in a variation of lubrication behaviour.

Naturally, nonpolar lubricants have inherited high electrical resistance that can act as superior insulating agents in the 800 V EVs, with minimal 25KV breakdown voltage.[86] This property is true for the most common lubricants as the ester-based oils' dielectric strength is comparable to mineral oil. However, ester-based oils' dielectric values have a greater coefficient of variance, suggesting its unpredictability and potentially a higher likelihood of oil breaking down at lower voltages.[86] Nevertheless, breakdown voltage decreases dramatically for mineral oil with the rise in water content and contaminants.[86] This electrical resistivity depends on a fully formed lubricating film between the rubbed pairs, which is not always the case in high torque conditions of EVs operation and metal-to-metal contact is almost always inevitable.[62]

Another possibility of facing harmful electrical discharges challenge is the utilisation of high conductivity lubricants that can prevent the build-up of high potential discharges bypassing the currents safely between the parts. In this technique, ionic liquids (ILs) come in as a first choice. As a lubricant additive, ILs can effectively improve wear resistance and lower lubricant components' conductivity.[87] In general, ILs consist of an organic cation, usually containing nitrogen or phosphorus, and an anion that is weakly coordinated. Imidazolium, phosphonium, pyridinium and ammonium are some of the most common cations, while some common anions are BF_4, PF_6, CF_3SO_3 and $N(CF_3SO_2)$.[88] ILs do not emit volatile organic compounds, rendering them "green" lubricants. However, possible drawbacks to ILs as lubricants are their corrosive nature to the substrate and the formation of flammable or harmful by-products when decomposed.[89]

Another radical solution can depend on utilising different construction insulating materials, such as ceramic sheeting, on the bearing to block the high-frequency current.[90] However, an insulated bearing reduces the heat flow dissipation from the rotor, which can result in severe mechanical failure due to thermal shocks at high rpm.[91] Therefore, another engineered solution must be devised in which NPs can participate in solving this obstacle.

3.2 | NPs as anti-electro-discharge additives

It is essential to choose the functional purpose of NPs when formulating a lubricant that works under electrically charged conditions. This essentiality comes from the fact that NPs working as AEDA play two contradictory roles. One route for NPs functionality is to increase the insulation properties of the oil-based lubricants. In this case, elevating lubricant's electrical resistance and dielectric strength are directly proportional to the threshold voltage in which electrical discharge with destructive currents can occur,[92] thus increasing the tribo-protection.

On the other hand, NPs can be employed to increase the lubricants' electrical conductivity to conduct the electric current so that point-to-point flashovers are eradicated and no build-up for electrical potential occurs. This effect has been proven as fluting can be prevented by high conductive greases.[93]

Tribological studies of NPs as AEDA in literature are still scars as the importance of electro-mechanical lubrication is just on the rise alongside modern applications like EVs tribological designs. Nevertheless, Ge et al. have shown that when applying oleophilic nano-TiO_2 and nano-SiO_2 as additives in oil-based grease, the alternating current (AC) breakdown strength increases by 10.4% and 8.2% at power frequency, respectively.[94] Additionally, when the additives in naphthenic oil are 0.1%, the grease volume resistivities are also enhanced by 23% and 30% compared to base grease. Figure 3a, shows the greases' volume resistivity; as the content of nano-TiO_2 and nano-SiO_2 increases, the volume resistivity escalates. However, an inverse pattern is observed in the case of Sb doped SnO_2 (ATO).

The study explains this insulating behaviour of NPs with the principle of electron capture, as illustrated in Figure 3b. This principle relies on incorporating electrons with oil molecules by polarising them and forming a group that will float for a short period under the local electric field's influence. Then in a trap manner, the capture and release of electrons due to the groups splitting and reforming results in slow electrons passage in the base matrix and eventually contribute to the slow development of the electrical channel.[95,96] Li et al. have also indicated that the electron trap and release mechanisms are function of size as nanometric particles are more efficient than micrometric ones.[96] This drawback of microparticles is due to the defects they impart within the matrix allowing electrons to float effortlessly, which leads to a reduction in the base matrix's breakdown strength and volume resistivity.[97]

In another dry friction study, Guo et al. studied Al_2O_3/Cu composites (1.0 vol%) reinforced with different sizes of αAl_2O_3 particles on an electrical sliding wear test.[98] The results show that Al_2O_3/Cu composites' wear rates have a reverse variation with the composite hardness of Al_2O_3/Cu, and the composite electrical conductivity decreases with the NPs size increment. The highest wear resistance properties are in the 50–100 nm range of αAl_2O_3 NPs, which corresponds to relatively high electrical conductivity and high hardness. The wear mechanisms are due to a combination of adhesive wear, plastic deformation accompanied by arc damage.

In the alternative approach that depends on electrical conductivity reduction, Christensen et al. have utilised carbon nanotubes (CNTs) as lowering electrical resistivity additive.[99] The study showcased that the addition of hydroxyl functionalized multiwall carbon nanotubes (MWCNT-OH) in both oil-based and water-based lubricants can result in an extremely low electrical resistivity, as shown in Figure 4a. This low resistivity is attributed to the functionalization of MWCNT with hydroxyl groups as resistivity drops to 22.4 Ω·cm with 7.5%wt of the additive in oil-based grease in contrast to the resistivity of an equivalent sample made with MWCNT of 7880 Ω cm. In a water-based grease sample formed from 75% glycerol, 25% water and 4.5%wt of MWNT-OH, the resistivity measured plummeted ton10.0 Ω cm. The study suggests this electric conductivity improvement is due to hydrogen bonding into the grease of any form, easing electrons movement.

The later water-based grease can be advantageous in EV's electrical motor lubrication due to its low viscosity nature compared to oil bases. However, as the study highlights, such high-load nanotube grease with low electrical conductivity will present a problem for commercial applications. A highly conductive grease with a lower carbon loading that can have the same or better efficiency would benefit several respects, including a more favourable viscosity and improved cost savings. Additionally, such densely surface-functionalized NPs can negatively affect the grease's structure as discussed earlier in NPs tribological role in the greases section.

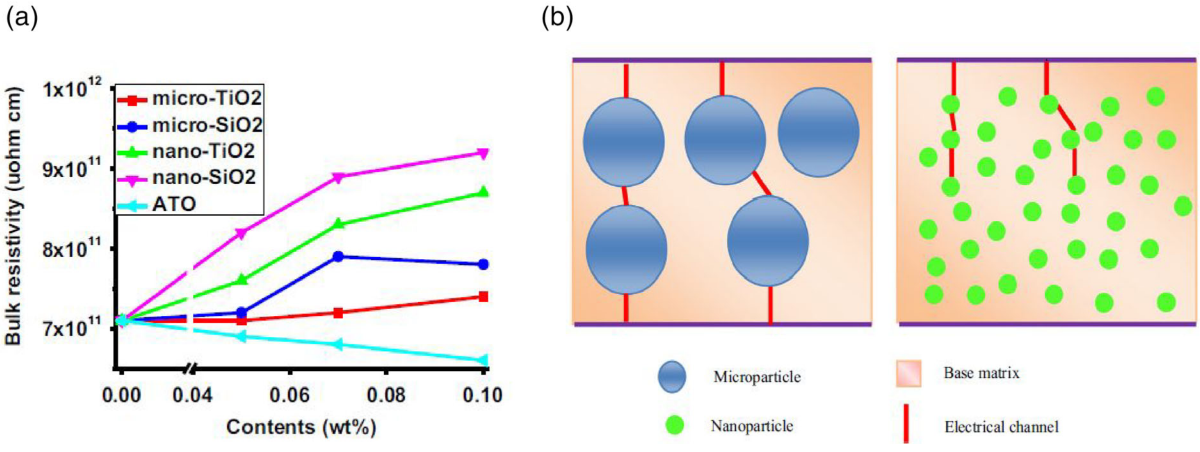

FIGURE 3 (a) Volume resistivity of greases with varying weight concentrations of micro/nano TiO_2, SiO_2, and ATO, (b) the insulating mechanism of the base matrix nanoparticle and microparticles, reproduced with authors permission and copyrights holder of Ref. 94

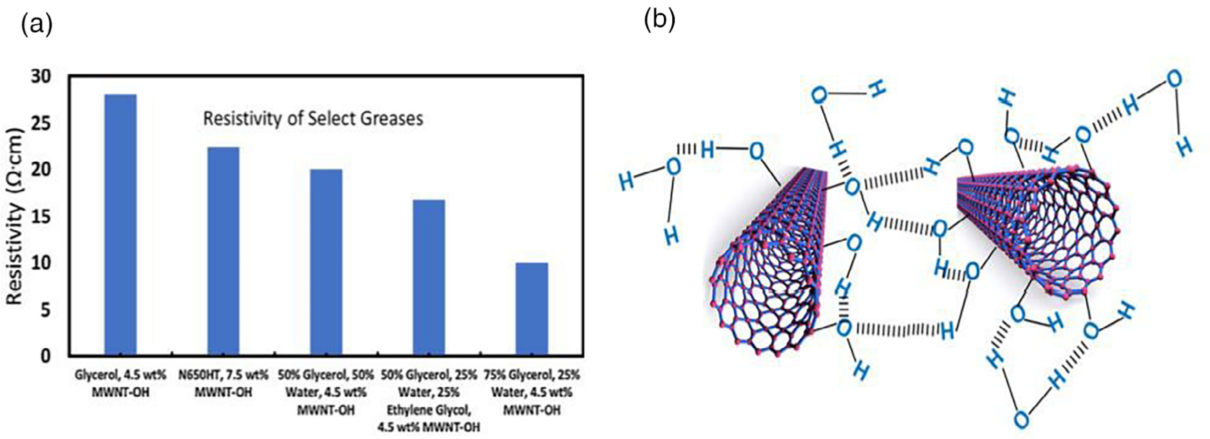

FIGURE 4 (a) Resistivity of diverse samples of grease, (b) hydrogen bonding schematic between CNT-OH and a water molecule, reproduced with authors permission and copyrights holder of Ref. 99

4 | NPS IN LOW-VISCOSITY LUBRICANTS

Low-viscosity lubricants and greases are desired for EVs' energy efficiency improvements, as the electrical power economy is crucial for the manufacturers. This correlation stems from the ability to diminish the torque required for an EV operation by lowering the lubricant's viscosity, as reducing the base oil viscosity is the most obvious way to decrease viscous friction. Additionally, a fluid's ability to remove heat from e-motors and electrical devices is of great significance. This capability is related to characteristics such as thermal conductivity of fluids and fluid density, and most importantly, viscosity. A base oil with low viscosity has a higher fluidity that facilitates oil supply to the contact zone,[100] which facilitates heat removal and reduction in viscous heating in case of high EV's rpm.

However, there is a significant trade-off in reducing the lubricant viscosity, which results in thin oil films that contribute to increased sliding surface wear rate and contact of asperities.[101] Furthermore, this decreased film thickness raises the operating temperature due to frequent surface contact and decreases the bearings' estimated fatigue life.[102] Additionally, reducing oil viscosity contributes to decreased oil's load-carrying capacity.[103] The increased frequency and intensity of mixed and boundary contact conditions with low-viscosity lubricants mandate the utilisation of AF, AW and EP additives as a practical solution. Some of the conventional additives commonly found in fully formulated oils working in such conditions are typically based on key organic compounds, including sulfurized olefins such as sulfurized isobutylene or dialkyl pentasulfide and phosphorus-containing compounds such as tricresyl phosphate.[104,105] However, these additives are poisonous and contain non-environmentally friendly precursors chemicals with cost-intensive synthesis. In general, this transition from full film to boundary lubrication can give rise to the importance of NPs as additives as an alternative solution for the industry while moving towards low-viscosity lubricants.

Usually, base oils have a viscosity range of 20–500 cSt at 40°C. However, as this literature scan is focused on the utilisation of NPs in the lower range from this viscosity spectrum, 100 cSt at 40°C is selected as the threshold for high temperature and high shear (HTHS), (Table 2). This pre-condition is satisfied by synthetic high-performance gear oils based on PAO as considered to be tried-and-tested lubricants. Additionally, a thorough discussion is performed on the utilisation of NPs in hydro lubricants, being one of the future promising lubricants.

4.1 | NPs in synthetic oil lubricants (PAO)

PAOs are commonly used in many industrial fields, such as automotive engine oil, vehicle gear oil, automotive automatic transmission fluid, industrial gear oil and compressor oil. They have a superior operating temperature range due to their high viscosity index, good oxidation stability, shear stability and low corrosion efficiency.[106] Additionally, PAO lubricants with a viscosity of 32 cSt at 40°C have shown superior performance in process pumps and their electric motor drivers.[107] However, due to the downsides of low viscosity lubricants, researchers are trying to improve their performance by dispersing NPs into them.

The addition of the MoS_2 nanotubes to the base PAO oil was examined by Kalin et al., resulting in a substantial

TABLE 2 Literature scan on the ability of NPs in reducing wear scar diameter (WSD) and friction coefficient (COF) in different low viscosity lubricants

Type of NPs	Size	Type of base oil	Viscosity @ 40°C (cSt)	Reduction CoF	Reduction WSD	Mechanism	References
Al_2O_3 TiO_2	8–12 nm 10 nm	PAO	54	50%	30%	Protective film	109
MoS_2 (NTs)	D (100–500 nm), L (NA)	PAO	30	50%	80%	Exfoliation of nano-sheets from nanotubes under shear stress and protective film.	108
Ni	20 nm	PAO	31	30%	45%	NA	106
CDs	2.2–3.5 nm	PAO	46	30%	60%	Protective film	110
Cu (C coated)	25 nm	PAO	31	29%	No effect	Rolling	111
ZnO	20 nm	PAO	31	NA	36%	Protective film	112
CuS	4 nm	Water	NR	78.3%	93.7%	Protective film	127
Cu	3 ± 1 nm	Water	NR	42%	17%	Protective film	128
TiO_2	20 nm	Water	NR	70.5%	84.3%	Protective film and rolling	123
GO	30–60 nm	Water	NR	60%	62% (WR)	Protective film	129
OLC	30–60 nm	Water	NR	50%	25% (WR)	Rolling	
CNC	50 nm	Water	NR	75%	50%	Protective film and rolling	130
Al_2O_3	83–1061 nm	Water	NR	50%	12%	NA	131
MWCNTs-g PAM	D (60–80 nm), L (NA)	Water	NR	45%	30%	Rolling	107

Note: Besides, an indication of the different tribological mechanisms played by NPs. The blue highlighted rows signify the utilisation of NPs as mixtures to form composites.

Abbreviations: C coated, carbon-coated; CDs, carbon quantum dots; GO, graphene oxide; MWCNTs-g PAM, multi-wall carbon nanotubes grafted with polyacrylamide; NR, not relevant; OLC, onion-like carbon; WR, wear rate.

improvement in friction and wear behaviour under boundary lubrication conditions.[108] The CoF was reduced by more than two times, while the wear was reduced by five-nine times as much. In the observed period, the use of nanotubes nearly completely removed any abrasion or deformation of the surfaces. The mechanism assigned by the author is related to the surface adhesion of thin MoS_2 nano-sheets, described in several steps, as shown in Figure 5.

Chou et al.[106] studied the impact of introducing Ni NPs (20 nm) on the tribological activity of synthetic oil (PAO6). The reduction in friction occurred between 7% and 30%, and wear fell between 5% and 45%. Regarding PAO6, the PAO6 + 0.5%wt Ni suspension displayed the highest friction and wear reduction. Additionally, for all examined suspensions, the load-wear index is greater than that of the base oil, with increases between 3.4% and 30.8%. In another study, Ali et al. examined the suspension of Al_2O_3, TiO_2 and Al_2O_3/TiO_2 hybrid NPs in commercially available engine oil (5 W-30) based on PAO for formulating nanolubricants at a concentration of 0.25 wt%.[109] Low kinematic viscosity and a 2% increase in the viscosity index were observed when adding NPs to the base oil. Tribological tests showed a 40%–50% and 20%–30% reduction in CoF and wear rate of the ring, respectively. The decrease in viscosity may be due to the presence of NPs between the layers of lube oil, facilitating the relative movement between the layers of nanolubricants.

Carbon quantum dots (CDs) were obtained directly from methyltrioctylammonium chloride by Chimeno-Trinchet et al., which proved to be a good candidate as an additive in synthetic base oils.[110] Adding 0.1% wt/vol of CDs in harsh lubrication regimes decreased CoF by approximately 30% and WSD by more than 60% even under the most extreme conditions tested (120 N). Alternatively, Viesca et al. analysed the effect on the tribological activity of PAO6 of the addition of 25 nm carbon-

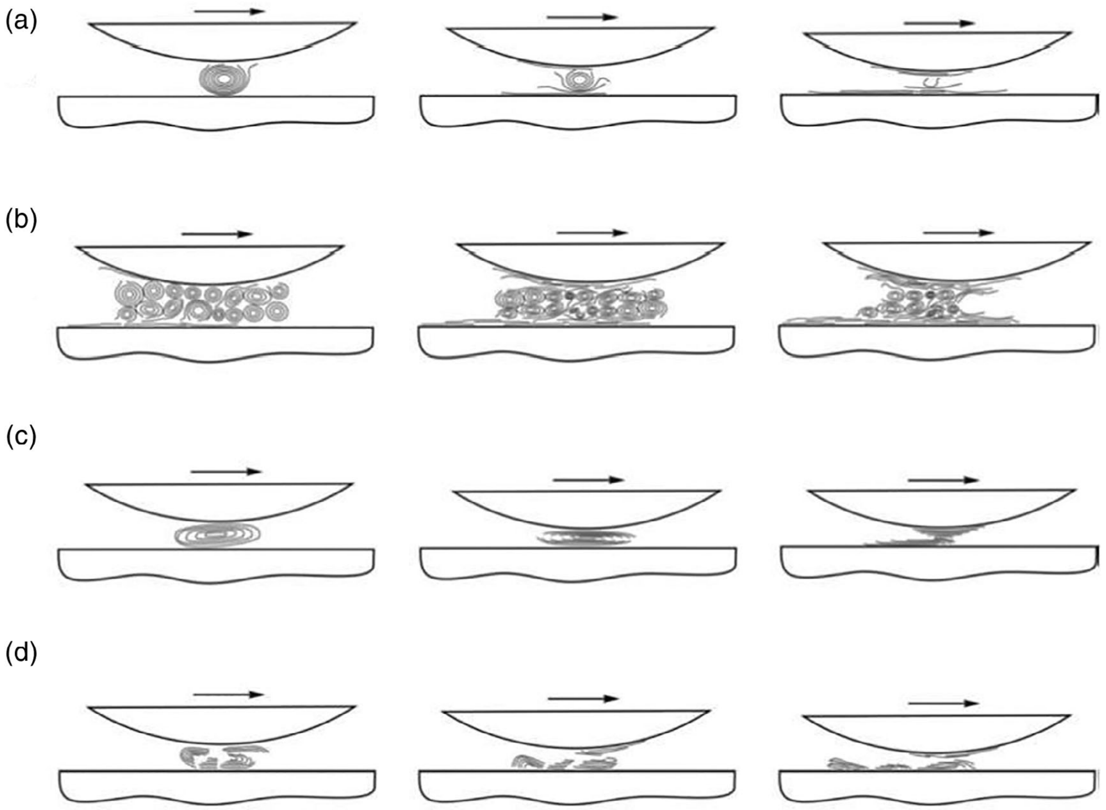

FIGURE 5 Schematic presentation of the various mechanical routes for the exfoliation process: (a) individual exfoliation of nanotubes; (b) exfoliation of aggregate nano-sheets; (c) exfoliation of nanotubes; (d) breaking of nanotubes and exfoliation of smaller, broken multi-wall pieces. The sliding direction is shown by the arrows, reproduced with authors permission and copyrights holder of Ref. 108

coated copper (Cu C_{coated}) NPs and contrasted this behaviour with the case of non-coated copper NPs, evaluating the impact of the coating.[111] The results showed that all suspensions decreased wear under mixed lubrication between 10% and 50% for PAO6. Moreover, under extreme pressure conditions, the load-wear index for all suspensions examined is higher than that of the base oil, with increases between 7% and 29%. This tribological enhancement is due to the deposition on the rubbing surfaces of NPs and possibly through their function as small bearings. The copper NPs coated with carbon did not behave better than the non-coated ones. Battez et al. studied the tribological activity of ZnO NPs as an additive in PAO6 and the effect of commercial stabilising agent dispersing agents (OL100 and OL300).[112] The findings showed that the best EP activity with 36% wear reduction was shown by PAO6 + 3% OL300 + 0.3% ZnO.

Regarding tribological behaviours of NPs as a function of viscosity in different lubrication conditions, it was found that, when the viscosity of raw oil was low under high normal load conditions, the addition of NPs additives to lubricant was more effective.[113] Contradictory, the addition of NPs to lubricants increases their viscosity, as Guimarey et al. have investigated the viscosity behaviour of synthetic oils and ZrO_2 NPs-based nanolubricants.[114] The study was performed on dimethoxy end-capped poly(propylene glycol) and synthetic esters (isotridecyl trimellitate, TTM and biodegradable polymer ester, BIOE). The results show that the density increases (around 2%) as the mass concentration of ZrO_2 NPs increases. The same happens with the viscosity of nanolubricants; however, lubricants based on isotridecyl trimellitate ester have higher increments of up to 8%. Furthermore, the decrease in particle size increases the viscosity of the fluid.[115] This behaviour was also confirmed by Sui et al. as the viscosity activity of silica NPs as lubricant additives have been affected by both functional groups and particle size.[116]

Another aspect that must be considered is NPs interactions with the relatively high polarity of ester base oils in contrast to mineral oils.[117] The polar nature of these base stocks is correlated with NPs detrimental effects on the lubrication process.[118] The unfavourable polar compound effects are connected to the fact that the polar molecules will also attract metallic NPs,[118,119] covering them with an oil film that prevents their ball-bearing role and deposition. This hurdle can be overcome by surface functionalization of NPs with non-polar compounds to minimise these interactions.

Most NPs are metal-based and are predominantly hydrophilic and hence unstable in organic media, which eventually contributes to aggregation/ sedimentation and the loss of desired properties. Therefore, the efficient use of NPs must resolve problems such as the stability of dispersion and abrasiveness.[120] Furthermore, nanolubricants performance is a function in the aging and sedimentation process. Although there are no specific studies conducted on the matter, many studies have linked the good performance of NPs with many factors, such as the method of stabilisation and concentration utilised.[121,122]

4.2 | NPs in hydro lubricants

Water is a good choice for lubricants' raw material when considering a product that can keep up with general and industry-specific challenges: globally abundant, non-toxic and non-flammable. However, hydro lubricants have many tribological limitations. These limitations include extremely low viscosity, evaporation, freezing points, microbiological growth, oxidation, corrosion and high electrical conductivity. Water-based lubricants consisting of less than 5% additives may give many advantages compared to traditional oil and grease lubricants, such as high thermal conductivity and oil cost savings.[123] Recent research has been dedicated to using different NPs as nanoadditives dispersed in water in order to enhance the lubrication capacity of water.[124–126]

Via modifying CuS NPs with Bis (2-hydroxyethyl) dithiocarbamic acid (HDA), Zhao et al. prepared water-soluble CuS NPs as water-based lubricant additives.[127] The results show that HDA-CuS NPs, as prepared, can effectively increase the tribological behaviour and thermal conductivity coefficient of distilled water. The CoF and wear rate are decreased by 78.3% and 93.7%, respectively and thermal coefficient enhancement of 3% with a concentration of only 0.8 wt%. It was found that, during the friction process, a complex lubricating film was created on the surface of the friction pairs. A different study on Cu NPs capped by methoxylpolyethyleneglycol xanthate, formulated by Zhang et al., used as an additive in distilled water.[128] The load-caring capacity value can be increased from 88 N of distilled water to 696 N by adding 5%wt of these modified NPs. This increment is due to the formation of boundary lubrication film composed of Cu, FeS and $FeSO_4$ on the rubbed steel surface.

Wu et al. investigated the tribological efficiency of water-based NPs using TiO_2 NPs in the presence of sodium-dodecyl-benzene-sulfonate (SDBS) and glycerol, exhibiting outstanding dispersion stability and wettability.[129] In contrast to pure water, the water-based nanolubricant containing 4 wt% TiO_2 and 0.4 wt% of SDBS showed superior tribological efficiency by minimising friction and ball wear coefficients by up to 70.5% and 84.3%, respectively. The lubrication mechanisms were primarily attributed to the TiO_2 NPs' lubricating film formation and ball-bearing effect.

Su et al. have investigated the lubricating performance of graphene oxide (GO) nano-sheets and onion-like (OLC) as lubricant additives in water.[124] Also, the effects of sandblasting of a steel disc were evaluated on the tribological behaviour. The results show that, when used as lubricant additives in the water, the two nanomaterials, GO and OLC, effectively reduce the friction and wear of sliding discs, which is independent of the treatment of the disc surface. It is noted that GO exhibits superior friction-reducing and antiwear capabilities when applying heavy loads compared to OLC. A trace amount of GO can achieve a lubricating capacity equivalent to an abundant OLC amount. OLC's friction-reduction and antiwear capabilities in water can be due to its onion-like structure that induces rolling action and tribofilm formation during the process of sliding. The GO's excellent lubricating ability was due to the forming on the contact surfaces of thin protective films and its 2D structure providing better shear and slipping between the two surfaces of mating wear.

The use of cellulose nanocrystals (CNC) as additives in water-based lubricants was investigated by Shariatzadeh, Mohammad Javad and Dana Grecov.[130] It was found that the addition of 2 wt% of CNC in water improved lubrication and provided a very low CoF of approximately 0.09. The wear depth and width can reduce by more than 50%. The enhancement of the friction and wear coefficient was primarily due to the high strength and alignment of CNC rods.

The effect of alumina NPs (Al_2O_3) suspended in an aqueous acetate buffer solution was studied by Radice et al. by adding 10% volume of Al_2O_3 NPs to an acetate buffer solution. It was possible to minimise CoF by a factor of 2 and the wear of stainless steel by a factor of 10.[131] Solutions containing either sedimented NPs or larger-sized Al_2O_3 particles were less effective than stable suspensions in reducing wear and friction. Multi-walled carbon nanotubes grafted with polyacrylamide (MWCNTs-g PAM), soluble in polar solvents such as water, tetrahydrofuran and acetone, were formed by Pei et al. The results indicated that the composites exhibit strong antiwear and friction reduction properties as well as load-carrying capacity. This merit was due to the likelihood that the composites would behave during lubrication as nano-meter-sized small bearings.[123]

In the case of hydro lubrication, pH can also play a role in the tribological behaviour as He et al. illustrated that the flexible and large GO sheets were broken down and reduced chemically when the pH increased from 3.1 to 9.7.[125] Besides, by using the 0.06 wt% GO suspension, noise and vibration were removed in tribological studies, while COF and WSD were decreased by 44.4% and 17.1% relative to baseline water, respectively. While the pH increases of the GO suspensions substantially increased COF and wear. These different results under elevating pH were due to variation in the GO sheets' morphological and physicochemical properties.

The main challenge of utilising NPs as nanoadditive in hydro lubricants is their poor dispersibility, which is similar to oil-based.[126] Although efforts were made to decrease NPs high activity on the surface and avoid aggregation, problems, such as avoiding water evaporation, which changes the lubricant's concentration, are still to be solved.[132]

5 | THERMAL MANAGEMENT CHALLENGES IN EVS

Electric motors are designed to be lightweight, with higher rotational speeds to save space which results in superior performance as an EV can travel equal to or more distance than a traditional vehicle can travel with a full tank. Such agile design philosophies are referred to as in-wheel setup, in which wheels are directly mounted by the driving motor, which has the advantages of improving driving efficiency by maximising mass distribution and improving the degree of freedom in terms of vehicle layout and design.[133] However, as mentioned, such structures are carried out in a limited space in which such systems need effective cooling to achieve proper miniaturisation and high-power output and durability.[134,135] Studies on the thermal effects of electric motors in EVs have shown that motor heat generation reduces range, charging, longevity and endangers its safe operation.[136,137] Furthermore, knowing that EV's lithium batteries' operating temperature ranges from −40 to 84°C,[66] and the heat generated from the motor can reach up to 221°C while the requirements for motor control restrict the maximum temperature to 150°C,[138] heat management gains significant importance.

Depending on the operating conditions, the driving motors for EVs have different cooling modes: oil,[139] air,[135,140] and water.[141] Based on the capability of the motor, the most appropriate mode is selected. While air-cooled mode has the advantage of a simple cooling system design for its cooling capacity, it is relatively limited, making it challenging to apply to a miniaturised high-capacity motor. The oil-cooled mode typically has a lower cooling power than the water-cooled model; however, it has simultaneously cooling and lubricating effects.

Today's EVs run at about 20 000 rpm, and it is expected that the next generation speed to exceed 30 000 rpm.[142] This increase in speed will result in excessive heat generation; therefore, the current lubricant cooling capacities need to be improved accordingly. In that sense, nanolubricants can play a significant role in adapting to these new challenges.

5.1 | Heat transfer mechanisms in nanofluids

Almost before 150 years, Maxwell's mixture states theory suggested that the suspension of solid particles in a liquid would significantly increase this liquid's effective thermal conductivity (k).[143] Following these, researchers used millimetre or micrometre particles dispersed in traditional heat transfer fluids in early studies.[144] Even though these dispersions' thermal conductivity had increased, the practical application was hindered by stability and particles sedimentation. However, nano-sized particles have shown superior stability and heat transfer performance compared to that of larger dimensions. This phenomenon is evident in many experimental studies that have been carried out on heat transfer of nanofluids.[145–147] Additionally, the studies have indicated that nanofluids' heat transfer is more than that calculated by the theoretical predictions.[148–150] This abnormality can be explained by the unfathomable large specific surface areas some of these NPs have, such as graphene that can have a specific surface area up to 2600 m^2/g,[151] coupled with its outstanding thermal conductivity of roughly 5200 W/mK.[152]

The thermal improvement imposed by NPs dispersed into a base fluid can be classified into three main mechanisms as illustrated by Figure 6, which can be summarised by:

1. Enhanced liquid molecules organisation at NPs/liquid interface: Choi et al. first observed this phenomenon when they produced suspensions of nanotubes-in-oil and measured their thermal properties.[153] With nanotube loadings, the measured thermal conductivity is anomalously more superb than theoretical predictions and is non-linear. For solid/liquid suspensions, the anomalous phenomena demonstrate the fundamental limits of conventional heat conduction models. The nature of heat conduction in nanotube suspensions and an organised structure at the solid/liquid interface interprets this enhanced thermal conductivity as two

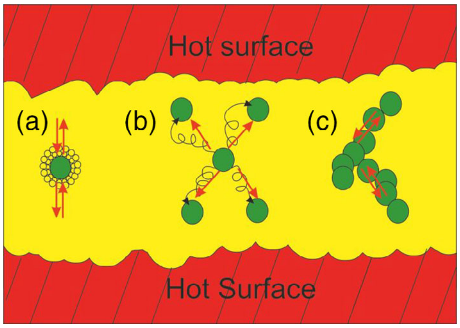

FIGURE 6 Illustration graph about the suggested mechanisms of heat transfer induced by NPs in nanofluid, (a) enhanced liquid molecules organisation at NPs/liquid interface, (b) NPs Brownian motion, and (c) agglomeration of NPs

consequences of nanotubes' presence in the liquid. Thus, it was hypothesized that such ordered liquid molecules could link through the interface to generate more efficient thermal transport.[154,155]

2. Brownian motion: Because of the surrounding liquid molecules' random collisions. It is expected that Brownian motion-induced particle collisions will increase heat transport between particle diffusion modes and thus increase the nanofluids' thermal conductivity.[156,157] The particles' Brownian motion can lead to convection of the surrounding base fluid and increase thermal conductivity.[158]
3. Agglomeration of NPs: Suspended NPs, driven by their high surface energy, is forced to attract each other.[159] Since cluster structures allow more heat to be transported along the heat flux path, the heat conduction could be increased.[160] The conventional effective medium theory predicts the nanofluid has a more excellent thermal conductivity in these aggregates.[161,162]

5.2 | Factors affecting thermal conductivity in nanofluids

Various studies have shown that the enhancement in different nanofluids' thermal conductivity relies on NP's concentration,[163–166] size,[160,167] morphology,[168] base fluid nature,[169,170] and temperature.[171,172] Regarding NPs concentration in the base fluid, it seems that k increases with the addition of NPs in a linear manner.[164,165,173] However, non-linear increases in thermal conductivity with NP volume fraction have also been reported.[174] While the NPs size seems inversely proportional to k as decreasing the grain size, the heat transfer coefficient increases.[166] This inverse proportionality was confirmed by Liu Kan, when investigating the impact of Cu NPs having a grain size of 25, 40–60 and 60–80 nm dispersed into PAO on heat transfer rate. [175] The results showed that the smallest particle size (25 nm) had the highest heat transfer increase. Nevertheless, this behaviour is not always consistent, as smaller particles are expected to be more efficient. This phenomenon was confirmed as clusters formed in a uniform distribution due to aggregation of particles have also been found to enhance k of nanofluids better than individual NPs.[160]

Moreover, the morphology of NPs can be a factor in nanofluid performance as Jeong et al. studied the ZnO nanofluids' thermal conductivity, which increased for the spherical and semi-rectangular shaped NPs by up to 12% and 18% at 5.0 vol%, compared to that of the water, respectively.[168] In another study conducted by Cui et al. comparing spherical and cylindrical Cu NPs, it was found that cylindrical NPs outperformed spherical NPs in the air with k enhancement of 20% and 14%, respectively, in the air,[176] attributed to the enhanced cylindrical shape micro-convection from rotational motion, increasing thermal conductivity.

A promising alternative concept to enhance thermal conductivity in EVs lubricants is the utilisation of nanowires dispersions. Nanowires are metallic elongated one-dimensional nanostructures with a percolated network for rapid heat conduction in a low conducting fluid. For example, Maji and Chakraborty dispersed copper nanowire powder in ethylene glycol to create nanofluids with a substantial increase in thermal conductivity (20%) at low loading (0.15 vol%).[177] In another case, Zhang et al. synthesised silver nanowires prepared by the poly-vinyl-pyrrolidone (PVP), and their nanofluid dispersions were investigated.[178] It was found that when loading 0.46 vol% silver nanowires in ethylene glycol, the thermal conductivity enhancement of nanofluids are as high as 13.42%.

Concerning base fluid nature, experimental results indicate that the Brownian motion and the convection-like action are very active in the low viscous base fluid and cause the measurable enhancement of thermal conductivity.[169] Additionally, NPs thermal conductivity improvement in PAO base fluids is higher than that of water-based fluids.[170]

In general, nanofluids temperature increment results in proportional thermal conductivity enhancement.[147,179] This pattern is due to the rising bulk temperature, which is associated with an increase in the distribution of NPs in the base fluid, which promotes the increasing Brownian motion of the NPS, therefore elevating the heat transfer of the base fluid.

In general, carbon-based nanofluids, particularly CNT, have been known to outperform all metallic and metal oxide nanofluids in thermal conductivity, as shown in Figure 7, even in small concentrations,[163,180–182] while graphene oxide outperforms pristine graphene in water base fluid due to the latter's poor stability in the polar medium.[183] Gupta et al. measured the temperature-dependence thermal conductivity of graphene nanofluid. They stated that the thermal conductivity depended on the temperature, unlike the case of CNTs nanofluid,[172] which was attributed to Hybrid Brownian Motion-percolation.

5.3 | Thermal conductivity enhancement of different NPs in different base fluids

Many scientific reports revealed the positive effects of adding different NPs, with different sizes, shapes and concentrations in a fluid in thermal conductivity improvement. Some of these studies are summarised in Table 3; for instance, the thermal conductivity of Al_2O_3 in ethylene glycol nanofluids was experimentally determined by Pastoriza-Gallego et al. as a function of volume concentration and temperature.[115] Thermal conductivity is found to increase with the concentration of NPs and temperature rise (viscosity reduction), resulting in thermal conductivity increases with improvements of up to 19%. In a different investigation, Wei, Baojie, Changjun Zou and Xiaoke Li. studied TiO_2 NPs dispersed in diathermic oil.[157] The thermal conductivity of nanofluids was tested, and the results showed that the thermal conductivity of TiO_2 nanofluids was greater than that of the base fluid. Also, there was a linear association between the change in thermal conductivity and the rise in NPs concentration. Two of the significant variables affecting the thermal conductivity of TiO_2 nanofluids are the nature of heat transfer in NPs and Brownian motion. Thermogravimetric analysis conducted by Ali, Mohamed Kamal Ahmed and Hou Xianjun, revealed that when utilising Al_2O_3/TiO_2 hybrid in reference oil (SAE 5 W-30), the oxidation initiation temperature and burnout temperature can be delayed by 54.9 and 38.7°C, respectively.[184] Additionally, compared to the reference oil, the Al_2O_3/TiO_2 nanolubricants showed an improvement in heat transfer characteristics and by 9%–14%.[184]

Liu et al. examined thermal conductivity enhancements in ethylene glycol and synthetic oil in the presence of MWCNTs.[185] The study used the volume concentration of suspensions of MWCNTs-ethylene glycol of 1.0 vol% and that of suspensions of MWCNTs -synthetic engine oil of 2.0 vol%. Thermal conductivity is increased by 12.4% for MWCNTs -ethylene glycol. On the other hand, thermal conductivity is increased by 30% for MWCNTs -synthetic engine oil suspension. Another study that utilised MWCNTs done by Ahmadi et al., it was functionalized by dodecylamine to avoid their agglomeration and precipitation in the base oil (SAE 20 W-50). It was dispersed using the planetary ball mill.[186] Thermal conductivity improved by 22.7% at a concentration of 0.5 wt% of MWCNTs. This shift can be attributed to the improved stability in the base oil bulk phase induced by fictionalisation. However, the rise in nanoadditive concentrations due to agglomeration and nanotubes precipitation has decreased the oil's lubricating properties. Asadi assessed the Al_2O_3/MWCNT combination in engine oil nanolubricant heat transfer efficiency over various temperatures (25–50°C) and NPs ratios (0.125%–1.5%).[187] The thermal conductivity with the temperature and solid concentration increased to 10% compared to pure oil.

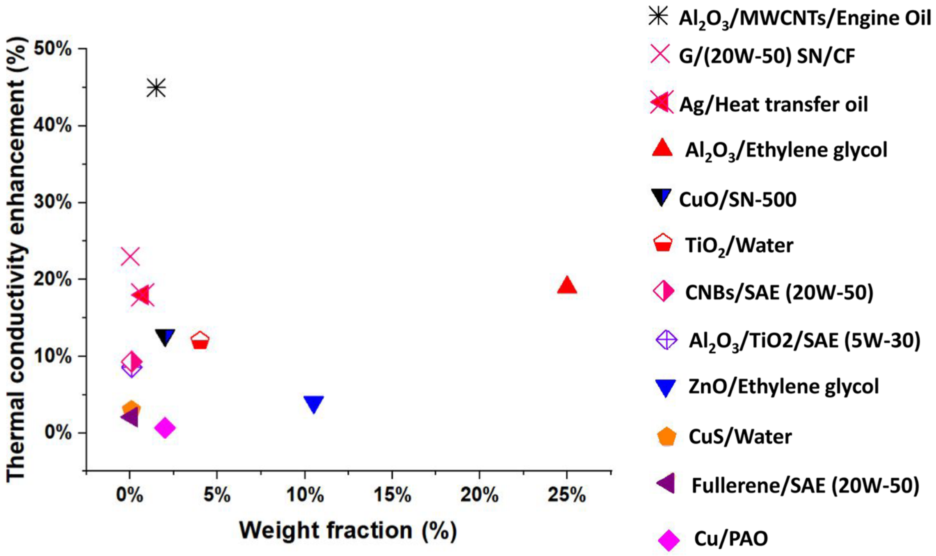

FIGURE 7 Thermal conductivity enhancement of different NPs and different base fluids versus NPs weight fraction[115,127,147,165,175,184,187–189,191,222]

TABLE 3 Literature scan on the ability of NPs in thermal conductivity enhancement in different base fluids

Type of NPs	Size	Type of base oil	Concentration	Thermal conductivity enhancement	References
Al_2O_3 TiO_2	10 nm 8–12 nm	SAE (5 W-30)	0.1 wt%1	3.9%–8.6%	184
Al_2O_3 MWCNTs	20 nm D (10–20 nm), L (10–30 nm)	Engine Oil	1.5 wt%	45%	187
Al_2O_3 SiO_2	13 nm 30 nm	Polyalkylene glycol	0.1 vol%	2.4%	193
Al_2O_3	40–50 nm	Ethylene glycol	25 wt%	19%	115
TiO_2	10 nm	Water	4 vol%	12%	222
TiO_2	10 nm	Diathermaic oil	1.0 vol%	8%	157
SiO_2	20–30 nm	Water- Ethylene glycol	5 vol%	45.5	192
Cu	25 nm	PAO	2 wt%	0.7%	175
CuO	50 nm	SN-500	2 wt%	12.7%	191
CuS	4 nm	Water	0.08 wt%	3%	127
ZnO	30 nm	Ethylene glycol	10.5 wt%	4%	165
G	12 nm	(20 W-50) SN/CF	0.01 wt%	23%	188
MWCNTs	D (20–50 nm), L (NA)	Ethylene glycol	1.0 vol%	12.4%	185
		Synthetic oil	2.0 vol%	30%	
CNBs	70 nm	SAE (20 W-50)	0.1 wt%	9.3%	189
Diamond	30–50 nm	Ethylene glycol	1.3 vol%	75%	238
Fullerene	10 nm	SAE (20 W-50)	0.1 wt%	2.1%	189
Ag	20 nm	Heat transfer oil	0.72 wt%	18%	147

Note: Also, the concentrations in which these NPs are used are reported. The blue highlighted rows signify the utilisation of NPs as mixtures to form composites.

Abbreviations: CNBs, carbon nanoballs; G, graphene; MWCNT, multi-wall carbon nanotubes.

Rasheed et al. experimented on nanolubricants formulated using graphene nanoflakes (G) and engine oil compliant with API 20 W-50 SN/CF and API 20 W-50 SJ/CF requirements.[188] The addition of 0.01% graphene to API 20 W-50 SN/CF results in a thermal conductivity increase of 23% at 80°C. Besides, in the presence of graphene, a 70% improvement in the engine's heat transfer rate is also achieved. In an experimental scan Rashidi, et al. studied the thermal activity of various carbon nanostructures when applied to SAE 20 W-50 oil, including MWCNTs, G, carbon nanoballs (CNBs) and fullerene NPs (C60).[189] CNBs exhibited superior performance in enhancing the coefficient of thermal conductivity and the base fluid's flashpoint by 9.3% and 18%, respectively, at 0.1 wt% in concentration. Hwang et al. studied NPs with different natures, to boost thermal conductivity and lubrication, including MWCNTs, fullerene, CuO, SiO_2 and Ag.[190] DI water, ethylene glycol, gasoline, silicon oil and PAO were used as base fluids. This study's findings concluded that with growing particle volume fraction, nanofluid thermal conductivity increases except for water-based fullerene nanofluid as it was lower than that of pure DI water.

Saeedinia et al. prepared stable CuO-Base oil nanofluids with various fractions of particle weight of 0.25%–2% for thermal properties investigation in different flow conditions.[191] The maximum heat transfer increase was for 2 wt% nanofluid at the highest Reynolds number tested, with an increase of 12.7% in the heat transfer coefficient was observed. Alternatively, a recent study performed by Zhao et al. showed that when applying water-soluble CuS modified NPs to water, its thermal conductivity can be increased by 3%, coupled with friction heat reduction, and tribological performance enhancement.[127] The modification was done by bis(2-hydroxyethyl) dithiocarbamic acid (HDA) to ensure the water solubility of NPs.

Esfahani and Toghraie analysed SiO_2 NPs in water-Ethylene glycol thermal conductivity as the base nanofluid. The measurement was conducted in a temperature range of 25–50°C with volume fractions of 0.1%, 0.5%, 1%, 1.5%, 2%, 3% and 5%.[192] According to the measurements, thermal conductivity improved as temperature and volume fraction increased. Also, a higher cumulative effect on thermal conductivity was shown by volume fraction. The results also showed that at 50°C, the maximum thermal conductivity (45.5%) took place in the 5% volume fraction. Zawawi et al. investigated the thermo-physical properties of Al_2O_3/SiO_2 (50:50, hybrid) in PAG nanolubricant for various NPs ratios at 30–80°C temperatures.[193] At the 80°C temperature, a maximum thermal conductivity gain of 2.41% occurred.

Li et al. prepared ethylene glycol (EG)-based nanofluids containing ZnO NPs, with different mass fractions of 1.75% and 10.5%.[165] The experimental results show that as the temperature rises from 15 to 55°C, the thermal conductivity increases slightly. It relies heavily on the concentration of particles and increases non-linearly with the concentration within the range studied. Sharma et al. demonstrated that, relative to pure ethylene glycol, the thermal conductivity of Ag NPs nanofluid with concentrations of 1000, 5000, and 10 000 ppm increased to 10%, 16%, and 18%, respectively.[194] In conclusion, the increase in thermal conductivity of nanofluids relies mainly on the volume fraction of the suspended NPs and the temperature range adopted in the experiments. Simultaneously, carbon-based NPs have excellent properties in boosting thermal conductivity compared to other types of NPs. This dominance is evident from the literature overview, as other NPs need to be employed in an elevated concentration to achieve the same effect as carbon-based NPs.

6 | LUBRICANT OXIDATION CONTROL

Thermo-oxidation stability of lubricants is critically tested in EVs, as harsh conditions such as elevated temperature and high rpm accelerate the oxidation phenomenon. Additionally, EV's low-viscosity lubricants, designated for friction loss reduction, are linked with oxidisation, as a low-thin layered lubricant is more prone to oxidise than a thicker one. Oxidation is a chemical reaction that, upon exposure to an oxidising agent such as oxygen, occurs in lubricants and can be catalysed by copper and iron, which are components abundantly available in EV's structure.[195] Besides, an electrically charged environment can also encourage lubricant oxidation, as mentioned in the electrical compatibility section. The oxidised lubricant products may polymerise and form layers, such as sludge and varnish, as the degradation progresses.[196] This deterioration results in a major colour change, viscosity, greater acidity, sludge, and varnish formation and corrosion.[197] Therefore, the stability of oxidation is one of the most significant parameters responsible for lubricant aging, in general.[198] Furthermore, these negative consequences are of particular importance in EVs, as low viscosity lubricants and anti-corrosiveness are two main vital attributes in smooth and consistent performance, as discussed in the previous sections.

One of the most appropriate additives for extending lubricants' lifespan is a group of chemicals termed anti-oxidants. Anti-oxidants are categorised as primary anti-oxidants (radical scavengers), secondary anti-oxidants (peroxide decomposers) and metal deactivators, based on the mechanism of action (complex-forming or chelating agents).[195] However, a critical decision needs to be made in selecting anti-oxidants combinations in a formulation, as that relies on the base oil, application and other ingredients present in fully formulated oil. The presence of certain other antagonistic ingredients in the product may also suppress the role of anti-oxidants.[195] This counterintuitive behaviour can shorten the lubricant's life span. As a result, novel antioxidation techniques must be presented to the evolving industry. Promising solutions can rely on adding electrically conductive NPs or advanced polymers such as rubber, polypropylene and methyl pentene, all of which have shown encouraging outcomes in high-speed applications, the problem of thermal and oxidative stability can be alleviated.[25]

Considering NPs role in this matter, NPs can act as a sacrificial material, oxidising instead of the lubricant bulk phase. Li, Dan, Wenjie Xie and Wenjun Fang highlighted this action in a thermal oxidation reaction by measuring the hydroperoxide concentration level in Cu kerosene nanofluids.[199] The resulting low concentration after the test indicated that before the kerosene was oxidised, the Cu NPs reacted with oxygen. Moreover, Rasheed et al. studied thermal degradation of mineral oil lubricants based on graphene using thermogravimetric analysis (TGA).[200] The study procedure included synthesising different test samples, as-synthesised graphene sheets of 8, 12 and 60 nm thick, and engine oil formulations 20 W-50 SN/CF and 20 W-50 SJ/CF were used. TGA showed that in the presence of graphene, the starting temperature of oxidation for the SN/CF oil could be delayed by 13–17°C, as shown in Figure 8. Likewise, the rate of oxidation could be delayed by more than 30°C when the weight loss of oil in the presence of graphene reaches 40%–20%.

In a different study conducted by Ivanov et al. that investigated the catalytic behaviour of colloidal dispersions of various mineral and synthetic oil nanocarbon additives, Fullerenes and a conventional chemical anti-oxidant were compared with the oxidation performance of mineral oil and synthetic oil containing detonating nanodiamonds (NDs/DNDs), detonating soot and

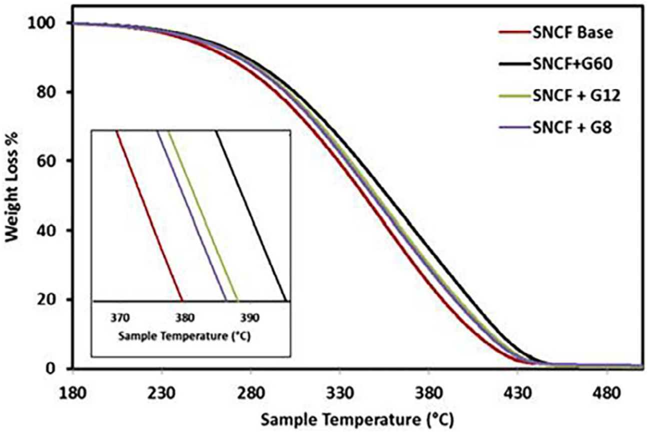

FIGURE 8 Left: SAE 20 W-50 SN/CF thermogravimetric (TG) curves with graphene (60, 12, 8 nm). Right: Derivative weight % of SAE 20 W-50 SN/CF with graphene (60 nm) under a nitrogen purge of 20 ml/min at a heating rate of 5°C/min, reproduced from open access journal, Ref. 200

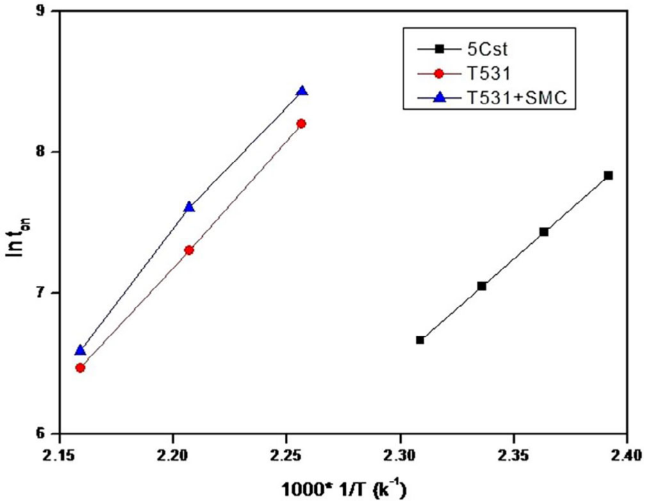

FIGURE 9 Oxidation induction period (ln ton ≈1/T) curve at different temperatures, Reproduced from open access journal, Ref. 202

commercial analogs. The anti-oxidant properties of both fullerenes and DNDs were shown in mineral oil, with DND performance depending on the deagglomeration method.[201] In PAO oil, DNDs and fullerenes' anti-oxidant performance is less effective than in mineral oil.

Zhongyi et al. evaluated the synergistic tribological and anti-oxidant behaviours of Sulphonate-modified nano-calcium carbonate (SMC), of 35 nm average size, and with ashless anti-oxidant N-phenyl-a-naphthylamine (T531) in hydrogenated oil (5 cSt).[202] The results show that adding this synthetic additive even at a low quantity (2.0 wt%) can have a good synergistic anti-oxidant effect with T531 as revealed by the oxidation induction period test shown in Figure 9, which verifies that a multi-functional and high-performance role of the nanocalcium carbonate compound.

Zaarour et al. reported another revolutionary method that utilises NPs nano-mesh for lubricant anti-oxidation objective.[203] Linde Type L zeolite (LTL), as shown in the TEM image of Figure 10, has been used in the study as proactive agent to extend commercial lubricants' lifetime. The nanosized zeolites were introduced into four lubricants and subjected to oxidation (90 and 150°C). Nuclear magnetic resonance (NMR) and Fourier-transform infrared (FTIR) spectroscopy results indicated that nano-zeolites protect the zinc dialkyldithiophosphate (ZDDP) additive, even after heating at 150°C for 24 h. The FTIR profiles of lubricants aged in the presence of LTL showed a lower degree of oxidation, while the oxidation products formed (aldehydes, ketones and acids) were adsorbed as scavengers on the zeolite crystals.

NPs seem to directly affect lubricants as oxygen scavengers resulting in antioxidation tributes coupled with synergetic action with conventional anti-oxidants chemicals. However, a synergism scan must be performed on NPs and anti-oxidant to guarantee the best performance. Another possibility that makes use of the natural affinity between some NPs and free radicals is the nano-absorbing mechanism.[204,205] In the latter procedure, NPs can act as free radicals collectors, breaking the oxidation reaction chain. However, more studies are required to be done in the field of nanolubricants.

7 | COPPER CORROSION PERFORMANCE

Copper is a vital element in EVs. Its longevity, malleability, reliability and superior electrical conductivity are used in electric motors, batteries, inverters, wiring and in charging stations. According to the copper development association, an EV can use 85–183 pounds of copper.[206] Consequently, the utilisation of lubricants compatible with copper and prevents its corrosion is of great significance. This compatibility is an additional task added upon lubricants in EVs operation. Other varieties of complementary roles lubricants include reducing friction and wear inside metallic components, providing a liquid seal on moving contacts and removing wear and soot particles.[207] In general, metallic elements undergo corrosion in reduction/oxidation reaction chains which are the primary mechanism of corrosion propagation.[208,209] Corrosion is even made worse in the presence of electrochemically reactive contaminants (such as water and air), which can further intensify metal dissolution by the association of metal cations with oxygen or halide ions.[210]

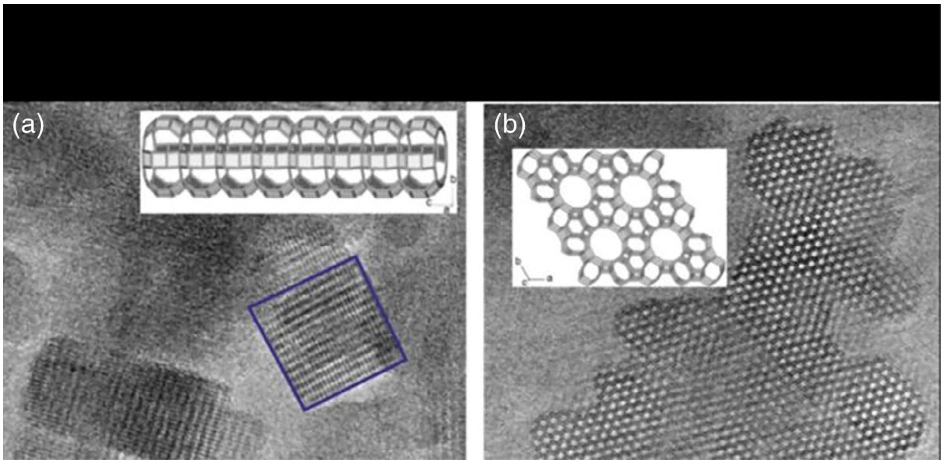

FIGURE 10 Resolution TEM images of LTL nanocrystals projected along with the directions, 100 in (a) and 001 in (b) (SG P6/mmm), reproduced from open access journal, Ref. 203

Present solutions for the use of metals in corrosive conditions rely heavily on passive metal oxide layers to restrict the spread of corrosion, significantly changing and restricting critical metal characteristics such as mechanical strength and electrical conductivity.[211] Alternative solutions conducted by lubricant formulators rely on corrosion inhibition and EPs performance enhancers, which are generally achieved with various chemical components for EHD and boundary lubrication regimes. Although these performance-enhancing additives have distinct chemical compositions, they are usually “surface active” agents that seek out and attach themselves by polar bonding to the metal surfaces being lubricated. Rust inhibitors and EP additives can interact with each other without proper additive selection and result in a decreased effectiveness of one or both additives.[212] This chemisorption competition is not as prominent in nanolubricant, giving it an extra merit characteristic.

When comparing nano-coating and nanolubricant in a corrosion protection perspective, it can be argued that the former always relies on the existence of a uniform layer of NPs on the surface, which is not always the case; moreover, it can act as a pocket for corrosive reactants. Lee and Berman, discussed this behaviour in a study case in which graphene-coated surfaces had higher than regular corrosion rates (i.e., pitting corrosion) were found at the defective edges of the graphene films, led to the trapping of the corrosive chlorine ions,[213] as derived from the energy-dispersive X-ray spectroscopy (EDS) results (Figure 11).

An alternative solution is to replenish the corrosion-inhibiting properties of the metal surfaces by providing a liquid suspension with a protective coating (i.e., using a nanofluid).

The research on nanolubricant corrosion performance does not seem to be the main focus of tribologists; instead, it is on nano-coated materials as there are no studies conducted on the topic, and it is even less in the case of copper corrosion. However, recently Lee et al. showed that the suspension of silica NPs can be beneficial not only for heat transfer rate but also for copper corrosion inhibition.[214] The study indicates that when silica NPs covers only 10% of the surface with a nominal particle diameter of 10 nm, combined results of the quartz crystal microbalance (QCM) technique and atomic force microscopy suggested a substantial decrease in corrosion rates (up to four times). The negative surface potential of silica NPs preferentially stops negatively charged ions (such as chlorine ions) from entering the metal surface and thereby acts as an impediment, increasing the rate of metal dissolution when the NPs precipitate on the copper surface, forming “nano-fins”.

Furthermore, Malshe and Wengyang have patented a dielectric nanolubricant composition based on the addition of modified MoS_2. The addition of dielectric NPs was conducted in various lubricants.[215] According to ASTM D130 standards, the dielectric nanolubricant prepared by this method can have a copper corrosion rating of 1B at 100°C.

Alternatively, carbon-based NPs seem to possess anti-corrosion properties. As 2D-material, graphene not only shears swiftly at the sliding contact interfaces but also offers corrosion and oxidation protection.[216] In contrast to graphene, oxidised graphene does not have as good two-dimensional protection, and the presence of oxygen in graphene oxide will cause steel corrosion, thus raising wear.[216]

An additional option can rely on boron compounds such as boric acid nano-powders, which improve EP performance of lubricants, oxidation and thermal stability for corrosion protection.[217,218] An out-of-the-box solution can depend on NPs as carriers for other beneficial chemicals towards corrosion. This approach was accomplished in previous experiments, indicating that by using mesoporous NPs as containers filled with corrosion inhibitors, corrosion in metals can be suppressed,[219,220] as shown in Figure 12.

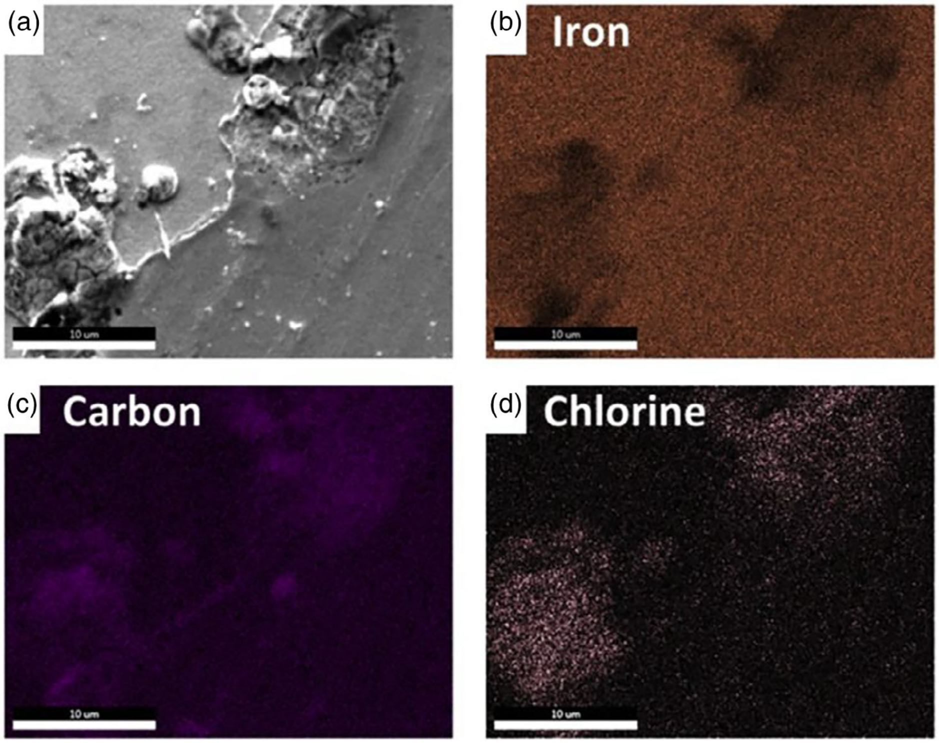

FIGURE 11 EDS mapping of the CVD-coated iron sample in NaCl solution after 10 h: EDS mapping of (a) CVD graphene on iron samples for the graphene tear region for the atomic concentration of (b) iron, (c) carbon, and (d) chlorine. The transfer of graphene resulted in the right bottom corner of the sample being partially covered. The analysis confirms a high chlorine presence right at the edge of the graphene flake, Reproduced from open access journal, Ref. 213

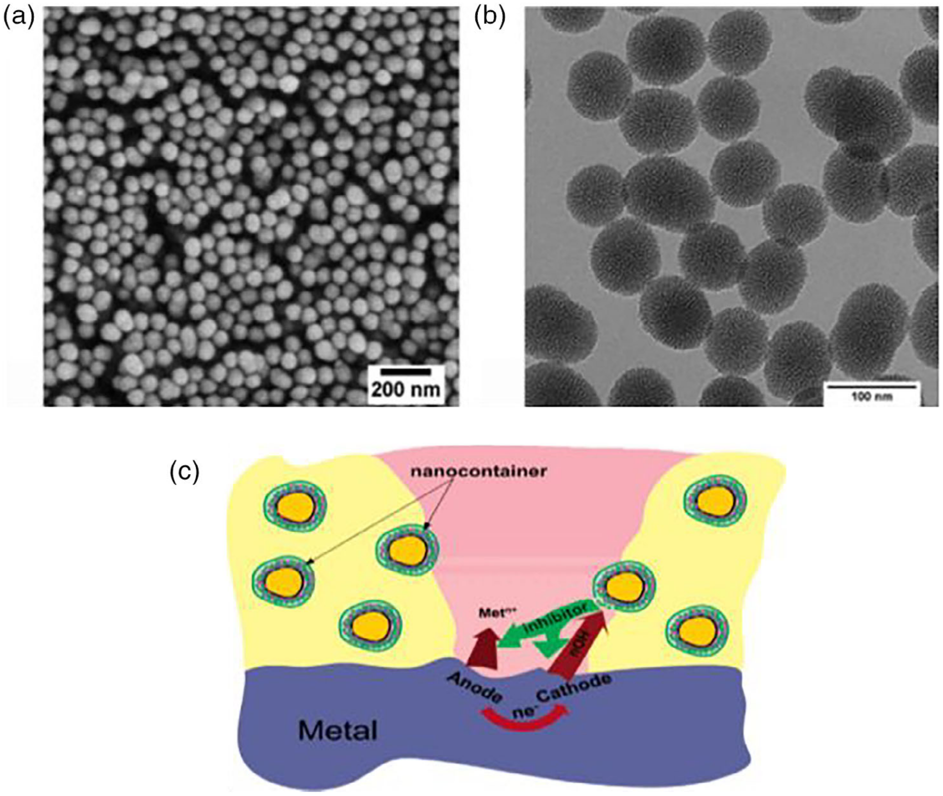

FIGURE 12 (a) Scanning electron microscopy (SEM), (b) TEM micrographs of nanoparticles of mesoporous silica, reproduced with authors permission and copyrights holder of Ref. 219, and (c) Method of the nanocontainers' controllable releasing of the inhibitor and the "smart self-healing" mechanism, reproduced with authors permission and copyrights holder of Ref. 220

Another point of view that should be considered besides copper corrosion is the compatibility of nanolubricants towards elastomer polymers and rare earth elements interaction. Regarding the elastomer polymers, present in different components within EVs but mainly in the sealing parts, NPs may affect their swelling behaviour compromising the sealing capacity. Thus, the possible use of nanolubricants within EVs needs to meet ASTM D4289 specifications regarding elastomers compatibility. [102] Also, nanolubricants need to be investigated in terms of rear earth element reaction as rear earth elements are present in vital components of EVs such as permanent magnets and batteries. However, in both cases, specific studies are required to understand better how nanolubricants may perform.

8 | CONCLUSIONS

This review highlights the different attributes and pre-existing challenges regarding the use of nanolubricants as a novel class of lubrication dedicated to EVs. The method conducted in this study relies on critically discussing and coupling theoretical research knowledge with practical information. The following key points are the main conclusions arrived from this work:

1. Incorporating NPs in electrical motor greases formulation can significantly improve the tribological and rheological performance, as proven by many studies. Moreover, pristine NPs (without surface modification) seem to be the best pick to avoid the adverse effects of NPs-thickeners interactions, leading to an incompatibility that can destroy grease's structure. Additionally, the optimum NPs concentration must be selected to reduce the possibility of NPs abrasive action at excessive concentrations.
2. NPs can be used to face harmful electrical currents discharges by both enhancing insulating or conductivity of the lubricants. Therefore, choosing the functional objective of NPs is essential when utilising them as AEDA. When NPs are desired to increase the breakage voltage of a lubricant, the focus should be on the particles' size, as smaller sizes are more effective in electron trapping. Meanwhile, to increase lubricants' electrical conduciveness, it seems that surface-functionalized NPs are more efficient than pristine NPs. Nevertheless, the degree of functionalization needs to be considered in the case of greases as it can be detrimental, as mentioned earlier. Also, to achieve high conductivity in lubricants, functionalized NPs need to be employed in high concentrations, affecting both the tribological performance and the lubricant's economic feasibility. The latter point is an issue that needs to be opted for by future research.
3. The tribological performance of low viscosity lubricants can be significantly boosted with a small number of NPs. This merit holds for both synthetic lubricants based on PAO and hydro lubricants. NPs in both PAO and hydro bases need to be stabilised to prevent aggregation and sedimentation with time. Additionally, NPs tend to increase viscosity which can be counter-intuitive with low viscosity lubricants in EVs; however, low concentration use of NPs can be considered to overcome this obstacle.
4. Regarding copper corrosion protection induced by NPs, it seems that silica-based nanolubricants are superior. This protection can reach up to 400% with only 10% surface coverage of silica NPs. Besides, nanolubricants can outperform nano-coating in the prevention of pocket-trapping of corrosive substances under nano-layering.
5. The rise in nanolubricants thermal conductivity relies primarily on the concentration of the suspended NPs and the environment's temperature, in a proportional increment which can be advantageous in EVs conditions. Additionally, relative to other forms of NPs, carbon-based NPs have superior capabilities to increase thermal conductivity.
6. NPs appear to directly affect lubricant as an oxygen scavenger, resulting in antioxidation tributes coupled with synergetic action with conventional anti-oxidants. However, a synergism scan must be performed on NPs and anti-oxidant to guarantee the best results. Nano-absorbing is another option that allows the use of the affinity between free radicals and specific NPs. The latter procedure will serve as a collector of free radicals, breaking the oxidation reaction chain. Nevertheless, further studies are expected to be carried out by researchers on the subject.
7. Proposed future research may utilise magnetic and electric fields in EVs powertrains to control the behaviour of surface-charged NPs, which can result in controlled lubrication for optimum tribological results.

Finally, it is always possible to give EV's lubricated parts the best opportunity for damage-free operation by selecting the proper lubricant and additives combinations for the specified designs and conditions. These combinations can include different NPs in recipes designated to different roles in an optimised approach.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

No datasets were generated or analyzed during the current study, and the findings presented were licensed from copyright holders.

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