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Carbon Nanomaterial-based Friction Modifiers in Machines: Review of Recent Developments

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Current research primarily focuses on developing and using carbon Nanomaterials (NM) in tribology. This includes creating nano lubricants, producing self-lubricating materials, and formulating coatings to enhance automotive surfaces' anti-friction and wear characteristics. The primary objective of this work is to provide a comprehensive understanding of how carbon NMs and their derivatives enhance the tribological behavior and thermophysical characteristics of engine lubricants. This study has clarified the primary methods by which nanolubricants enhance their anti-friction and wear-resistant capabilities. This research examines the primary issues and recommends future study approaches. To summarize, the study outlined the primary accomplishments of carbon nano lubricants to inform the advancement of lubricating oils.

Keywords: Carbon Nanomaterial, Friction Modifiers, Machines, Nanolubricants.

1. Introduction

Friction and wear are natural occurrences when two surfaces in close contact move relative [1]. These objects are ubiquitous in daily life and are essential, frequently serving as the primary factor in obtaining optimum performance in numerous industrial applications. Managing friction and wear is necessary for multiple applications that demand low and high levels of these procedures [34]. The latter's recognition has resulted in extensive investigation and the gathering of significant empirical data in the mid-20th century [40]. This has led to the establishment of tribology, a scientific discipline that examines friction, wear, and other associated phenomena that occur when surfaces come into contact. Tribology is the scientific discipline that regulates and manages wear, friction, and lubricants [2][29][30].

Friction is a significant attribute of the movement between surfaces that are in touch. It results in the liberation of heat energy and the occurrence of wear. Wear and friction contribute to engine failure, gears, bearings, and other mechanical components [3]. The efficiency of these systems, particularly in the transportation, industrial, and energy sectors, relies heavily on the quality of their functioning. Energy dissipation is the primary issue linked to high friction and wear factors. Beyanagari et al. reported that around 33% of fuel energy is wasted due to friction caused by moving components such as gearboxes, tires, brakes, etc [4][31].

After 15-25 years, the friction losses would be reduced by 61%, resulting in a worldwide savings of EUR 576 billion. This trend is seen in large cars. The group analyzed trucks and buses and demonstrated that 33% of the fuel energy is used on friction losses in their motor [5][28]. These findings indicate that in 2023, 240 billion gallons of gasoline were used worldwide to counteract friction in large cars [32]. Utilizing lubricants in different formats is one of the most efficient methods to address the problems above. Lubricants are categorized into the following classifications:

(a) Solid: Films made of organic or inorganic materials such as graphite, chromium iodide, molybdenum disulfide bonds, spherical boron nitrate, tungsten-based diselenide, etc. (b) Plastic: Complex colloidal structures comprised of a liquid foundation (distribution substance) and thickening agents or structure modifications as the dispersed phase. (c) Liquid: Fluids are typically liquid under normal circumstances, including petroleum-based, vegetable-based, animal oil-based, synthetic, etc[38].

Although there are no restrictions on the range of materials used to decrease friction in mechanical structures, lubricants are chosen based on particular criteria [6][33]. Over time, various oils and lubricants have been used to facilitate the seamless movement of two objects, such as bearings or engines. When two surfaces come into contact, a multitude of imperfections on both surfaces resist distortion by stretching and returning to their original shape. An increase in the contact pressure results in the plastic deformation of the imperfections and a reduction in the dimension of the oil film. It is well acknowledged that lubricants made from pure hydrocarbon mixes derived from petroleum or synthesized hydrocarbon combinations only fulfill some of the necessary criteria. Modest quantities of functional additives or elements to base lubricants are used to enhance their tribological and other properties.

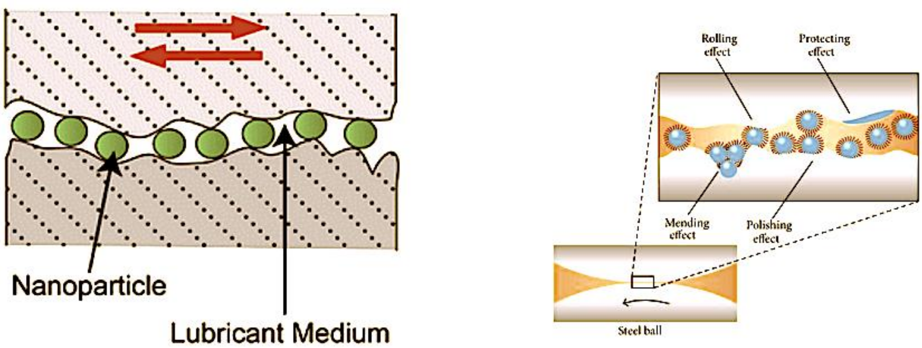

Figure 1. Working on nano lubricants

Nanolubricant substances can be beneficial due to the small size of the nanoparticles that fill in the gaps between rough surfaces in the lubricant [7]. Figure 1 shows the working of nanolubricants. This has a repairing effect and helps to smooth the outermost layer of the engine parts, improving their resistance to friction and wear in automobile engines.

Nanolubricants, including carbon Nanomaterials (NM), are viable for enhancing lubrication performance due to their exceptional thermal and lubricating characteristics. Their non-toxic and environmentally benign characteristics expand the range of their use as lubricant additives.

2. Carbon Nanomaterials as a Solid Lubricant

The lubricity process is contingent upon a substance's tribological properties and the prevailing operational circumstances. It manifests as either (i) a fluid coating, a thick coating, or hydrodynamic lubricant, (ii) a thin coating or boundary lubricant, or (iii) severe pressure lubricating. Carbon-based nanoscale lubricants are used in either barrier hydrodynamic or combined regimes [8][35][36].

Thick film lubrication occurs when tribosurfaces are kept apart by a substantial and unbroken layer of lubricants, often in situations with minimal loading and high velocity. Viscosity is paramount in minimizing friction as the regions are not in direct touch. Hydrocarbon oils are extensively used for fluid film lubricating. Tribosurfaces in lightweight lubricating do not experience total separation but coexist under higher load and lower speed conditions.

Solid lubricants have low friction characteristics and are used when liquid alternatives are ineffective due to higher temperatures, vacuum environments, or substantial mechanical forces. The study of how carbon NMs interact with surfaces has significantly advanced, making them a promising lubrication due to their diverse architectures and exceptional physical, electrical, chemical, and heating capabilities. Carbon NMs are tribology's solid lubricating components and super lubricating oils. Solid lubrication is employed when liquid and semi-liquid lubrication are inadequate in delivering satisfying outcomes. A solid lubricant has notable characteristics in conditions of extreme temperatures and pressures. Solid carbon nanostructures enhance certain surface qualities when applied as a coating, Graphite, and graphene.

2.1. Graphite

Graphite, a standard 3D carbon substance, is used as a lubricant in tribology [9]. Graphite comprises many layers of carbon atoms arranged in a hexagonal pattern, making it very suitable for lubricating in the presence of air. Graphite has superior lubricating characteristics in humid air compared to dry air. Water vapor is essential for lubricating graphite because it reduces the bonding energy that links the hexagonal surfaces of graphite when it is deposited. The presence of water molecules among graphite layers reduces friction. Hu et al. conducted a comparative analysis of the tribological characteristics of graphite in their previous investigations on graphene [10]. The tribological testing results indicate that graphite powder lubrication resulted in lower friction levels in humid conditions but higher friction and wear expenses in dry nitrogen. The wear of graphene was significantly decreased in both humid conditions and dry nitrogen settings. Graphite can be used to reinforce bulk material composites. Jadhav et al. created composites using five wt% graphite as a reinforcing material [11]. They found a significant reduction in friction and wear, which was attributed to the self-lubricating properties of graphite.

Graphite functions as a lamellar solid to enhance lubrication. The structure is described as a stack of cards, each representing a layer of graphite weakly connected to the others. Graphite exhibits lubricity whenever the two edges that slide make contact, as it rolls up the layers of loosely placed graphite sheets, functioning similarly to roller brakes. As a result of this roller system, the surfaces that come into contact experience a reduced coefficient of resistance. The roller system's friction efficiency is affected by the ambient temperature of the gliding area and the surrounding environment, such as vacuum, dry air, water steam, etc. Inserting water atoms between the graphite plates in mass graphite dramatically enhances its ability to reduce friction in humid conditions.

The friction factor is significantly influenced by the graphite amount and the graphite granules' dimension in graphite-based lubrication. Fasihi et al. demonstrated that solid lubrication based on graphite, with a reduced carbon concentration, decreases the adhesion coefficient [12]. Zhao et al. found that increasing the volume percentage and reducing the size of graphite NMs leads to a drop in the coefficient of resistance [13][37]. This was seen when graphite NMs were incorporated into vegetable-based oil as a flavoring. The lubricating process is based on forming a physical depositing layer across the contact that appears, facilitated by the graphite NMs' tiny size and elevated surface energy.

A lack of perfect smoothness characterizes contact surfaces and might consist of several convex and concave areas. When the convex areas first touch each other while sliding, it results in an elevated factor of friction. Including graphite NMs in oil as an addition reduces dual friction. To fix the damage, they can infiltrate the concave region between the contact areas. The rubbing area can be coated with graphite NMs to provide a thin layer that separates the contact areas.

2.2. Graphene

Graphene is a two-dimensional carbon NM with exceptional friction and wear characteristics [14]. It is a monolayer of carbon atoms that are sp2 hybridization. Graphene has garnered global interest in research due to its excellent mechanical, heat, and electrical capabilities. It is widely regarded as one of the most significant findings of the twenty-first century. Graphene has many essential benefits, including excellent chemical inaction, low surface power, exceptional strength, and the capacity to undergo shear easily on its extraordinarily dense and fundamentally clean surface.

It exhibits excellent tribological characteristics. One significant benefit of graphene is its tribological capabilities, unaffected by the surrounding conditions. Graphene can efficiently minimize wear on tribosurfaces and significantly decrease friction in wet and dry situations.

Graphite does not possess this unique characteristic. The elasticity of graphene and graphite resistance under humid environments is within the range of 0.15–0.17. Graphene significantly decreases the degradation of tribosurfaces compared to graphite. This is due to creating a thin layer that provides superior coating coverage and allows for effortless shearing at the contact point of the rib surfaces. Graphene is used in nanoscale or micro-scale structures, such as microelectromechanical structures and nanoelectromechanical structures, to minimize friction and wear in moving, revolving, and gliding connections [15]. This is possible due to its ultrathin nature, even when used in many layers.

The regular arrangement of C60 molecules in a cobblestone pattern, which leads to the formation of curved surfaces, was the cause of the enhanced tribological efficiency. The production of a film containing fullerene C60 decreased the contact region between a moving microsphere and the a-graphene-C60 film, thereby reducing friction. Graphene significantly contributed to lowering the nanofriction factor of the hybrid film, indicating its potential for use in MEMS systems.

2.3. Diamond-like Carbon-Based Coatings

Diamond-Like Carbon (DLC) is a well-known three-dimensional allotrope of carbon-based materials distinguished by sp3 bonding among carbon molecules [16][39]. The broad bandgap, outstanding hardness, and extraordinary chemical resistance of DLC have attracted considerable attention from research. The polished edges of carbon nanodiamonds play a vital role in determining the wearing and friction properties of the self-mated tribology mechanism. DLC films are used in metal contact and engine systems because of their outstanding hardness, exceptional lubrication efficiency, exceptionally low friction, and chemical resistance. Zeng et al. conducted a study that showed a DLC film's friction value at ultra-high pressure with a hydrogen concentration of 42 at.% was as minimal as 0.02 [17]. When exposed to humid circumstances, the DLC coating with hydrogen components exhibits an even lower factor of friction, which becomes more pronounced as the water steam pressure grows.

3. Lubricant nano additives

In recent decades, several research has investigated the impact of different NMs on the tribological characteristics of lubrication. The recognized nano-additives include metals, metallic oxides, metal oxide composite NMs, and carbon-based NMs. Scholars are currently concentrating on studying the tribological characteristics of metal NMs. Cu NMs have shown exceptional self-healing attributes and positively impacted tribological efficiency. These NMs are ecologically beneficial. These NMs get significant focus and consideration among all metallic nano additives.

Mousavi et al. examined Cu NMs' impact on diesel fuel's tribological characteristics [18]. The lowest friction and wear were reported when the copper content was 7.5 wt.%. It was discovered that including Cu nanostructures leads to a more significant reduction in friction and wear at elevated temperatures and high pressures. It is essential to acknowledge the impact of the remaining metal nanostructures on the tribological characteristics of lubricants. Pd decreased the electrical contacting impedance between surfaces. Liu et al. investigated the effect of Sn and Fe NMs on the tribological characteristics of multiply-alkylated cyclopentanes [19]. They demonstrated that the presence of these NMs led to a reduction in wear caused by friction in the oil, which is often used as a lubrication in the aerospace sector. It was observed that Fe NMs had superior anti-wear capabilities.

Ali et al. described the characteristics and actions of TiO2 and CuO NMs when employed as nano additives in lubricating oils [20]. The CuO NMs were discovered to significantly outperform the TiO2 NMs in reducing friction inside the oil systems. Min et al. investigated the impact of nano- and microparticles on the friction and wear characteristics of vegetable (rapes seeds) oil that underwent chemical modifications via hydroxylation, epoxidation, and esterification process [21]. According to their research, the friction coefficient decreased by 14.8% and 5.7% after adding TiO2 and CuO NMs. It was observed that the abrasion area of the rapeseed oil, which underwent chemical changes, decreased by 12% and 5.3% for the nano- and microscale TiO2, correspondingly. A few additional studies in the literature examine the tribological properties of TiO2 NMs.

Zinc oxide (ZnO) NMs are the focus of significant interest because of their notable characteristics, including their elevated surface energy, expansive surface region, efficient diffusion, powerful adsorption, and lower boiling point. According to Vyavhare et al., a grease with 1.2 wt.% ZnO and wearing spot length had the most minor friction factor [22]. The limited dispersion of the ZnO NMs might provide challenges when attempting to disperse them in the base oil. Krishnakumar et al. studied the production of ZnO NMs by homogeneous deposition utilizing sodium dodecyl sulfate [23]. They investigated the solubility of these NMs in oils and their anti-corrosion and tribological capabilities. When 1.0, 2.0, 3.0, and 4.0 wt.% ZnO was added to the oil specimens; they became clear and did not form crystals until they were left undisturbed for ten days. Using customized nanometer ZnO components decreased friction and wearing of the foundation oil.

Wang et al. demonstrated that using spherical Al2O3 NMs treated with a 0.1-wt.% siloxane coupling solvent as a lubricating nano additive formed a protective coating, decreasing the friction ratio and wear spot dimension [24]. The properties of ZnAl2O4 NMs have been extensively investigated owing to their exceptional characteristics. Similar to other NMs, these aggregates have limited chemical solvents and oil stability, significantly restricting their potential as nano additives for lubricants. The production of monodisperse ZnAl2O4 NMs has significant value. They altered their outer layer using the solvothermic technique with oleic acid, significantly enhancing their ability to disperse in oil. Following the alteration, the NMs exhibited a near-uniform distribution inside the lubricant. The study revealed that adding ZnAl2O4 NMs at a density of 0.1 wt.% significantly improved the oil's resistance to wear and friction, surpassing the effects of Al2O3 and ZnO.

Several studies have shown the importance of employing NM formulations that provide superior tribological characteristics compared to individual element NMs. Al2O3 and TiO2 NMs are very effective nano additives for anti-wear and anti-friction purposes. NM is expected to be an excellent choice for tribological purposes. Luo et al. examined the tribological characteristics of NMs by friction and wear testing [25]. The NMs exhibited outstanding durability in the foundation oil. Incorporating a mere 0.1 wt.% of NM resulted in enhanced anti-wear properties and a reduction in coefficient of friction. NMs exhibit superior anti-wear and anti-friction characteristics compared to pure Al2O3 or TiO2.

Baraı et al. demonstrated using Al2O3/CuO NMs in paraffin-based lubricants, resulting in a substantial enhancement in surface smoothness compared to traditional lubricants [26]. A 41% reduction in roughness was reported at a concentration of 0.8 wt.%. Aluminum oxide combined with copper oxide. Choudhary et al. altered intricate ZrO2 and SiO2 NMs using an Al-Zr binder, then utilized them as nano additives for lubricating oil while adjusting the proportion, quantity, and intensity [27]. The incorporation of these modified NMs (0.1 wt.%) into the essential oil resulted in an enhancement of the lubricant's tribological characteristics. This was shown by significantly lowering the friction factor, which decreased by around 16.24%.

Acknowledging that the metal-based NMs added to the lubricating medium-sized formulation might have beneficial and detrimental impacts on tribosystems is essential. The beneficial effect is a result of elements that enhance the endurance of the tribosystem, such as the strengthening of surface layering and the formation of small-angle ruggedness via surface flattening. The efficiency of lubricants can decline due to tribodestruction and oxidation, leading to the development of wear components with collected buildings. This can increase the abrasive operation, causing excessive wear on the contact pair parts and leading to the organization of lubrication oils. All of these factors contribute to the abnormal thickened and corrosive impact on the surface coatings of the frictional unit components.

The intricate impact of the metallic nano additives necessitates the establishment of specific circumstances inside the tribosystems to facilitate beneficial processes that mitigate wear. Most research has demonstrated that nano additives exhibit superior tribological capabilities to traditional solid lubricating additives. Numerous publications have shown the potential use of carbon NMs as lubricating additives since the inception of research in this field. It is important to emphasize that the unfavorable traits mentioned earlier are not fundamental to nanotechnology.

4. Nanoparticle variable affecting the properties of lubricants

NMs can influence the tribological characteristics of lubricants. Their exceptional size and other qualities are the cause. The size, shape, building, multifunctional surface categories, and NMs' concentration primarily influence NM-based lubrication tribological characteristics.

4.1 Nanoparticle size effect

The internal physical and physicochemical characteristics of NMs are directly influenced by their size, which subsequently impacts their tribological characteristics. According to the Hall-Petch equation, the hardness of NMs improves as the grain size decreases to less than 100 nm. It is often observed that their flexibility increases when the grain size is less than 10 nm. If NMs possess more hardness than the surfaces they come into contact with during rubbing, it might result in wear. It is essential to consider the alterations induced by the size of the NMs during the development of a nano additive-enhanced lubricant. It is crucial to consider the surface roughness when dealing with rubbing interfaces. If the diameter of the NMs is greater than the dimension of the surface imperfections, using nano additives will not result in any tribological benefits.

When the coarseness of the coating is much more than the diameter of the NMs, the addition of NMs will fill in the imperfections, resulting in an artificial flattening of the friction areas. This will lead to an enhancement in the tribological characteristics. The uniformity of the lubricant component is contingent upon the size of the NMs. Stokes’s law suggests that reducing the size of NMs might potentially enhance their dispersion resilience.

4.2 Nanoparticle form effect

The morphology of NMs is another crucial factor to be considered while developing nanomodified lubricants. Due to the former's much lower contact surface region, nano-spheres will undergo more pressure at a particular load than nanoplatelets. Using lamellar NMs will minimize the likelihood of distortion occurring on rubbing areas.

4.3 Internal nanostructure effect

The internal composition of NMs impacts their mechanical characteristics and, therefore, their tribological qualities. The presence of vacancies, known as Schottky defects, in NMs restricts the movement of displacements, enhancing durability. A small number of molecular vacancies might enhance the physical robustness of NMs and positively impact their tribological characteristics. An excessive quantity of flaws might diminish the physical robustness of NMs.

4.4 Surface functionalization effect

The outermost functionalization is crucial in the creation of nano-modified lubrication. Unmodified NMs often clump together because powerful van der Waals interactions hold them together. Surfactant-coated nano-particles have enhanced tribological characteristics due to the following factors:

i) Surfactant particles adhere to the NMs, forming a protective layer around each particulate. This weakens the van der Waals forces as the atoms move apart, preventing them from clumping together. ii) Surfactant atoms bind to the NMs, causing the outer exterior of the atoms to have a uniform polarity. The equal charge on the exteriors of all NMs causes repulsion, preventing them from clumping together. The surfactant acts as a protective layer, avoiding direct interaction between the NM exterior and pressing substrates. The surfactant-anchored NMs have a hybrid system with a solid interior and an adaptable external layout. This synergistic combination minimizes friction under high-pressure conditions.

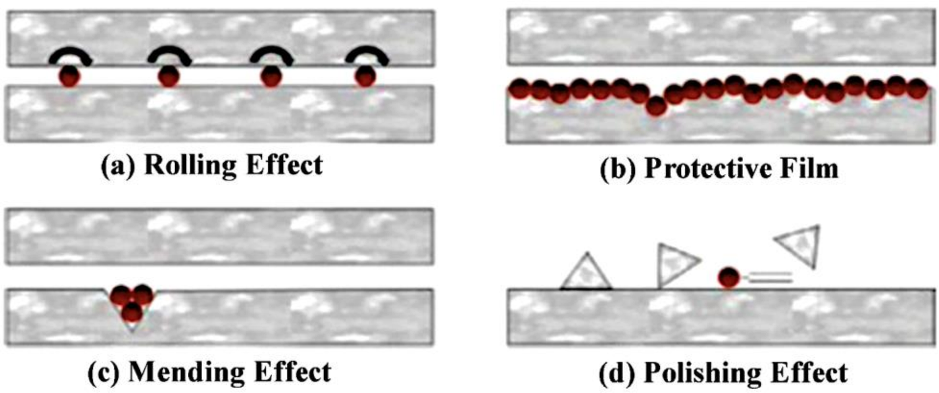

Figure 2. Carbon NM effects as a Friction Modifier

Figure 2 shows the different effects where carbon NM acts as a Friction Modifier, which includes rolling, protective, ending, and polishing effects. Surface functioning is essential when there is a need for enhanced colloidal stabilization and uniform dispersion of NMs in the substrate oil.

4.5 Nanoparticle concentration effect

Research has shown that the quantity of NMs present in base oils impacts the tribological characteristics of lubrication. To determine the ideal concentration for achieving the lowest friction factor, it is essential to consider all the operating system's characteristics.

5. Main challenges

The findings of the carbon nano-additives demonstrate the promising potential of these nanolubricants for use in physical applications. There has been a growing number of research on using nano lubricants in lubrication structures, particularly in automobiles, with an increasing frequency. The concerned researchers encounter several hurdles and issues, including the inconsistency in findings among different studies and the limited comprehension of the chemical principles behind the capabilities of nanolubricants at the nanoscale. For innovative nanolubricants to be widely implemented, they must be evaluated in terms of their environmental impact, technical capabilities, and economic viability according to the criteria set by ecologically adapted nano-additives guidelines.

5.1 Dispersion stability

Due to the powerful van der Waals forces, sedimentation and aggregation pose significant challenges in producing nano lubricants, which hinder widespread commercialization. The durability of nano-lubricants impacts tribological efficiency and the characteristics of lube oils since the association of the NMs influences them. The durability of NMs in liquids can be explained by the Waals principle, which states that it is determined by the combined effect of repulsive forces from the electricity doubling layers and attracting pulls from van der Waals interactions. Due to Brownian motion, these forces come into play as NMs approach each other. An unstable equilibrium occurs when the pulling forces exceed the repellent forces. A suspension will remain stable if the NMs exhibit repulsive solid forces. To decrease the clumping of NMs, one uses mechanical or chemical techniques, such as adding lubricants or modifying the surface of the NMs.

Solvents are chemical substances that lower the surface tension of baseline liquids and enhance nano-additives' incorporation into NMs. Surfactants are not suitable for oils since they need to meet the viscosity requirements set by producers for mechanical components. It has been said that an excessive quantity of surfactant hurts the chemical, density, and thermal properties. Careful control, including the surfactants, is highly recommended. A surfactant enhances the thermal resistance among the underlying liquids, decreasing thermal conduction enhancement. The durability of nano lubricants is closely linked to the enhancement of thermal conductivity.

Surface alteration methods do not include the use of surfactants. It utilizes NMs that have been chemically modified to enhance the durability of nanofluids. The interaction between the modification and the outside of the NMs alters their outermost shape and condition. The presence of modifiers on the outermost layer of the NMs leads to a decrease in the surface pressure caused by hydroxyl groups. This breaks the hydrogen connections among NMs and prevents the formation of oxygen-bridging bonds, thus reducing accumulation. This process involves using detergents or dispersing agents, which are beneficial in reducing the surface energies and interfacial pressure in NMs. Choosing an appropriate approach is a significant problem due to the unique features of NMs.

5.2 Increased viscosity

The friction between contacting areas in physical systems is categorized into two types: hydrodynamic (fluid) friction, which occurs due to the shearing of lubrication, and boundary friction, which occurs at the points where metal areas come into the interface. The friction factor is proportional to the lube oil density, which directly affects the thickness of the lube oil layer. If the consistency of the lubrication oil is decreased by about 25% while preserving the anti-friction/wear characteristics, the resulting reduction in fuel consumption ranges from

0.4% to 4.9%. The fuel efficiency of gear oil was enhanced by 0.3 - 2.7% by reducing viscosity. Several recent experiments have explored the impact of incorporating NMs into lubricating lubricants. The density of the nano lubricants was found to rise as the weight % of NMs improved. The rise in stiffness of the nano lubricants leads to increased fluid drag.

When the viscosity is reduced, the depth of the lubrication oil coating decreases, resulting in a rise in boundary roughness and wear rates, which allows for metal-to-metal interaction in some areas. This scenario could result in a reduction in the engine's lifespan. Nanolubricants are necessary to regulate fluidity to provide minimal friction among worn areas without increasing fluid drag and ultimately enhance the efficiency of automotive engines.

Additional challenges when using nano lubricant additives in lubricants involve the exorbitant expense associated with the fabrication of NMs. Nanotechnology operations need stringent purity standards. The manufacturing process must be trustworthy to provide consistent control over the features of NMs. As a result, the cost of producing NMs is more significant.

6. Conclusion and findings

The authors have assessed the tribological effectiveness of carbon-based NMs that demonstrate enhanced anti-friction and wear characteristics compared to commercially available lubricating oils. The anti-friction capabilities mainly stem from the physical contact between the NMs and the areas that are rubbing against one other, such as the effects of nano-rolling, repairing, and polishing. The primary reason for this is the spherical morphology of carbon NMs, which effectively reduces the contact area and adhesion during friction under certain loading circumstances. The anti-wear capabilities were primarily attributed to the chemical interaction among NMs, lubricating fluids, and substrate areas, which played a crucial role in producing the protective film known as tribofilm. Carbon nanostructures' distortions and exceptional characteristics are mainly attributed to the morphologies and hybridization of carbon molecules.

Using carbon NMs in the films enables the development of transparent conducting films with excellent wear resistance. The thermophysical characteristics of carbon nano lubricants were improved due to the decrease in thermal contact impedance among the carbon NMs and the lubricating oils. The friction and thermophysical features are primarily influenced by many critical factors, including NMs' volume, shape, and dimension, lubricating circumstances, and dispersing durability of carbon NMs.

A significant amount of work is still to be done to improve further and industrialize carbon as a super lubricant in mechanical system lubricants.

- Further exploration and understanding of the anti-friction processes of carbon NMs at the nanoscale were achieved via molecular dynamics modeling.

- More research is needed on integrating experimentation and simulation characterization to offer a new theoretical foundation for friction management in physical systems at the nanometer.

- Additional research is needed to investigate novel methods for modifying the surface of carbon NMs to achieve stable distribution in lubricating fluids and improve their tribological performances.

- Studies should be undertaken to examine the toxicities of carbon-based NMs to mitigate possible health risks associated with their bio-tribological properties in technical and medical fields.

- Studies should focus on developing novel techniques for cost-efficient mass production of carbon nanolubricants, facilitating their industrialization.

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