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Review

Tribological Properties of CNTs-Reinforced Nano Composite Materials

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Abstract: High modulus of about 1 TPa, high thermal conductivity of over 3000 W/mK, very low coefficient of thermal expansion (CTE), high electrical conductivity, self-lubricating characteristics and low density have made CNTs one of the best reinforcing materials of nano composites for advanced structural, industrial, high strength and wear-prone applications. This is so because it has the capacity of improving the mechanical, tribological, electrical, thermal and physical properties of nanocomposites. So, this study is aimed at providing the latest discoveries on the tribological behavior of CNTs-reinforced composites. The composites reviewed included metal matrix composites (MMCs), polymer matrix composites (PMCs) and ceramic matrix composites (CMCs) reinforced with CNTs. Their tribological characteristics, uses, production challenges, conclusion and recommendations are presented. The work presented the best technique to disperse CNTs on matrices to avoid its agglomeration, since agglomeration is one of the major challenges in reinforcing with CNTs. It was discovered that ball milling destroys the outer walls of CNTs but recommended that ultrasonication and functionalization before ball milling eliminate this adverse effect of ball milling. In addition, it was discovered that addition of CNTs to composite matrices improved the wear resistance, reduced the wear volume, decreased the coefficient of friction (COF) and provided self-lubricating effect on MMCs, PMCs and CMCs.

Keywords: carbon nanotubes; metal matrix composites; polymer matrix composites; ceramics matrix composites; tribology

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1. Introduction

Reciprocating movement of pistons inside engine cylinders, rotation of bearings and crankshafts, walking or running on tracks/roads, engaging and disengaging of brakes and clutches etc., are affected by a phenomenon called friction. Friction is the force which tries to resist motion of one body sliding over another. The classic law of friction was discovered back in 15th century by Leonardo da Vinci, even though it was not published then. It was Guillaume Amontons who rediscovered the laws in 1699. The laws were called Amonton's laws of dry friction, which summarily stated that the force of friction (F) is directly proportional to the applied normal load (N) or that the coefficient of friction (μ) is directly proportional to the friction force and inversely proportional to the normal load.

Ever since then, research has been on-going on friction and tribology. Tribology is the science of friction, wear and lubrication. Light metals such as Al, Ti and Mg are applied in aerospace, automotive, agricultural and electrical industries because of their low density and their high strength per unit weight, besides other excellent properties. However, they are easily eroded and worn away by friction and wear which undermine their utility and efficiency in service. However, this anomaly can be augmented by introducing reinforcement which improves their tribological properties. Polymers, on the other hand, are more resistant to chemicals, are cost effective and require no post-production treatment like metals do, but they are weaker to friction and wear. So, to eliminate this challenge and improve durability and efficiency in service, they require some reinforcement with nanomaterials. Ceramic materials have high hardness, good thermal stability and high wear resistance, but they are very brittle. So, to improve their fracture toughness, they are reinforced with high-strength and high-modulus nanoparticles or nanomaterials. Lubrication can be referred to the practice of applying oil, grease or nanomaterial on a surface in order to minimize friction and wear. Among all the known nanoparticles/nanomaterials used in lubrication and improving wear resistance, strength and fracture toughness of materials, carbon nanotubes (CNTs) stand out [1–5].

It was in 1991 that Iijima discovered, for the first time, a particular carbon with a structural configuration that looked like a tubule [6]. It consisted of some tens of graphite layers (walls) that were later identified as multi-walled carbon nanotubes (MWCNTs) or simply (CNTs) (Figure 1). Successive walls of the tubule are 0.34 nm apart, with diameter of 1 nm and massive aspect ratio. When graphite exists in 2 dimensional forms, it is called graphene (Figure 1a). Two years on, Iijima and his co-workers developed single-walled carbon nanotubes (SWCNTs) (Figure 1b), which were formed when graphene was rolled into a seamless cylindrical tube [7]. Carbon nanotubes (CNTs) have been recognized as the stiffest material (bequeathed by its SP^2 hybridization) which buckles elastically under massive bending or compressive stress. It possesses huge tensile strength of about 100 GPa and exceptional elastic modulus of 1.27 TPa, its thermal conductivity ranges from 3000–6000 W/mK, and its current density is about 1015 A/m^2, with a conductance of 13 $k\Omega^{-1}$ [6–10].

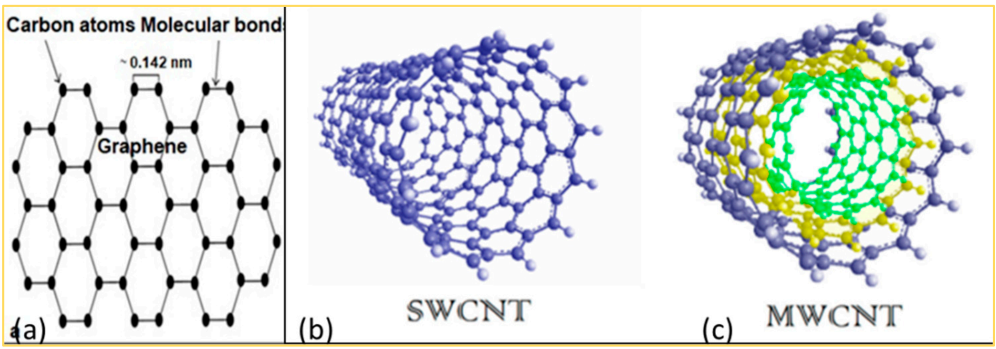


Figure 1. Structural Forms of Graphite: (**a**) Graphene, (**b**) SWCNTs and (**c**) MWCNTs [10].

These exceptional characteristics of CNTs have provoked the interests of researchers on this material. The production techniques of CNTs are manifold, and they include: electric arc discharge, laser ablation, vaporization induced by a solar beam, and chemical vapor deposition (CVD) [11–13]. Consequent upon the essential properties of CNTs, they have been applied as a reinforcement for metal, polymer, ceramic and carbon matrices. Based on its mechanical-cum-tribological characteristics in metal matrices, Park, Keum [14] reported three types of strengthening mechanisms in CNTs-reinforced composites, which included Orowan looping, thermal mismatch and load transfer kinetics. Orowan looping occurs during plastic deformation and is as a result of dislocation of atoms in the crystals. Thermal mismatch occurs when there is a wide difference between the coefficients of thermal expansion (CTE) of the matrix and reinforcement, just like in CNTs (2.1×10^{-6} K^{-1}) and Al (2.36×10^{-5} K^{-1}) [15]. In this case, thermal mismatch raises the dislocation density through strain hardening which culminates in the strengthening of the composite [16]. More so, CNTs can efficiently absorb the load incident on its base material through the dynamic load transfer mechanism, thereby raising the load bearing capacity of the composite system.

Among the three mechanisms, it was reported that load transfer kinetics contributed more than 50% of the improvements [14].

Nonetheless, there is a relationship between the mechanical strength and tribology of composite systems. It was in 1953 that Archard [17] propounded that the wear volume loss (*V*) of a material is inversely proportional to its hardness (*H*) and directly proportional to the sliding distance (*S*) and normal load (*L*). So, it can be inferred that materials with high strength (hardness) experience lower wear loss than those with low strength and vice versa. Meanwhile, the tribology of a composite system entails: the interaction of the surface with another surface when they are in a relative motion; the coefficient of friction (COF) of the system; the wear rate and wear loss of the system; and the lubrication properties of the system. Therefore, since it has been established that CNTs reinforcement improves the mechanical properties of composites, it is logical to assert that it improves the tribological properties of materials too. In addition, it has been shown that CNTs is a good solid lubricant [18]. Hence, incorporation of CNTs into a base material not only reduces the wear volume loss of the material but reduces the COF of the system which is promoted by the decrease in both the adhesive and deformation components of its coefficient [19]. Metal matrices reinforced with CNTs have exhibited excellent tribological properties, and this has caused the expansion of its engineering applications, industrial utility, automotive usage, aerospace, electrical and electronics applications [20,21]. In an experiment to investigate the tribological properties of Nickel-CNTs composite, it was discovered that 2 vol.% of CNTs gave the least COF of 0.22. When the volume fraction was increased to 5%, the COF increased, and other properties depreciated, because there was agglomeration of the reinforcement in the microstructure [22]. It was shown that the COF of Ni-2CNTs composite improved by 332% in comparison with monolithic Ni. The information herein is that optimizing the volume fraction of reinforcement is of paramount importance. This is because the high aspect ratio of CNTs provokes its agglomeration. So, once the optimal volume fraction is exceeded, homogenous dispersion becomes difficult. The COF improvements of different metals, ceramics and a number of polymers reinforced with CNTs are shown in Table 1. It can be observed in Table 1 that ceramics accommodated a higher volume fraction of CNTs than metals and polymers. A small volume fraction of CNTs (0.7 wt.%) improved the COF of polymers optimally. For metals, 4 wt.%–5 wt.% produced the optimal COF. This trend was equally observed by Watanabe et al. [23] who posited that ceramics are more hydrophilic than polymers due to their surface roughness. So, the degree of hydrophilicity of base materials controls the volume fraction of reinforcements that can be absorbed. Ceramics possess the highest hydrophilicity, followed by metals and then polymers.

Table 1. Improvement of COF in Metals, Ceramics and Polymers Reinforced with CNTs.

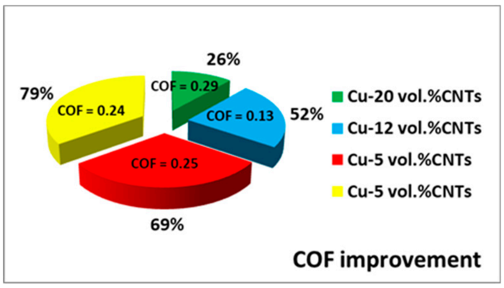
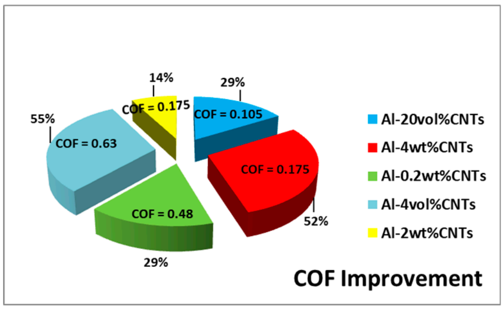
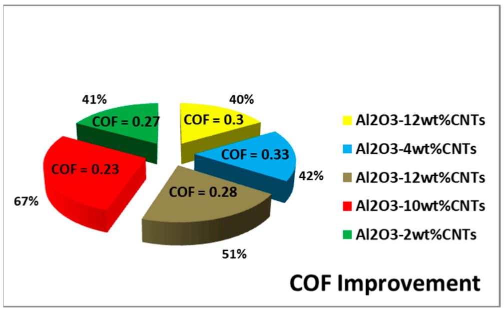
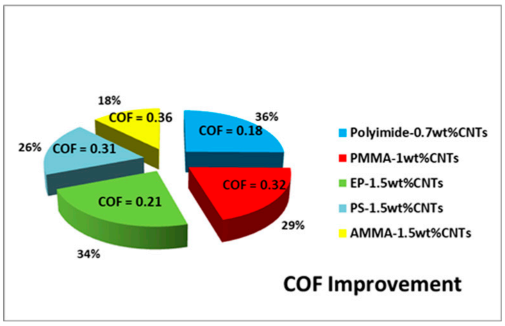
Plots of COF Improvements	Remark	Ref.
	5 vol.% of CNTs gave the optimal COF improvement. As the concentration increased, the COF depreciated in the Cu alloy.	[24–27]

Table 1. *Cont.*

Plots of COF Improvements	Remark	Ref.
	At a very low concentration of CNTs, the composite had low COF improvement; at too excessive a volume fraction, the improvement was still low. It was an optimal concentration (4 vol.%) that gave the highest improvement in Al alloys.	[28–32]
	The COF improvement in Al2O3 ceramic-CNTs composite absorbed higher volume fraction of CNTs than in metals and polymers. An optimum value of 10 wt.% gave the highest COF improvement of 67%.	[33–37]
	Polymer matrices can wet out only minute fraction of CNTs. Optimum concentration of CNTs that gave the highest COF improvement was 0.7 wt.%. (PMMA, polymethyl methacrylate; EP, epoxy; PS, polystyrene; AMMA, polyacrylonotrile).	[38–40]

Furthermore, when CNTs reinforcement is incorporated into polymers, strong interfacial bonding between the nano-carbon chains and polymer matrices are achieved, and this increases the modulus of polymer composites and expands its industrial, engineering, pharmaceutical and agricultural applications [41]. There was a report that there exists strong interfacial adsorption energy in polymer-CNTs reactivity, which helps to bond the polymer chains on the surface of CNTs stoutly, thereby enhancing the strength of the CNTs-polymer composite [41]. Campo et al. [42] studied the effect of CNTs addition into epoxy matrix composite. The results showed that addition of 0.5 wt.% CNTs into epoxy matrix reduced the mass loss by 900%, decreased the wear rate by 1367%, and decreased the COF by 275%. However, the improvements were more pronounced when the CNTs were functionalized, as functionalization decreased the Van der Wall forces and hydrogen bonding in CNTs molecules. Wang et al. [43] studied the tribological behavior of plasma-sprayed carbon nanotubes-reinforced TiO_2 coatings and discovered that the coating that had CNTs reinforcement exhibited about a 93.6% decrease in wear volume with a moderate decrease in the COF when compared with unreinforced TiO_2. By and large, CNTs reinforcement has proven to be a good tribological nanomaterial for composite development. Reports on the tribological properties of CNTs-reinforced composites are scant in the literature [44]. Singh and Beloka [45] reported Al- and Mg-based composites reinforced with CNTs; Chan et al. [46] studied the effect of nanofillers on polymer composites; Goswami et al. [47] concentrated on mechanical and tribological properties of CNTs/graphene-reinforced alumina, while

Choudhary et al. [48] dwelt more on the effect of processing route, processing parameters and CNTs length on the properties of CNTs-reinforced composites. For the present work, efforts have been made to extend scope of the review to accommodate the three major composites, namely, metal matrix composites (MMCs), polymer matrix composites (PMCs) and ceramics matrix composites (CMCs), so as to grasp wider knowledge of the tribological characteristics of CNTs reinforcement on the three major matrix composites, studying their respective characteristics and drawing conclusive remarks on their various lubrication, wear and friction properties. So, the aim of this work is to discuss the wear, friction and lubrication properties of the three major composites reinforced with CNTs with the sole aim of discovering their potential applications together with projecting their strengths and weaknesses and how to remedy their shortcomings.

2. CNTs-Based Nano Materials

Two factors that are responsible for high strength of materials reinforced with CNTs are as follows: (a) the interlocking carbon-to-carbon covalent bonds of CNTs providing strong metallurgical bond to the composite and increasing its dislocation density. (b) The carbon nanotube existing as one large molecule which does not possess grain boundaries at all, let alone weak ones that separate crystal grains of high strength materials such as steel or tungsten [49]. Hence, there is no danger of grain boundary weakness or failure. Figure 2 gives a schematic idealization of a CNTs-reinforced composite system. As shown in Figure 2, each particle of the matrix is actively held together or bonded by the CNTs molecules making it difficult to be broken without application of enormous force. So, the SP^2 covalent bond as well as single unit molecule of CNTs account for the exceptional strength of CNTs-based composite materials.

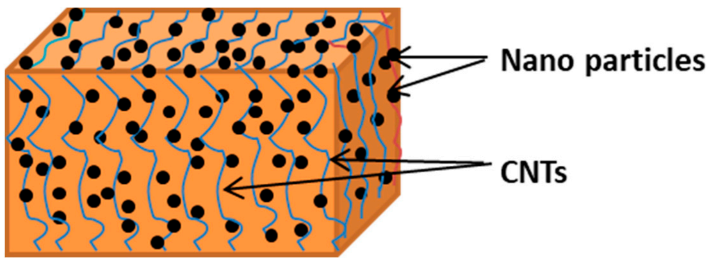


Figure 2. Image of CNTs-Reinforced Nanocomposite.

Researchers have studied the traditional fibers such as carbon-, glass- and Kevlar-based composites via computational and empirical techniques. Energy densities, ballistic impact capacity, wear and penetration resistances of these traditional fiber-based composites were investigated. Challenging issues such as delamination, compressive failure in the fiber/matrix interface, matrix cracking, and tensile failure of yarns were all identified as the principal failure mechanisms after characterization [50–52]. However, it was observed that failures in these conventional composites occur within the range of a micrometer. This implies that reinforcement based on nanomaterials such as CNTs can withstand such failures. Hence, they can improve the mechanical/tribological properties of nanocomposites under steady and repeated loading and prevent such failures that occur at the micrometer scale. So, conventional composites are now being replaced by nanocomposites and hybrid composites in most advanced applications, due to their excellent mechanical, tribological, and thermal properties [53]. Improvement in strength and energy absorption of CNTs-reinforced polymer/glass composites has been reported [54]. Also reported is the improvement in tribological, thermal, corrosion and mechanical properties of CNTs-reinforced metal/ceramics matrix composites [55–57]. It is because of the excellent mechanical and tribological properties, thermal and electrical conductivities that carbon-based nanofillers such as CNTs and graphene are employed in the development of nanocomposites [58,59]. It was reported that CNTs-reinforced polymers nanocomposites are presently being used in the place of steel in the development of bullet-proof shields, jackets, wear resistant surfaces, shock and impact absorbers, and ballistic impact-resistant materials [60,61], and they are much cheaper, less dense, more corrosion resistant and more robust than the conventional steel-based military armors and shields. CNTs-reinforced metal matrix composites, on the other hand, are used in the development of aerospace components, automotive piston and sleeves, nozzles, turbine blades, transmission conductors, electronic sensors and transmitters [20,62–64], as they outperform monolithic Al, Ti, Mg or steel alloys. Fracture toughness is one of the principal properties imparted on ceramic matrices by CNTs. Hence, CNTs-reinforced ceramic composites are used in the development of high temperature nozzles and turbines, cutting and drilling tools, blades of lathes, pulverizers etc. [65,66], and they are cheaper, less dense and more robust than tungsten, diamond and steel alloys that were the traditional materials for these equipment.

The production techniques of CNTs-reinforced nanocomposites are manifold. They can be grouped based on the similarity of processes involved. These groups include (i) powder metallurgy, (ii) electrochemical techniques, (iii) casting method, (iv) thermal spraying and (v) other novel techniques. Table 2 shows sketches of the production techniques used in the development of nanocomposites.

Table 2. Production Techniques of Nanocomposites.

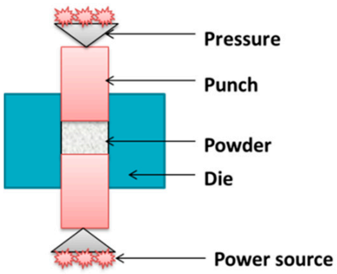
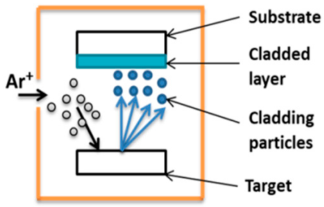
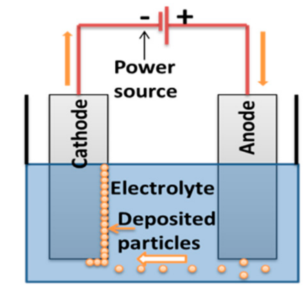
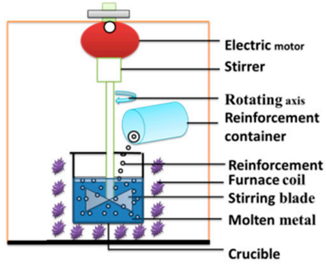
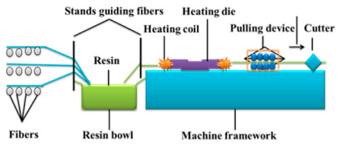
Production Technique Sketches	Description	Remarks	Ref.
 (a) Powder metallurgy	Powder metallurgy: This comprises spark plasma sintering, vacuum sintering, microwave sintering, hot pressing and conventional sintering. Prior to consolidation, matrix and reinforcement are blended via ball milling, tubular mixing and molecular mixing. Then, the application of heat and pressure is used to consolidate the composite.	In SPS and other forms of advanced sintering, heat and pressure are applied concurrently, while in conventional sintering, heat is applied after green compaction. There is zero waste of materials.	[67]
 (b) Additive process	Additive manufacturing: This comprises laser cladding, sputtering, nanoscale dispersion, sandwich processing, plasma spraying and vapor deposition.	This technique reduces material wastes to the lowest level.	[68]
 (c) Electrochemical method	Electrochemical technique: This comprises electro deposition via amperometry, potentiometry, conductometry, voltammetry or the galvanic cell technique. This involves the passing of electric current to initiate dissolution and deposition of materials.	The major advantages of this technique are its simplicity, low cost and speed.	[69]

Table 2. *Cont.*

Production Technique Sketches	Description	Remarks	Ref.
 (d) Casting method	Casting method: This comprises stir casting, ultrasonic cavitation, squeeze casting, liquid casting etc. Casting involves melting of base material, addition of reinforcing phase, stirring and solidification.	Virtually every component can be casted, using metal composites, ceramics or polymer composites. It is cheap and uses simple tooling.	[67]
 (e) Pultrusion/Extrusion	Low melting-point metals and polymer composite fabrication that comprises pultrusion and extrusion. This involves melting and pushing or pulling the melt through an orifice to assume specific shape.	This is used in the production of long components such as electric transmission conductors. It is very fast and economical.	[67]

Wear and Friction Properties of Composites Developed with CNTs Reinforcement

Wear and friction characteristics of composites developed with CNTs reinforcement are presented in Table 3.

Table 3. Wear and Friction Characteristics of CNTs-Reinforced Composites.

CNTs/Composites	Tribology Properties	Remarks	Ref.
AlSi-10Mg-CNTs	Wear grove of composite = 150 μm^2 Wear grove metal matrix = 224 μm^2 Wear rate of composite is 33% lower	The improvement in wear rate is attributed to the fact that CNTs increased the hardness of the MMCs and improved the microstructure. Selective laser melting (SLM) was the technique employed. This composite is useful in automotive brake pad and lining, pistons and engine sleeves.	[70]
WC-20Co-6CNTs	Wear rate = 0.000307 $\pm$ 0.1 $mm^3/N.m$ COF = 0.08 $\pm$ 0.012	The introduction of CNTs on WC-20Co improved the wear loss, wear rate and coefficient of friction greatly through improving the mechanical strength. The processing technique was high-velocity oxy-fuel (HVOF) spraying. This ceramic composite is useful in cutting tools and grinding wheels.	[57]
Al2O3-3%TiO2-3% CNT,	Wear resistance = 5800 Nm/mm^3 Mass loss = 0.0035 g Average mass loss of unreinforced ceramics was 3.85 mg, while average mass loss of CNTs/ceramics was 3.45 mg (11.6% improvement).	Uniform CNTs dispersion and good adhesion of coatings with the substrate invoked the enhancement of the wear properties. The method was Plasma Spraying of Al2O3-3TiO2-CNTs on AISI 1020 steel substrate. This ceramic composite is replacing steel pipes in oil and gas industrial pipes.	[71]
316 L Stainless steel-8CNT	Wear rate = 1.1×10^{-7} mm^3/Nm (218% improvement) COF = 0.25 (60% improvement) The COF of unreinforced 316 L was 0.4, and the wear rate was 3.5×10^{-7} mm^3/Nm.	The tribology improvement was made possible because the larger surface area of CNTs provided large surface roughing, thus having a better lubrication effect. Vacuum hot-press sintering was the technique applied. This steel composite is replacing conventional stainless steel in advanced applications.	[55]

Table 3. *Cont.*

CNTs/Composites	Tribology Properties	Remarks	Ref.
AZ61Mg-0.5%CNTs	Volume loss = 0.81 mm^3 (48% improvement) Mass loss = 0.008 g (38% improvement) COF = 0.3 (17% improvement) There was very low COF (0.22) at 1 wt%CNTs. The unrefined AZ61 had volume loss of 1.2 mm^3, mass loss of 0.011 and COF of 0.35.	The strengthening and bonding characteristics of CNTs led to a reduction in mass loss. Additionally, the CNTs provided lubrication effect which led to enhancement of the tribology. Stir casting with annealing was the method used. This MMC is useful in electrical and electronics packaging.	[72]
Al3Ti-Cu-SiC-CNTs	Average COF = 0.46 Average COF of substrate = 0.57 This gives an improvement of 24%	The COF was enhanced by the dispersion strengthening and fine grain strengthening of CNTs. The production technique was laser cladding. This is an advanced hybrid composite which can compete favorably with high entropy alloy in aerospace applications.	[73]
Al2O3-3TiO2-6CNTs	Wear depth = 4 ± 0.8 µm Wear rate = 0.0003 ± 0.1 mm^3/Nm COF = 0.11 ± 0.009	The improvement was attributed to bridging of CNTs in between the splats of the ceramics matrix. The technique used was Plasma Spraying of the composite on AISI 1020 mild steel. This is replacing steel alloy in bridges, rails and other structural applications.	[74]
Polyimide-0.1CNTs	Wear rate = 0.0002 mm^3/Nm COF = 0.26	The functionalization of CNTs contributed to the improvement of the wear resistance. This polymer composite is used as high temperature structural glues and laminating resin. It is used in wood work, structural and car body parts applications.	[38]
Polyimide-0.7CNTs	Wear rate = 0.00065 mm^3/Nm COF = 0.18	There was strong interfacial bonding between PI matrix and MWCNTs-COOH nanofillers, which enhanced the transfer of load effectively from the matrix to the functionalized CNTs. So, this improved its hardness, which in turn reduced the wear rate and COF. It is now prominent in automotive industries.	[38]
Phosphate ceramic-0.75CNTs	Wear rate = 0.008 mm^3/Nm COF = 0.39	It was observed that at temperatures below 500 °C, the lubrication effect of CNTs was intact. However, when this temperature was exceeded, the tribology properties diminished.	[75]
Al_2O_3-2CNTs	Wear rate = 0.00000269 mm^2/kg Wear rate of pristine Al_2O_3 = 0.00000294 mm^2/kg	The improvement in wear rate was attributed to the uniform dispersion and the reinforcement efficiency of CNTs. The composite was produced with cold spraying. This is a high-temperature structural ceramic composite that is replacing BN, WC etc.	[76]
Al-CNTs	Specific wear rate of micro-sized channel reinforcement filling (MCRF) = 0.018 mm^3/Nm Wear rate of pure Al = 0.022 mm^3/Nm (20% improvement)	The improvement in wear rate was attributed to the uniform dispersion of CNTs in MCRF-fabricated composite, which formed a solid lubricant layer. Friction stir processing was the method applied. This MMC is useful in electrical, electronic and structural applications which can replace conventional steel conductors.	[77]
Al-Si-0.75CNTs	Wear rate = 0.00095 mm^3/m Wear rate Al-Si = 0.0018 mm^3/m (89% improvement)	The improvement was attributed to the formation of a carbon layer which acted as a solid lubricant at a higher speed. Powder metallurgy was employed in the fabrication.	[78]

Table 3. *Cont.*

CNTs/Composites	Tribology Properties	Remarks	Ref.
Al-4CNTs	COF = 0.18 (52% improvement) Wear rate = 0.34 μm^3/s (23% improvement) Wear volume = 20 μm^3 (23% improvement)	The improvement was attributed to strong densification and refined microstructure influenced by spark plasma sintering technique. Useful for high temperature transmission conductor.	[18]
Al-8CNTs-8Nb	COF = 0.10 (79% improvement) Wear rate = 0.49 μm^3/s (23% improvement)	The improvement was attributed to the solid lubrication property of CNTs and formation of Nb_2O_5 that acted as a solid lubricant too. This can conveniently replace steel-reinforced aluminum conductors.	[79]
Epoxy-10Carbon fibre-0.3CNTs	COF = 0.3 (97% improvement) Wear rate = 4×10^{-6} mm^3/Nm (425% improvement)	The improvement in the tribological properties was attributed to the lubricating effect as well as strengthening action of C-C bond between CNTs and short carbon fibre. This polymer composite is useful in high-temperature applications.	[80]

3. Effects of Prevailing Conditions on Tribology of CNTs-Reinforced Composites

Wear resistance, wear loss, coefficient of friction and lubrication properties of composites reinforced with CNTs are affected by a plethora of factors. In this section, the response of CNTs-reinforced composites to those factors are explored, analyzed and presented.

3.1. Response of CNTs-Reinforced Composites to Applied Load

Tribological properties of composites are affected by the magnitude of load that is applied on them. It has been shown that when load is increased in systems undergoing relative motions, the wear rate and wear volume increase while the coefficient of friction decreases [81]. Some authors reasoned that at higher loads, plastic deformation is higher, fatigue damage is more pronounced, asperities penetrate deeper and material removal increases [82]. Others opined that higher load induces greater shear stress, which delaminates more materials, thus increasing the wear volume and wear rate [83]. However, some authors reported an increase in the COF when the applied load increased [82]. However, according to Amonton's law of friction, the COF of systems is inversely proportional to the normal load [84], while the total volume loss increases when the applied load increases [85]. It will be noted that when the applied load is increased, the temperature of the contact surface rises, inducing more material loss. However, if the wear rate is measured in relation to the applied load, there exists a critical load where the wear rate is not severe. However, when this critical load is exceeded, the wear rate becomes aggressive [86]. This critical load diminishes with increase in temperature [87]. A further increase in applied load above the critical load results in seizure with accompanying heavy wear rate, damaging noise and vibration, normally called galling seizure [88]. Therefore, an increase in the applied load increases the wear rate and wear loss but decreases the COF. However, incorporation of CNTs into a composite system tends to increase the critical load at which seizure occurs. This makes the CNTs-reinforced composites withstand higher loads than composites without CNTs. CNTs-reinforced composites have better a self-lubricating effect, which acts as a film shielding the surfaces in contact. By this effect, the wear rate/loss and COF act as if they are independent of the applied load because the shielding film minimizes the delamination and erosion effects of friction.

3.2. CNTs-Reinforced Composites' Response to Sliding Speed

The tribological properties of composites have a direct relationship with the sliding speed of the contacting surfaces. When the sliding speed is increased, the wear rate increases as well. This can be attributed to the fact that a higher speed induces higher heat generation, which in turn weakens the interfacial bonding between the matrix and reinforcement [89]. A load of 2 kg was applied on the Al-Ni-CNTs composite. The angular speeds applied were 300 rpm, 500 rpm and 700 rpm, which gave wear rate of 0.00256, 0.0046 and 0.0058 mm^3/m, respectively, at a mixing ratio of 2 wt.% CNTs [90]. So, at constant load, the wear rate increased with an increase in sliding speed. In another study, the addition of 1.5 wt.% CNTs and 0.5 wt.% Al2O3 improved the tribological properties of the Cu-0.5Al2O3-1.5CNTs composite [82]. However, when the sliding speed was increased, the wear properties increased, as shown in Figure 3a.

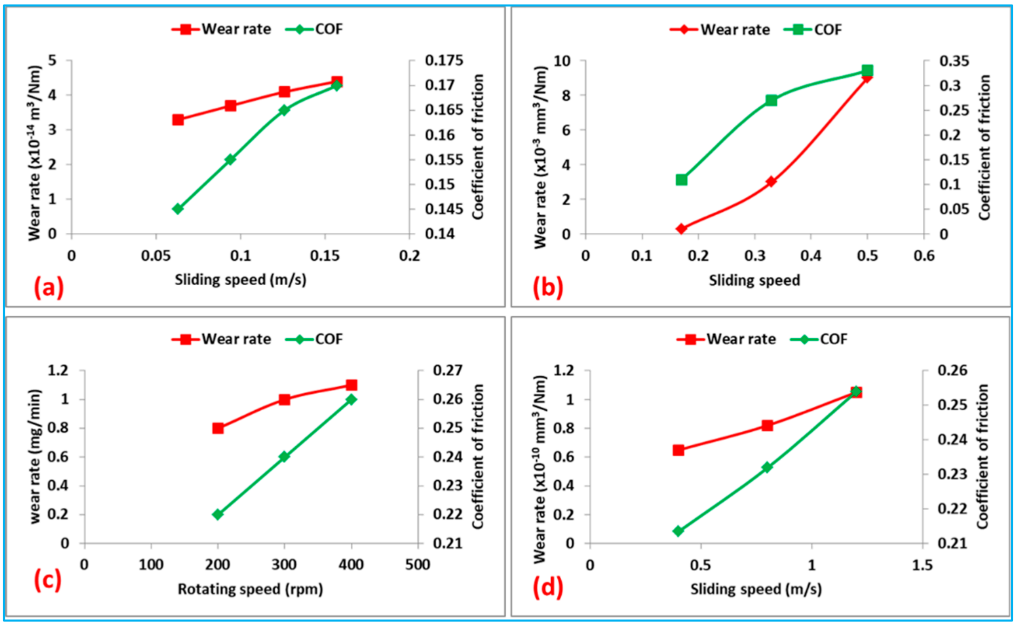


Figure 3. Effect of Sliding Speed on the Wear rate and Coefficient of Friction of: (**a**) Cu-0.5Al_2O_3-1.5CNTs, (**b**) Al_2O_3-3TiO_2-6CNTs, (**c**) Glass Fiber-Reinforced Plastic-1CNTs and (**d**) Polyamide-30Cabon fiber-0.5CNTs Composites [74,82,91,92].

In another study, 6 wt.% CNTs was used to reinforce Al2O3-3TiO2. It was reported that when the sliding speed was increased from 0.17 m/s to 0.5 m/s (Figure 3b), the COF increased by 200%, while the wear rate increased by 2900% [74]. In Figure 3c, 1 wt.% CNTs was used to reinforce glass fiber-reinforced plastic. An increase in sliding speed from 200 rpm to 400 rpm increased the COF by 18%, and it increased the wear rate by 38% [91]. More so, 0.5 wt.% CNTs was used to reinforce Polyamide-30carbon fiber (Figure 3d). The results showed that an increase in sliding speed from 0.4 m/s to 1.2 m/s increased the COF by 19%, and increased the wear rate by 50% [92]. In all the CNTs-reinforced composites studied and shown in Figure 3, it can be seen that the COF had a steeper slope than wear rate. This implies that a small increase in the sliding speed generates a higher change in the COF than in the wear rate. This is because an increase in sliding speed increases the temperature of the contacting surfaces drastically, thus inducing a higher increase in the COF, which depends majorly on the temperature of surfaces in contact and velocity, but inducing little effect on wear rate. This reduced effect on the wear rate is because the wear rate is dependent on multiple factors such as hardness, temperature, surface roughness, wear debris and velocity. In a nutshell, the COF is mainly affected by a temperature rise, while the wear rate is affected by so many other factors besides temperature.

3.3. *Effect of Temperature on CNTs-Reinforced Composites*

Tribological properties respond aggressively to an increase in temperature. An increase in temperature helps in softening the interfacial bonding of matrix and reinforcement, thereby increasing wear loss [79,93]. Wear loss increases considerably when the transition temperature which exists between the mild and severe wear is exceeded [94,95]. The transition from mild to severe wear loss takes place when friction-induced temperature raises the contact surface temperature beyond a critical value [88], which is most often 0.4 times the absolute melting temperature of the constituent materials. However, it has been reported that the critical temperature of composites is higher than that of unreinforced material. Then, it follows that wear volume loss of unreinforced materials is higher than that of the reinforced composites [96]. When the thermal conductivity of the reinforcement is high, the transition temperature of the composite will be high too, while the wear loss/rate will be low, resulting in an improved COF [97]. So, using CNTs as a reinforcement to improve the tribological properties of composites is not only effective but recommended because CNTs has very high thermal conductivity of over 3000 W/K, a very high melting temperature of 3550 °C and high oxidation resistance at high temperature, and is capable of imparting these properties on composites. Hence, CNTs is a good reinforcement for increasing the thermal resistance of composites, which invokes the characteristic properties necessary for reducing wear loss, COF and wear rate. A practical scenario of how temperature affects friction and wear of composites is when hot butter is pulled over a hot iron. It will be observed that the movement is faster than when it is pulled over a colder iron. This implies that the resisting force is lowered by the increased temperature. However, more butter is melted on the hot surface than on the colder surface. Hence, temperature increases wear loss but reduces friction coefficient.

3.4. CNTs-Reinforced Composites' Response to Various Media (Lubricants)

Generally, MMCs, PMCs and CMCs respond differently to different media. However, composite systems that are lubricated with a solid lubricant such as CNTs, SiC or graphite exhibit minimal wear rate, COF and wear loss [98]. This is because lubricants are good at raising the value at which sliding speed and applied loads cause seizure during rotation and sliding of surfaces over another. Secondly, lubricants form an interlaminar layer that prevents two contacting surfaces from wearing off their surfaces. Hard asperities of a counter surface find it difficult to touch the other surface because they are separated by a layer of the lubricant. More so, lubricants aid in the reduction in friction and wear by acting as coolants that attenuate the temperature emanating from the rubbing surfaces [93]. Among the four types of lubricants (oil, grease, penetrating lubricants and solid lubricants), CNTs stand out as a solid (dry) lubricant. So, a composite system that contains CNTs reinforcement enjoys reduced friction and wear. The reduction in wear by the application of lubricants is more effective whenever plastic abrasion is predominant [99]. The influence of lubrication in brittle materials is less predictive. It should be noted that the major functions of lubrication are: (i) to decrease the tangential force acting on the surface, and (ii) to diminish the incidence and harshness of asperity acting on the surface [100]. Even though decreasing the tangential force via lubrication decreases the incidence of cracking, sometimes it aids crack nucleation via local chemical reactions at the crack gradient. However, the damage does not outweigh the service. In a study to investigate the influence of lubricants on the abrasive wear of reinforced ceramics of SiC, alumina and carbide (Figure 4), it was observed that the wear rate differed by a factor of ≈10 among different environments [99]. From Figure 4, it can be seen that the wear rates in oil and in water were lower than wear rate in air and in tertiary amyl alcohol. The influence of lubrication on plastic materials and elastomers (rubbers) is a function of the predominant wear mechanism. For hard thermoplastics experiencing abrasion, their response will be that of ductile metals. However, for elastomers, the wear mode will be one of successive crack development driven by surface tractions [99]. Here, lubricant can reduce the wear rate by decreasing the friction force. This is the major reason why the abrasive wear of car tires (elastomer) in wet medium is lower than in dry condition. Hence, cars veer off the road more on wet roads than on dry roads since the COF diminishes in wet medium.

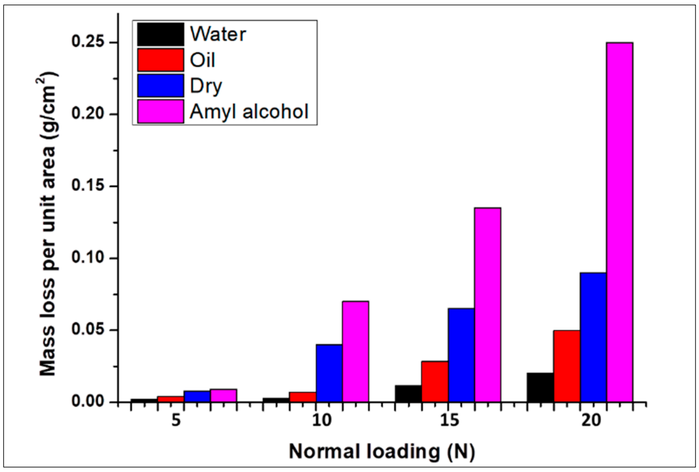


Figure 4. Comparison of Wear Loss of Ceramics–Carbide Composites on Different Lubricants, Adapted from [99].

3.5. Effect of Volume Fraction of Reinforcement on CNTs-Reinforced Composites

The relationship between volume fraction of CNTs and the tribological properties of composites follows a curve. The wear loss and COF decrease when the volume fraction is increased until an optimal value of volume fraction is attained. Once this limit is exceeded, the wear loss and COF tend to increase. Figure 5 shows the profiles at which CNTs-reinforced composites react to increase in volume fraction of reinforcement. It can be seen in Figure 5a that the friction coefficient and wear loss decreased as the volume fraction increased until the optimal volume fraction of 1 wt.% CNTs was attained [101]. Beyond the optimal limit, those wear properties increased. Excess volume fraction of CNTs agglomerates in the microstructure and reduces the crystallinity and hardness of composites [101–103]. Many authors, e.g., [35,104–107], who worked on the effect of volume fractions of CNTs on the wear loss and COF of composites also observed the same trends, as shown in Figure 5a–f. Therefore, for the effective development of robust CNTs-reinforced composites for industrial and wear-prone applications, the optimization of the CNTs content is not only imperative but recommended. This helps to avoid exceeding the optimal limit after which depreciation of tribo-characteristics ensues.

In another study, it was observed that the optimum weight percentage of CNTs on Al-Si-CNTs composite with the highest wear resistance was 3%. When this weight fraction was exceeded (at 4 wt.%), the wear rate increased and was attributed to increased porosity, deterioration of mechanical strength and nucleation of cracks [108]. To enhance dispersion of CNTs on Al 6061 and improve its tribological properties, SiC was used to coat CNTs. The SiC-coated CNTs was then used to reinforce the metal matrix. As the volume fraction of the reinforcement was increased to 5% (Al-5vol.%SiC@CNTs), the wear rate decreased by 45%, and the coefficient of friction decreased by 31% in comparison with unreinforced Al. The improvements were attributed to the switch from both adhesive and delamination wear modes to only abrasive wear stimulated by the hard particles of SiC-coated CNTs reinforcement [109]. Transition from adhesive and delamination wear mode to abrasive mode has been the mechanism that invokes the protection of surfaces from aggressive wear by CNTs incorporated into composites. Such reinforcement induces transition from brittle fracture to ductile fracture. In a study to improve the tribology of zinc–copper–magnesium alloy (ZC71), it was observed that addition of 5 wt.%SiC to the ZC71 alloy could only decrease the wear rate by 5%. However, when 0.5 wt.%CNTs was dispersed unto ZC71-5SiC, the wear rate decreased by 15% together with a significant decrease in friction coefficient and wear loss. These improvements were attributed to the self-lubrication property of CNTs [110]. To enhance the dispersion of CNTs and reduce its agglomeration which initiates depreciation of wear and friction characteristics, it is recommended that coating of CNTs with SiC or functionalizing it will improve the properties.

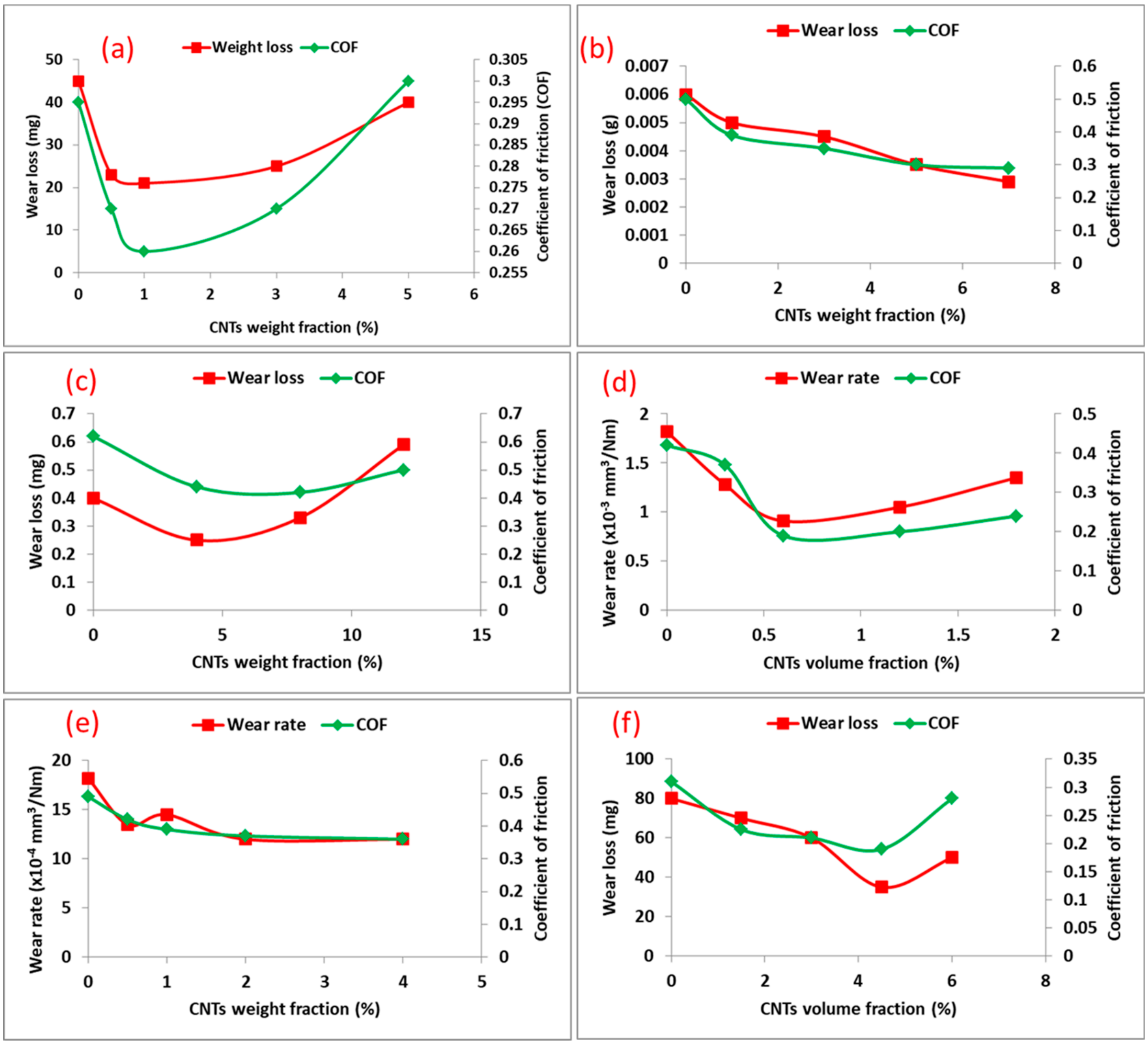


Figure 5. Effect of Volume Fractions of CNTs on Wear Loss and COF of (**a**) Polypropylene-CNTs, (**b**) Polypropylene-CNTs, (**c**) Alumina–CNTs, (**d**) Cu–CNTs, (**e**) Mg–CNTs and (**f**) Al-CNTs Composites, Adapted from [35,101,104–107].

3.6. Effect of Porosity on Tribology of CNTs-Reinforced Composites

The porosity of a composite material is the measure of the difference between the computed density (theoretical) and actual (experimental) density, all expressed in percentage. It is simply the amount of pores domiciled in the microstructure. Mathematically, it is captured as follows [20]:

$$\text{Porosity} = 100\% - \text{Relative densification} \quad (1)$$

$$\text{Relative densification} = \text{Actual density}/\text{Theoretical density} \times 100\% \quad (2)$$

From Equation (1), it can be seen that the higher the densification of a composite, the lower the porosity. Recall that mechanical strength of composites is dependent partly on its relative density. This is because highly densified composites exhibit high modulus and strength as a result of dislocation interlock [111], increased dislocation density field [112], strengthened grain boundaries, strong metallurgical bonding and strong matrix/reinforcement interface [113]. So, since porosity and densification (density) are inversely related, it follows that the higher the porosity in a composite, the more prone it is to wear loss. Resistance to wear has been reported to be inversely related to porosity [114].

More so, porosity is a defect principally caused by air entrapped into the microstructure during consolidation which leaves micro-voids after solidification. The pores are nucleating ground for dislocation and crack propagation [20]. Non-uniform dispersion of reinforcements generates high porosity in a composite. This implies that excess volume fraction of reinforcements generates high number of pores in a composite. So, incorporating a low volume fraction of CNTs and ensuring its homogenous dispersion helps to reduce porosity. It was reported that 5% porosity is the critical value of porosity in composite systems. This in essence means that if the porosity in a fabricated composite exceeds the critical value, the characteristic properties of such composite depreciate [115–117]. High porosity promotes poor tribological properties because material pull-out, debonding, delamination etc. that promote wear loss are provoked by porosity.

3.7. Effect of Wettability on CNTs-Reinforced Composites

Wettability is the degree of absorption or interfacial attraction between reinforcement and matrix in a composite system [118]. The matrix usually exists as a solid solution or liquid solution and presents an interface at which the reinforcement is absorbed and dispersed in the solution. Research has shown that wettability of the reinforcement directly affects the mechanical strength (micro-hardness) of the resulting composite [119]. This implies that good wettability improves tribological properties of composite systems, following Archard's theory. It was reported that a reduction in the COF and wear rate/volume was enhanced by high wettability and uniform dispersion of CNTs reinforcement in the matrix [120]. Many factors have been identified as the causes of poor wettability of reinforcements on matrices. These factors include (a) chemical reaction: high chemical reactivity between reinforcement and matrix reduces wettability [118]. (b) Contamination: the presence of oxide contamination on the surface of reinforcements reduces their absorption level on the matrix [121]. (c) Surface smoothness: the smoother the surface of the carbide reinforcement, the lesser the wetting angle and vice versa [122]. (d) Gas layer: the presence of gas layer on the surface of reinforcements prevents the physical contact of them with the molten matrices, thereby reducing wettability [123]. (e) Density: It will be noted that CNTs has very low density, and so, it is likely that it will float on top of molten matrices; in addition, this phenomenon reduces their contact with the molten matrices, thereby undermining its wettability. (f) Particle size: Micro- or nano-particle size reduces the wettability because the smaller the particle size, the higher the surface areas and higher agglomeration tendencies, as a consequence of higher van der Waals force [121]. Common ways to improve the wettability of CNTs on aluminum matrix, for instance, is by reducing the contact angle between them or by creating functional bonds such as covalent or hydrogen bonds through functionalization of CNTs [124]. It can equally be achieved through coating CNTs with Ni [125], Si [126], or adding Cu, Li, Mg and Ca in the composite [127]. These measures improve the wear resistance, wear loss and COF of CNTs-reinforced composite materials. Poor wettability, on the other hand, promotes agglomeration, which in turn weakens the strength, tribology and other properties of a composite. For instance, delamination and debonding are promoted by weak interfacial bonds provoked by agglomerated reinforcements. These defects bring about depreciation of tribological properties.

3.8. Effect of Dispersion of Reinforcement on CNTs-Reinforced Composites

The high aspect ratio of CNTs has made the material prone to agglomeration, which is as a result of its poor dispersion on the matrix. The dispersion of CNTs on matrices is usually difficult, and this phenomenon has affected properties of CNTs-reinforced composites. Poorly dispersed reinforcement generates micro-voids in the final product due to reinforcement clusters. Very unfortunately, micro-pores are the nucleating site for crack propagation and fatigue failures [128]. Research has shown that a high volume fraction of CNTs on composites promotes non-homogeneous dispersion [129]. Moreover, poorly dispersed reinforcements cannot absorb load from the matrix effectively, which implies that mechanical strength and tribological properties of such composite will be highly impaired. Chen et at. [130] studied the effect of dispersion method on tribological properties of carbon nanotube-reinforced epoxy resin composites. It was observed that the wear resistance increased when the dispersion rate increased. Any consolidation technique that promotes dispersion of reinforcement enhances tribological properties of the composites. This is because dispersing reinforcement homogeneously is a prerequisite for engendering excellent microstructure bereft of micro-voids and impurities, with enhanced mechanical and tribological properties [67,131]. In a comparative study to identify the effect of CNTs dispersion on the tribological properties of composite material, Lim et al. [35] fabricated an alumina–CNTs composite via tape casting, followed by lamination and hot pressing, and secondly via hot pressing. It was realized that tape casting process improved uniform dispersion of CNTs on the alumina more than the hot pressing. Incidentally, wear resistance of the sample prepared with tape casting was higher than that processed with only hot pressing. Other techniques such as SPS, laser cladding and sputtering, noted for enhancing the uniform dispersion of reinforcement, have reportedly improved the tribological properties of CNTs-reinforced composites.

3.9. CNTs as Solid Lubricant and Lubrication Additive

Lubricants are materials which can be liquid, gas or solid and which are applied to moving surfaces in order to smoothen their movement or to reduce the force of friction existing between the contacting surfaces [132]. Solid materials with a low COF are usually used as lubricants in the place of liquid lubricants or gaseous films because of the limitations of liquid/gaseous lubricants [133]. For instance, in food processing machinery, some liquid lubricants may be poisonous to the food being processed. So, applying liquid lubricant will contaminate the food product. Additionally, devices operating in a vacuum or in the space are liable to experience vaporization of liquid lubricants. Hence, it is only solid lubricants that are applied in such equipment. More so, liquid lubricants that can operate at high temperatures above 1000 °C without vaporizing are rare. Therefore, only solid lubricants are used in components operating at such temperatures. Oxidation or decomposition of liquid lubricants at high temperatures is more likely to occur than that of solid lubricants. The conventional solid lubricants include graphite and its derivative (CNTs, graphene), molybdenum disulfide (MoS2) and Polytetrafluoroethylene (PTFE) [134]. These materials have the capability of improving smooth movement of surfaces over another, or reducing the friction of moving parts by producing self-lubricating film that prevents the two surfaces from wearing off each other. They are incorporated into materials as thin coatings, or used for surface modification or as composite reinforcement. Graphite, and its derivatives, and PTFE are usually used as reinforcing phases to enhance the self-lubrication properties of composites. Graphite and MoS_2 may be incorporated in the form of dry powders to ease friction in moving parts. Sometimes they are introduced into liquid oils or greases as fine particles to offer boundary lubrication. The temperature limitations of the three solid lubricants include the following: graphite has a maximum operating temperature of 500 °C, MoS_2 has one of 300 °C, and PTFE has one of 250 °C, above which they become susceptible to oxidation and decomposition. More so, the lubricating efficiency of graphite is affected by condensable vapors while MoS_2 is heavily affected by high atmospheric humidity. So, CNTs, which represent a hybrid of graphite, are usually applied as solid lubricant to ease friction at elevated temperatures. In a study to investigate the lubrication efficacy of CNTs, Puchy et al. [36] consolidated Al2O3-CNTs with spark plasma sintering. The results of the composite's tribology showed that low volume fraction of CNTs invoked decreased friction force and shallow depth penetration. The improvement was attributed to grain refinement effect of CNTs together with reinforcement capability of CNTs. Bastwros et al. [135] blended CNTs with aluminum powder using high-energy ball milling. The blend was cold compacted followed by hot extrusion. It was observed that as the volume fraction of CNTs increased, the COF and wear rate decreased accordingly. When 5 wt.% CNTs was added to the Al matrix, the COF and wear rate of the composites improved by 55.6% and 78.8%, respectively. The wear mechanism transited from adhesion to abrasion as the weight fraction of CNTs increased. The self-lubricating characteristics of CNTs induced the formation of carbon film on the contacting surfaces which helped in attenuating the friction and wear rate. In another study, Zhang et al. [136] produced vertically oriented CNTs on an Inconel matrix via chemical vapor deposition (CVD), followed by electrodeposition of MoS2 on the surface of the CNTs. The produced composite exhibited high friction, wear and lubrication properties at both ambient and high temperatures. In summary, CNTs have exhibited extraordinary friction reduction and wear resistance, and these properties have broadened its applications. CNTs are used as lubricants in industrial machines [137,138] and electromechanical devices [139,140]. Figure 6 summarized the effect of CNTs additive on lubricants. From Figure 6, it can be seen that the addition of CNTs into lubricant reduced the wear loss of the material. It is an effective lubricant coating, good additive in lubricants, and standard reinforcement in bulk lubricating composites [141,142].

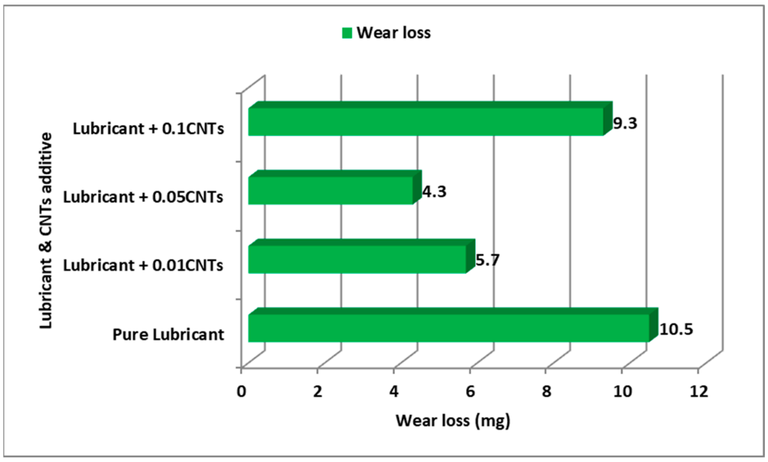


Figure 6. Wear Loss Profiles of Lubricant with CNTs Additives [142].

4. Challenges and Remedies in the Development of CNTs-Reinforced Composites

The tribological improvements of CNTs-reinforced composites are militated by a number of factors. The factors include high volume fraction of CNTs, porosity of the composite, wettability of the CNTs, agglomeration of CNTs, nature and type of the matrix. Incidentally, these challenges are provoked by inhomogeneous dispersion of CNTs on the matrix. Therefore, it is imperative to discuss effective ways of improving homogenous dispersion of CNTs on matrices in order to improve wettability, reduce agglomeration and porosity so as to ameliorate most of these challenges. Effective dispersion techniques of CNTs on matrices are discussed in this section.

One of the most effective ways of dispersing CNTs on matrices is by ball milling. Ball milling is a mechanical process used to pulverize powders into micro- or nanoparticles [143]. However, it is not only used for pulverizing powders but also used for the synthesis of nanocomposites and to promote optimal distribution of the reinforcing phases [144]. It was reported that ball milling contaminates powders and distorts the integrity of CNTs walls. During the ball milling, a high pressure is produced locally as a result of collision of rigid balls, powders and the walls of the vial. This method has been used to distribute and shorten the length of CNTs in a polymer matrix [145]. It was also reported that high-energy ball milling was employed in dispersion of CNTs unto the Al matrix [129,146]. This method has effectively broken entangled CNTs so as to enhance its homogenous dispersion on matrices; however, it inflicts morphological and structural damage to the walls of CNTs [147]. Esawi et al. [129,148] studied the effect of ball milling on the morphology and content of CNTs on the Al matrix composite. It was observed that CNTs with a bigger diameter were easier to disperse than those with a smaller diameter.

This implies that CNTs with a tiny diameter agglomerated more easily. Choi et al. [146] investigated the duration of ball milling in the production of Al-CNTs composite and observed that 6 h was the optimal duration that produced the best dispersion and excellent reinforcement/matrix bonding. Tserengombo et al. [149] studied the effects of functionalization and ball milling on the dispersion, thermal and electrical conductivity of MWCNTs in aqueous solution. Surface modifications using acid and alkaline media followed by ball milling were conducted. It was reported that the alkaline-modified MWCNTs exhibited better dispersion and superior properties than the acid-modified MWCNTs. However, only acid or alkaline treatment was not enough for effective dispersion, and ball milling must be incorporated.

Tubular mixing is another technique used in dispersing CNTs reinforcement on matrices [150]. This method is essentially used for blending and cannot be used to shorten the length of CNTs or reduce the particle size of powders. In the tubular mixing method, powders are weighed into containment, mostly plastic bottles. The containment with the powder is placed inside the tubular. Balls (steel, tungsten, alumina) are often introduced to the powder at a ball-to-powder ratio of 2:5 or 3:5 depending on the density of the constituent powders. A process control agent (PCA) incorporated into the powder eliminates cold welding of the powder by the balls. Stearic acid, methanol or ethanol is usually employed on blending the powders that contain CNTs [150,151]. It was essentially invented to reduce the effect of ball milling in terms of distorting the morphology and structure of CNTs. Researchers have reported effective dispersion of CNTs on Al matrix using the tubular mixing technique [18,20,102]. Peng et al. [152] combined ultra-sonication, magnetic stirring and tubular shaker-mixing technique in dispersing 0.5 wt.% MWNT on the Al matrix composite. It was observed that the structural and morphological integrity of CNTs was intact after fabrication of the composite as confirmed by the constant value of its I_D/I_G ratio in Raman spectra. The absence of defects of the CNTs promoted the excellent properties exhibited by the composite. Meanwhile, the deficiency of this technique is that it cannot shorten the length of the CNTs. So, the aspect ratio remains unchanged after blending, and a high aspect ratio generates high agglomeration.

Another efficient method of dispersing CNTs is sonication. This technique uses sound energy to vibrate powder particles and fibers inside a liquid. Ultrasonic frequencies (≈20 kHz) are usually employed in the agitation. So, this method is usually called ultrasonication technique of powder mixing [153]. Pressure generated during sonication forms bubbles, which break down intermittently to release massive energy that distorts the molecular/van Der Waal bonds of the CNTs and enhance their dispersion [154]. Simoes et al. [155] used ultrasonication to disperse CNTs on Al/Ni matrix with isopropanol as the PCA for 15 min. Homogenous dispersion of CNTs was recorded, and this increased the hardness of the Al-1vol%CNTs by 50%, together with other improvements. Thomas et al. [156] developed a Al-MWCNTs composite using the sonication mode of dispersion, with ethanol solution as the PCA. The sonication lasted for 30 min and was followed by magnetic stirring for another 30 min, and finally ball milling for 4 h at a speed of 200 rpm. The results showed that a combination of sonication, magnetic stirring and ball milling is more efficient, less injurious to the CNTs structure and less time consuming than only ball milling. Javadi et al. [157] equally opined that that ultrasonication before ball milling reduced the milling time and reduced damage to the morphology and structure of CNTs. Rais et al. [158] observed that ultrasonication not only improved homogenous dispersion of CNTs on Al matrix but also invoked strong bonding between the matrix and reinforcement. These measures used in dispersing CNTs on matrices are the effective panacea for developing robust CNTs-reinforced composites which can withstand severe friction and wear and can be used in wear-demanding applications.

5. Conclusions and Recommendations

A study on the tribological properties of CNTs-reinforced composites has been conducted. The following points were drawn from the study:

1. CNTs reinforcement increases the wear resistance and reduces the COF in MMCs and PMCs; for CMCs, it reduces their brittleness by increasing their fracture toughness besides reducing their COF.
2. Wear loss transits from mild to severe when the critical temperature (usually 0.4 times the melting temperature of the constituent materials) is exceeded. CNTs possess high thermal conductivity and high melting temperature can delay such a transition by increasing the critical temperature of CNTs-reinforced composites.
3. Incorporating CNTs reinforcement into metals, polymers or ceramics is challenging because of its high aspect ratio. It has low wettability, and so, the dispersion is difficult and can be improved by attaching functional groups to its unreactive covalent and hydrogen bonds via functionalization. More so, uniform dispersion can equally be achieved by coating it with Ni, Si, Cu, Li, Mg or Ca.
4. CNTs solid lubricant is preferred to liquid and gaseous lubricants in certain applications such as food processing devices because it cannot contaminate foods. Additionally, devices that operate in a vacuum, in the space or at very high temperature vaporize liquid and gaseous lubricants, leaving only solid lubricants such as CNTs that possesses high melting temperature as the choice lubricant.
5. CNTs lubricant is considered as the most effective for high temperature application as the temperature limit of CNTs (500 °C) is higher than other solid lubricants.
6. Shortening the aspect ratio of CNTs through ball milling helps in dispersing it on matrices. However, ball milling distorts the morphology and structure of CNTs. So, by subjecting CNTs to ultrasonication and magnetic stirring before ball milling, the blending and dispersion will be more effective, innocuous and timely.
7. CNTs-reinforced MMCs such as Al-CNTs can function better than steel-reinforced aluminum conductor in electricity transmission; polymer-CNTs composites have better properties than steel amours and shields used by military personnel; ceramic-CNTs composites can perform better than W and diamond for cutting tools. Conventional high temperature materials for producing boilers, nozzles and turbines will perform better if reinforced with CNTs.
8. CNTs reinforcement has been confirmed to be useful in improving wear, friction and lubrication properties of MMCs, PMCs and CMCs.

It is recommended that:

Volume fraction of CNTs on matrices plays a major role in its dispersion and wettability. Therefore, choosing a low volume fraction is recommended for better dispersion and high wettability. Additionally, the optimization of the volume fraction before developing CNTs-reinforced composite should not be compromised. Maximum tribological improvement of composites using CNTs reinforcement can only be achieved when there is uniform dispersion and full wettability of CNTs.

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References

1. Tyagi, A.; Walia, R.; Murtaza, Q.; Pandey, S.M.; Tyagi, P.K.; Bajaj, B. A critical review of diamond like carbon coating for wear resistance applications. *Int. J. Refract. Met. Hard Mater.* **2019**, *78*, 107–122. [CrossRef]
2. Awasthi, S.; Gaur, J.K.; Bobji, M. Advanced ferrogels with high magnetic response and wear resistance using carbon nanotubes. *J. Alloys Compd.* **2020**, *848*, 156259. [CrossRef]
3. Shrivastava, R.; Singh, K. Interlaminar fracture toughness characterization of laminated composites: A review. *Polym. Rev.* **2020**, *60*, 542–593. [CrossRef]

4. Makowiec, M.E.; Blanchet, T.A. Improved wear resistance of nanotube-and other carbon-filled PTFE composites. *Wear* **2017**, *374*, 77–85. [CrossRef]
5. Singh, G.; Ablyaz, T.R.; Shlykov, E.S.; Muratov, K.R.; Bhui, A.S.; Sidhu, S.S. Enhancing corrosion and wear resistance of Ti6Al4V alloy using CNTs mixed electro-discharge process. *Micromachines* **2020**, *11*, 850. [CrossRef]
6. Iijima, S. Helical microtubules of graphitic carbon. *Nature* **1991**, *354*, 56. [CrossRef]
7. Iijima, S. Carbon nanotubes. *MRS Bull.* **1994**, *19*, 43–49. [CrossRef]
8. Obitayo, W.; Liu, T. A review: Carbon nanotube-based piezoresistive strain sensors. *J. Sens.* **2012**, *2012*, 652438. [CrossRef]
9. Ujah, C.O.; Kallon, D.V.V. Trends in Aluminium Matrix Composite Development. *Crystals* **2022**, *12*, 1357. [CrossRef]
10. Abazari, S.; Shamsipur, A.; Bakhsheshi-Rad, H.R.; Ismail, A.F.; Sharif, S.; Razzaghi, M.; Ramakrishna, S.; Berto, F. Carbon nanotubes (CNTs)-reinforced magnesium-based matrix composites: A comprehensive review. *Materials* **2020**, *13*, 4421. [CrossRef]
11. Merchan-Merchan, W.; Saveliev, A.V.; Kennedy, L.; Jimenez, W.C. Combustion synthesis of carbon nanotubes and related nanostructures. *Prog. Energy Combust. Sci.* **2010**, *36*, 696–727. [CrossRef]
12. Munoz, E.; Maser, W.; Benito, A.; Martinez, M.; De la Fuente, G.; Righi, A.; Sauvajol, J.; Anglaret, E.; Maniette, Y. Single-walled carbon nanotubes produced by cw CO2-laser ablation: Study of parameters important for their formation. *Appl. Phys. A* **2000**, *70*, 145–151.
13. Laplaze, D.; Bernier, P.; Maser, W.; Flamant, G.; Guillard, T.; Loiseau, A. Carbon nanotubes: The solar approach. *Carbon* **1998**, *36*, 685–688. [CrossRef]
14. Park, J.G.; Keum, D.H.; Lee, Y.H. Strengthening mechanisms in carbon nanotube-reinforced aluminum composites. *Carbon* **2015**, *95*, 690–698. [CrossRef]
15. Ujah, C.O.; Popoola, O.M.; Popoola, A.P.; Aigbodion, V.S. Development and modelling of aluminium-carbon nanotubes-niobium composite conductor for high voltage transmission networks. In *Chemical, Metallurgical and Materials Engineering*; Tshwane University of Technology: Pretoria, South Africa, 2020.
16. Sarina, B.; Kai, T.; Kvithyld, A.; Thorvald, E.; Tangstad, M. Wetting of pure aluminium on graphite, SiC and Al2O3 in aluminium filtration. *Trans. Nonferrous Met. Soc. China* **2012**, *22*, 1930–1938.
17. Archard, J. Contact and rubbing of flat surfaces. *J. Appl. Phys.* **1953**, *24*, 981–988. [CrossRef]
18. Ujah, C.; Popoola, A.; Popoola, O.; Aigbodion, V. Enhanced tribology, thermal and electrical properties of Al-CNT composite processed via spark plasma sintering for transmission conductor. *J. Mater. Sci.* **2019**, *54*, 14064–14073. [CrossRef]
19. Mikhin, N.; Lyapin, K. Hardness dependence of the coefficient of friction. *Sov. Phys. J.* **1970**, *13*, 317–321. [CrossRef]
20. Ujah, C.; Popoola, P.; Popoola, O.; Aigbodion, V. Enhanced mechanical, electrical and corrosion characteristics of Al-CNTs-Nb composite processed via spark plasma sintering for conductor core. *J. Compos. Mater.* **2019**, *53*, 3775–3786. [CrossRef]
21. Ujah, C.O.; Kallon, D.V.V.; Aikhuele, D.O.; Aigbodion, V.S. Advanced Composite Materials: A Panacea for Improved Electricity Transmission. *Appl. Sci.* **2022**, *12*, 8291. [CrossRef]
22. Patil, A.; Walunj, G.; Ozdemir, F.; Gupta, R.K.; Borkar, T. Tribological Behavior of Carbon-Based Nanomaterial-Reinforced Nickel Metal Matrix Composites. *Materials* **2021**, *14*, 3536. [CrossRef]
23. Watanabe, T. Wettability of ceramic surfaces-A wide range control of surface wettability from super hydrophilicity to super hydrophobicity, from static wettability to dynamic wettability. *J. Ceram. Soc. Jpn.* **2009**, *117*, 1285–1292. [CrossRef]
24. Rajkumar, K.; Aravindan, S. Tribological studies on microwave sintered copper–carbon nanotube composites. *Wear* **2011**, *270*, 613–621. [CrossRef]
25. Guiderdoni, C.; Estournès, C.; Peigney, A.; Weibel, A.; Turq, V.; Laurent, C. The preparation of double-walled carbon nanotube/Cu composites by spark plasma sintering, and their hardness and friction properties. *Carbon* **2011**, *49*, 4535–4543. [CrossRef]
26. Dong, S.; Tu, J.; Zhang, X. An investigation of the sliding wear behavior of Cu-matrix composite reinforced by carbon nanotubes. *Mater. Sci. Eng. A* **2001**, *313*, 83–87. [CrossRef]
27. Chen, W.; Tu, J.; Wang, L.; Gan, H.; Xu, Z.; Zhang, X. Tribological application of carbon nanotubes in a metal-based composite coating and composites. *Carbon* **2003**, *41*, 215–222. [CrossRef]
28. Zhou, S.-M.; Zhang, X.-B.; Ding, Z.-P.; Min, C.-Y.; Xu, G.-L.; Zhu, W.-M. Fabrication and tribological properties of carbon nanotubes reinforced Al composites prepared by pressureless infiltration technique. *Compos. Part A Appl. Sci. Manuf.* **2007**, *38*, 301–306. [CrossRef]
29. Akbarpour, M.; Alipour, S.; Najafi, M. Tribological characteristics of self-lubricating nanostructured aluminum reinforced with multi-wall CNTs processed by flake powder metallurgy and hot pressing method. *Diam. Relat. Mater.* **2018**, *90*, 93–100. [CrossRef]
30. Manikandan, P.; Sieh, R.; Elayaperumal, A.; Le, H.; Basu, S. Micro/nanostructure and tribological characteristics of pressureless sintered carbon nanotubes reinforced aluminium matrix composites. *J. Nanomater.* **2016**, *2016*, 9843019. [CrossRef]
31. Ujah, C.O.; Popoola, P.; Popoola, O.; Ajenifuja, E. Effect of CNTs on the tribology and thermal behaviours of al nano-powder fabricated with SPS for industrial application. In *Conference on Diversification of Developing Economies: Imperatives for Sustainable Environment and Technological Innovations*; OAU Osun: Osun State, Nigeria, 2020.
32. Mansoor, M.; Shahid, M. Tribological properties of MWCNTs strengthened aluminum composite fabricated by induction melting. *Adv. Mater. Res.* **2015**, *1101*, 62–65. [CrossRef]
33. An, J.-W.; You, D.-H.; Lim, D.-S. Tribological properties of hot-pressed alumina–CNT composites. *Wear* **2003**, *255*, 677–681. [CrossRef]

34. Yamamoto, G.; Omori, M.; Yokomizo, K.; Hashida, T.; Adachi, K. Structural characterization and frictional properties of carbon nanotube/alumina composites prepared by precursor method. *Mater. Sci. Eng. B* **2008**, *148*, 265–269. [CrossRef]
35. Lim, D.-S.; You, D.-H.; Choi, H.-J.; Lim, S.-H.; Jang, H. Effect of CNT distribution on tribological behavior of alumina–CNT composites. *Wear* **2005**, *259*, 539–544. [CrossRef]
36. Puchy, V.; Hvizdos, P.; Dusza, J.; Kovac, F.; Inam, F.; Reece, M. Wear resistance of Al2O3–CNT ceramic nanocomposites at room and high temperatures. *Ceram. Int.* **2013**, *39*, 5821–5826. [CrossRef]
37. Zayed, A.S.; Kamel, B.M.; Abdelsadek Osman, T.; Elkady, O.A.; Ali, S. Experimental study of tribological and mechanical properties of aluminum matrix reinforced by Al2O3/CNTs. *Fuller. Nanotub. Carbon Nanostruct.* **2019**, *27*, 538–544. [CrossRef]
38. Nie, P.; Min, C.; Song, H.-J.; Chen, X.; Zhang, Z.; Zhao, K. Preparation and tribological properties of polyimide/carboxyl-functionalized multi-walled carbon nanotube nanocomposite films under seawater lubrication. *Tribol. Lett.* **2015**, *58*, 7. [CrossRef]
39. Yang, Z.; Shi, S.Q. Fabrication and tribological properties of polymer-carbon nanotubes nanocomposites. *Key Eng. Mater.* **2007**, *334–335*, 661–664. [CrossRef]
40. Wang, C.; Dong, B.; Gao, G.-Y.; Xu, M.-W.; Li, H.-L. A study on microhardness and tribological behavior of carbon nanotubes reinforced AMMA-CNTs copolymer nanocomposites. *Mater. Sci. Eng. A* **2008**, *478*, 314–318. [CrossRef]
41. Li, Y.; Wang, Q.; Wang, S. A review on enhancement of mechanical and tribological properties of polymer composites reinforced by carbon nanotubes and graphene sheet: Molecular dynamics simulations. *Compos. Part B Eng.* **2019**, *160*, 348–361. [CrossRef]
42. Campo, M.; Jiménez-Suárez, A.; Ureña, A. Effect of type, percentage and dispersion method of multi-walled carbon nanotubes on tribological properties of epoxy composites. *Wear* **2015**, *324*, 100–108. [CrossRef]
43. Wang, H.-D.; He, P.-F.; Ma, G.-Z.; Xu, B.-S.; Xing, Z.-G.; Chen, S.-Y.; Liu, Z.; Wang, Y.-W. Tribological behavior of plasma sprayed carbon nanotubes reinforced TiO2 coatings. *J. Eur. Ceram. Soc.* **2018**, *38*, 3660–3672. [CrossRef]
44. Moghadam, A.D.; Omrani, E.; Menezes, P.L.; Rohatgi, P.K. Mechanical and tribological properties of self-lubricating metal matrix nanocomposites reinforced by carbon nanotubes (CNTs) and graphene—A review. *Compos. Part B Eng.* **2015**, *77*, 402–420. [CrossRef]
45. Singh, N.; Belokar, R. Tribological behavior of aluminum and magnesium-based hybrid metal matrix composites: A state-of-art review. *Mater. Today Proc.* **2021**, *44*, 460–466. [CrossRef]
46. Chan, J.X.; Wong, J.F.; Petrů, M.; Hassan, A.; Nirmal, U.; Othman, N.; Ilyas, R.A. Effect of nanofillers on tribological properties of polymer nanocomposites: A review on recent development. *Polymers* **2021**, *13*, 2867. [CrossRef]
47. Goswami, S.; Ghosh, R.; Hirani, H.; Mandal, N. Mechano-tribological performance of Graphene/CNT reinforced alumina nanocomposites–Review and quantitative insights. *Ceram. Int.* **2022**, *48*, 11879–11908. [CrossRef]
48. Choudhary, M.; Sharma, A.; Raj, S.A.; Sultan, M.T.H.; Hui, D.; Shah, A.U.M. Contemporary review on carbon nanotube (CNT) composites and their impact on multifarious applications. *Nanotechnol. Rev.* **2022**, *11*, 2632–2660. [CrossRef]
49. Demircan, O.; Al-Darkazali, A.; İnanç, İ.; Eskizeybek, V. Investigation of the effect of CNTs on the mechanical properties of LPET/glass fiber thermoplastic composites. *J. Thermoplast. Compos. Mater.* **2020**, *33*, 1652–1673. [CrossRef]
50. Reddy, P.R.S.; Reddy, T.S.; Mogulanna, K.; Srikanth, I.; Madhu, V.; Rao, K.V. Ballistic impact studies on carbon and E-glass fibre based hybrid composite laminates. *Procedia Eng.* **2017**, *173*, 293–298. [CrossRef]
51. Sastry, Y.S.; Budarapu, P.R.; Krishna, Y.; Devaraj, S. Studies on ballistic impact of the composite panels. *Theor. Appl. Fract. Mech.* **2014**, *72*, 2–12. [CrossRef]
52. Chaurasia, A.; Mulik, R.S.; Parashar, A. Polymer-based nanocomposites for impact loading: A review. *Mech. Adv. Mater. Struct.* **2021**, *29*, 2581–2606. [CrossRef]
53. Hassanzadeh-Aghdam, M.; Ansari, R. Thermomechanical investigation of unidirectional carbon fiber-polymer hybrid composites containing CNTs. *Int. J. Mech. Mater. Des.* **2019**, *15*, 471–488. [CrossRef]
54. Boddu, V.M.; Brenner, M.W.; Patel, J.S.; Kumar, A.; Mantena, P.R.; Tadepalli, T.; Pramanik, B. Energy dissipation and high-strain rate dynamic response of E-glass fiber composites with anchored carbon nanotubes. *Compos. Part B Eng.* **2016**, *88*, 44–54. [CrossRef]
55. Zengin, E.; Ahlatci, H.; Zengin, H. Investigation of microstructure, tribological and corrosion properties of AISI 316 L stainless steel matrix composites reinforced by carbon nanotubes. *Mater. Today Commun.* **2021**, *29*, 102758. [CrossRef]
56. Munnur, H.; Nagesh, S.; Siddaraju, C.; Rajesh, M.; Rajanna, S. Characterization & tribological behaviour of aluminium metal matrix composites–A review. *Mater. Today Proc.* **2021**, *47*, 2570–2574.
57. Basha, G.; Bolleddu, V. Tribological Behavior of Carbon Nanotubes Reinforced High Velocity Oxy-Fuel Sprayed WC-20 wt.% Co Coatings. *J. Therm. Spray Technol.* **2021**, *30*, 1653–1665. [CrossRef]
58. Potts, J.R.; Dreyer, D.R.; Bielawski, C.W.; Ruoff, R.S. Graphene-based polymer nanocomposites. *Polymer* **2011**, *52*, 5–25. [CrossRef]
59. Arash, B.; Wang, Q.; Varadan, V. Mechanical properties of carbon nanotube/polymer composites. *Sci. Rep.* **2014**, *4*, 6479. [CrossRef]
60. Kumar, A.; Sharma, K.; Dixit, A.R. Carbon nanotube-and graphene-reinforced multiphase polymeric composites: Review on their properties and applications. *J. Mater. Sci.* **2020**, *55*, 2682–2724. [CrossRef]
61. Coleman, J.N.; Khan, U.; Blau, W.J.; Gun'ko, Y.K. Small but strong: A review of the mechanical properties of carbon nanotube–polymer composites. *Carbon* **2006**, *44*, 1624–1652. [CrossRef]
62. Carneiro, Í.; Simões, S. Strengthening mechanisms in carbon nanotubes reinforced metal matrix composites: A review. *Metals* **2021**, *11*, 1613. [CrossRef]

63. Kondoh, K.; Threrujirapapong, T.; Imai, H.; Umeda, J.; Fugetsu, B. Characteristics of powder metallurgy pure titanium matrix composite reinforced with multi-wall carbon nanotubes. *Compos. Sci. Technol.* **2009**, *69*, 1077–1081. [CrossRef]
64. Nieto, A.; Agarwal, A.; Lahiri, D.; Bisht, A.; Bakshi, S.R. *Carbon Nanotubes: Reinforced Metal Matrix Composites*; CRC Press: Boca Raton, FL, USA, 2021.
65. Meshalkin, V.P.; Belyakov, A.V. Methods used for the compaction and molding of ceramic matrix composites reinforced with carbon nanotubes. *Processes* **2020**, *8*, 1004. [CrossRef]
66. Chan, K.F.; Zaid, M.H.M.; Mamat, M.S.; Liza, S.; Tanemura, M.; Yaakob, Y. Recent developments in carbon nanotubes-reinforced ceramic matrix composites: A review on dispersion and densification techniques. *Crystals* **2021**, *11*, 457. [CrossRef]
67. Ujah, C.O.; Kallon, D.V.V.; Aigbodion, V.S. Overview of Electricity Transmission Conductors: Challenges and Remedies. *Materials* **2022**, *15*, 8094. [CrossRef]
68. Javaid, M.; Haleem, A.; Singh, R.P.; Suman, R.; Rab, S. Role of additive manufacturing applications towards environmental sustainability. *Adv. Ind. Eng. Polym. Res.* **2021**, *4*, 312–322. [CrossRef]
69. Dong, S.; Zhai, J. Biosensors: Microbial Sensors. In *Reference Module in Biomedical Sciences*; Elsevier: Amsterdam, The Netherlands, 2021.
70. Yu, T.; Liu, J.; He, Y.; Tian, J.; Chen, M.; Wang, Y. Microstructure and wear characterization of carbon nanotubes (CNTs) reinforced aluminum matrix nanocomposites manufactured using selective laser melting. *Wear* **2021**, *476*, 203581. [CrossRef]
71. Kalangi, C.; Bolleddu, V.; Allasi, H.L. Tribological characteristics of carbon nanotubes-reinforced plasma-sprayed Al2O3-TiO2 ceramic coatings. *Adv. Mater. Sci. Eng.* **2021**, *2021*, 8094640. [CrossRef]
72. Huang, S.J.; Abbas, A.; Ballokova, B. Effect of CNT on microstructure, dry sliding wear and compressive mechanical properties of AZ61 magnesium alloy. *J. Mater. Res. Technol.* **2019**, *8*, 4273–4286. [CrossRef]
73. Ye, Z.; Li, J.; Liu, L.; Ma, F.; Zhao, B.; Wang, X. Microstructure and wear performance enhancement of carbon nanotubes reinforced composite coatings fabricated by laser cladding on titanium alloy. *Opt. Laser Technol.* **2021**, *139*, 106957. [CrossRef]
74. Basha, G.T.; Bolleddu, V. Impact of Carbon Nanotubes Reinforcement on Microstructural and Tribological Characteristics of Air Plasma Sprayed Conventional Alumina-Titania (Al2O3-3wt% TiO2) Coatings. *Iran. J. Mater. Sci. Eng.* **2020**, *17*, 92–103.
75. Xu, R.; Bian, D.; Zhao, Y.; Xu, X.; Liu, Y.; Zhou, W. Tribological behavior studies of chemically bonded phosphate ceramic coatings reinforced with modified multi-walled carbon nanotubes (MWCNTs). *Int. J. Appl. Ceram. Technol.* **2020**, *17*, 1010–1016. [CrossRef]
76. Winarto, W.; Priadi, D.; Sofyan, N.; Wicaksono, A. Wear resistance and surface hardness of carbon nanotube reinforced alumina matrix nanocomposite by cold sprayed process. *Procedia Eng.* **2017**, *170*, 108–112. [CrossRef]
77. Sharma, A.; Fujii, H.; Paul, J. Influence of reinforcement incorporation approach on mechanical and tribological properties of AA6061-CNT nanocomposite fabricated via FSP. *J. Manuf. Process.* **2020**, *59*, 604–620. [CrossRef]
78. Shivaramu, H.; Nayak, V.; Umashankar, K. Dry sliding wear characteristics of multi-walled carbon nanotubes reinforced Al-Si (LM6) alloy nanocomposites produced by powder metallurgy technique. *Mater. Res. Express* **2020**, *7*, 045001.
79. Popoola, P.; Popoola, O.; Aigbodion, V.; Oladijo, P. Improving tribological and thermal properties of Al alloy using CNTs and Nb nanopowder via SPS for power transmission conductor. *Trans. Nonferrous Met. Soc. China* **2020**, *30*, 333–343.
80. Gbadeyan, O.J.; Kanny, K.; Mohan, T. Influence of the multi-walled carbon nanotube and short carbon fibre composition on tribological properties of epoxy composites. *Tribol. -Mater. Surf. Interfaces* **2017**, *11*, 59–65. [CrossRef]
81. Ujah, C.; Popoola, A.; Popoola, O.; Uyor, U. Analysis of the Microstructure and Tribology of Ti36-Al16-V16-Fe16-Cr16 HEA Developed with SPS for Engineering Applications. *JOM* **2022**, *74*, 4239–4249. [CrossRef]
82. Pan, Y.; Lu, X.; Volinsky, A.A.; Liu, B.; Xiao, S.; Zhou, C.; Li, Y.; Chen, M.; Qu, X. Tribological and mechanical properties of copper matrix composites reinforced with carbon nanotube and alumina nanoparticles. *Mater. Res. Express* **2019**, *6*, 116524. [CrossRef]
83. Ujah, C.; Popoola, A.; Popoola, O.; Uyor, U. Investigating the Tribology, Vickers Hardness and Microstructure of Ti20–Al20–V20–Fe20–Ni20 HEA Developed with SPS. *Trans. Indian Inst. Met.* **2022**, *75*, 3029–3038. [CrossRef]
84. Gao, J.; Luedtke, W.; Gourdon, D.; Ruths, M.; Israelachvili, J.; Landman, U. Frictional forces and Amontons' law: From the molecular to the macroscopic scale. *J. Phys. Chem. B* **2004**, *108*, 3410–3425. [CrossRef]
85. Kumar, S.; Balasubramanian, V. Developing a mathematical model to evaluate wear rate of AA7075/SiCp powder metallurgy composites. *Wear* **2008**, *264*, 1026–1034. [CrossRef]
86. Wang, Y.; Rainforth, W.; Jones, H.; Lieblich, M. Dry wear behaviour and its relation to microstructure of novel 6092 aluminium alloy–Ni3Al powder metallurgy composite. *Wear* **2001**, *251*, 1421–1432. [CrossRef]
87. Yu, S.Y.; Ishii, H.; Tohgo, K.; Cho, Y.T.; Diao, D. Temperature dependence of sliding wear behavior in SiC whisker or SiC particulate reinforced 6061 aluminum alloy composite. *Wear* **1997**, *213*, 21–28. [CrossRef]
88. Daoud, A.; Abou-Elkhair, M.; Rohatgi, P. Wear and friction behavior of near eutectic Al–Si+ ZrO2 or WC particle composites. *Compos. Sci. Technol.* **2004**, *64*, 1029–1040. [CrossRef]
89. He, P.; Jia, D.; Lin, T.; Wang, M.; Zhou, Y. Effects of high-temperature heat treatment on the mechanical properties of unidirectional carbon fiber reinforced geopolymer composites. *Ceram. Int.* **2010**, *36*, 1447–1453. [CrossRef]
90. Srinivasan, R.; Shivananad, H. Studies on tribological characterization of carbon nanotube reinforced with 6061 aluminium alloy metal matrix composites coated with nickel. *Int. J. Appl. Eng. Res.* **2019**, *14*, 3721–3729.
91. Venkatesan, M.; Palanikumar, K.; Boopathy, S.R. Experimental investigation and analysis on the wear properties of glass fiber and CNT reinforced hybrid polymer composites. *Sci. Eng. Compos. Mater.* **2018**, *25*, 963–974. [CrossRef]

92. Özsarıkaya, B.; Yetgin, S.H.; Ünal, H. Tribological properties of carbon fiber and multi-walled carbon nanotube filled polyamide 66 composites. In Proceedings of the 10th International Scientific Conference BALTTRIB 2019, Kaunas, Lithuania, 14–16 November 2019; Vytautas Magnus University: Kaunas, Lithuania, 2019.
93. Kumar, G.V.; Rao, C.; Selvaraj, N. Mechanical and tribological behavior of particulate reinforced aluminum metal matrix composites—A review. *J. Miner. Mater. Charact. Eng.* **2011**, *10*, 59. [CrossRef]
94. Martin, A.; Martinez, M.; Llorca, J. Wear of SiC-reinforced Al-matrix composites in the temperature range 20–200 C. *Wear* **1996**, *193*, 169–179. [CrossRef]
95. Martın, A.; Rodríguez, J.; Llorca, J. Temperature effects on the wear behavior of particulate reinforced Al-based composites. *Wear* **1999**, *225*, 615–620. [CrossRef]
96. Rodriguez, J.; Poza, P.; Garrido, M.; Rico, A. Dry sliding wear behaviour of aluminium–lithium alloys reinforced with SiC particles. *Wear* **2007**, *262*, 292–300. [CrossRef]
97. Vissutipitukul, P.; Aizawa, T. Wear of plasma-nitrided aluminum alloys. *Wear* **2005**, *259*, 482–489. [CrossRef]
98. Gibson, P.; Clegg, A.; Das, A. Production and evaluation of squeeze-cast graphitic Al-Si alloys. *Mater. Sci. Technol.* **1985**, *1*, 559–567. [CrossRef]
99. Hutchings, I.; Shipway, P. *Tribology: Friction and Wear of Engineering Materials*; Butterworth-Heinemann: Oxford, UK, 2017.
100. Barczak, L.M.; Batako, A.D. Application of minimum quantity lubrication in grinding. *Mater. Manuf. Process.* **2012**, *27*, 406–411. [CrossRef]
101. Mertens, A.J.; Senthilvelan, S. Mechanical and tribological properties of carbon nanotube reinforced polypropylene composites. *Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl.* **2018**, *232*, 669–680. [CrossRef]
102. Ujah, C.; Popoola, A.; Popoola, O.; Aigbodion, V.S. Influence of CNTs addition on the mechanical, microstructural, and corrosion properties of Al alloy using spark plasma sintering technique. *Int. J. Adv. Manuf. Technol.* **2020**, *106*, 2961–2969. [CrossRef]
103. Guo, B.; Song, M.; Zhang, X.; Liu, Y.; Cen, X.; Chen, B.; Li, W. Exploiting the synergic strengthening effects of stacking faults in carbon nanotubes reinforced aluminum matrix composites for enhanced mechanical properties. *Compos. Part B Eng.* **2021**, *211*, 108646. [CrossRef]
104. Gandhi, R.A.; Palanikumar, K.; Ragunath, B.; Davim, J.P. Role of carbon nanotubes (CNTs) in improving wear properties of polypropylene (PP) in dry sliding condition. *Mater. Des.* **2013**, *48*, 52–57. [CrossRef]
105. Zhao, L.; Yao, P.; Zhou, H.; Gong, T.; Deng, M.; Zhang, Z.; Xiao, Y.; Deng, H.; Li, Y.; Luo, F. Effect of CNTs in copper matrix on mechanical characteristics and tribological behavior under dry sliding and boundary lubrication conditions. *Materials* **2019**, *12*, 2203. [CrossRef]
106. Mindivan, H.; Efe, A.; Kosatepe, A.H.; Kayali, E.S. Fabrication and characterization of carbon nanotube reinforced magnesium matrix composites. *Appl. Surf. Sci.* **2014**, *318*, 234–243. [CrossRef]
107. Choi, H.; Lee, S.; Bae, D. Wear characteristic of aluminum-based composites containing multi-walled carbon nanotubes. *Wear* **2010**, *270*, 12–18. [CrossRef]
108. Savina, J.; Raghavendra, B.; Rangappa, D. Experimental investigation on mechanical and tribological behaviour of surfactant coated multi-walled carbon nano tubes reinforced aluminium 6065-silicon metal matrix composite. *Lett. Mater.* **2021**, *11*, 73–78. [CrossRef]
109. Yoo, S.C.; Kang, B.; Van Trinh, P.; Phuong, D.D.; Hong, S.H. Enhanced mechanical and wear properties of Al6061 alloy nanocomposite reinforced by CNT-template-grown core–shell CNT/SiC nanotubes. *Sci. Rep.* **2020**, *10*, 12896. [CrossRef]
110. Nafari, A.; Ghandvar, H.; Nekouee, K.; Nordin, N.A.; Torkamani, H. Microstructural characterization, mechanical and tribological properties of ZC71 hybrid composite einforced with SiC and MWCNT. *J. Appl. Res. Technol.* **2021**, *19*, 345–363. [CrossRef]
111. Li, H.; Zong, H.; Li, S.; Jin, S.; Chen, Y.; Cabral, M.J.; Chen, B.; Huang, Q.; Ren, Y.; Yu, K. Uniting tensile ductility with ultrahigh strength via composition undulation. *Nature* **2022**, *604*, 273–279. [CrossRef]
112. Ujah, C.; Popoola, A.; Popoola, O.; Afolabi, A.; Uyor, U. Mechanical and Oxidation Characteristics of Ti20-Al16-V16-Fe16-Ni16-Cr16 High-Entropy Alloy Developed via Spark Plasma Sintering for High-Temperature/Strength Applications. *J. Mater. Eng. Perform.* **2022**, *32*, 18–28. [CrossRef]
113. German, R.M. Titanium sintering science: A review of atomic events during densification. *Int. J. Refract. Met. Hard Mater.* **2020**, *89*, 105214. [CrossRef]
114. Franesqui, M.A.; Yepes, J.; García-González, C. Improvement of moisture damage resistance and permanent deformation performance of asphalt mixtures with marginal porous volcanic aggregates using crumb rubber modified bitumen. *Constr. Build. Mater.* **2019**, *201*, 328–339. [CrossRef]
115. Thomson, K.; Jiang, D.; Yao, W.; Ritchie, R.; Mukherjee, A. Characterization and mechanical testing of alumina-based nanocomposites reinforced with niobium and/or carbon nanotubes fabricated by spark plasma sintering. *Acta Mater.* **2012**, *60*, 622–632. [CrossRef]
116. Starke, E., Jr.; Rashed, H. Alloys: Aluminum. In *Reference Module in Materials Science and Materials Engineering*; Elsevier: Amsterdam, The Netherlands, 2017; pp. 18–24.
117. Yu, M.-F.; Files, B.S.; Arepalli, S.; Ruoff, R.S. Tensile loading of ropes of single wall carbon nanotubes and their mechanical properties. *Phys. Rev. Lett.* **2000**, *84*, 5552. [CrossRef]
118. Malaki, M.; Fadaei Tehrani, A.; Niroumand, B.; Gupta, M. Wettability in metal matrix composites. *Metals* **2021**, *11*, 1034. [CrossRef]

119. James, J.; Annamalai, A.R.; Muthuchamy, A.; Jen, C.-P. Effect of Wettability and Uniform Distribution of Reinforcement Particle on Mechanical Property (Tensile) in Aluminum Metal Matrix Composite—A Review. *Nanomaterials* **2021**, *11*, 2230. [CrossRef]
120. Huei-Long, L.; Wun-Hwa, L.; Chan, S.L.-I. Abrasive wear of powder metallurgy Al alloy 6061-SiC particle composites. *Wear* **1992**, *159*, 223–231. [CrossRef]
121. Hashim, J.; Looney, L.; Hashmi, M. The wettability of SiC particles by molten aluminium alloy. *J. Mater. Process. Technol.* **2001**, *119*, 324–328. [CrossRef]
122. Tekmen, C.; Saday, F.; Cocen, U.; Ljungberg, L.Y. An investigation of the effect of SiC reinforcement coating on the wettability of Al/SiC system. *J. Compos. Mater.* **2008**, *42*, 1671–1679. [CrossRef]
123. Zhou, W.; Xu, Z. Casting of SiC reinforced metal matrix composites. *J. Mater. Process. Technol.* **1997**, *63*, 358–363. [CrossRef]
124. Jiang, L.; Fan, G.; Li, Z.; Kai, X.; Zhang, D.; Chen, Z.; Humphries, S.; Heness, G.; Yeung, W.Y. An approach to the uniform dispersion of a high volume fraction of carbon nanotubes in aluminum powder. *Carbon* **2011**, *49*, 1965–1971. [CrossRef]
125. Riahi, A.; Alpas, A. The role of tribo-layers on the sliding wear behavior of graphitic aluminum matrix composites. *Wear* **2001**, *251*, 1396–1407. [CrossRef]
126. So, K.P.; Jeong, J.C.; Park, J.G.; Park, H.K.; Choi, Y.H.; Noh, D.H.; Keum, D.H.; Jeong, H.Y.; Biswas, C.; Hong, C.H. SiC formation on carbon nanotube surface for improving wettability with aluminum. *Compos. Sci. Technol.* **2013**, *74*, 6–13. [CrossRef]
127. Li, R.; Pan, Z.; Zeng, Q.; Xiaoli, Y. Influence of the Interface of Carbon Nanotube-Reinforced Aluminum Matrix Composites on the Mechanical Properties—A Review. *Arch. Foundry Eng.* **2022**, *22*, 23–36.
128. He, R.; Wang, H. Fatigue crack nucleation and growth behaviors of laser melting deposited Ti–6Al–2Zr–Mo–V. *Mater. Sci. Eng. A* **2010**, *527*, 1933–1937. [CrossRef]
129. Esawi, A.M.; Morsi, K.; Sayed, A.; Taher, M.; Lanka, S. Effect of carbon nanotube (CNT) content on the mechanical properties of CNT-reinforced aluminium composites. *Compos. Sci. Technol.* **2010**, *70*, 2237–2241. [CrossRef]
130. Chen, H.; Jacobs, O.; Wu, W.; Rüdiger, G.; Schädel, B. Effect of dispersion method on tribological properties of carbon nanotube reinforced epoxy resin composites. *Polym. Test.* **2007**, *26*, 351–360. [CrossRef]
131. Torralba, J.D.; Da Costa, C.; Velasco, F. P/M aluminum matrix composites: An overview. *J. Mater. Process. Technol.* **2003**, *133*, 203–206. [CrossRef]
132. Sapawe, N.; Hanafi, M.F.; Samion, S. The use of palm oil as new alternative biolubricant for improving anti-friction and anti-wear properties. *Mater. Today Proc.* **2019**, *19*, 1126–1135. [CrossRef]
133. Scharf, T.; Prasad, S. Solid lubricants: A review. *J. Mater. Sci.* **2013**, *48*, 511–531. [CrossRef]
134. Slapnik, J.; Stiller, T.; Wilhelm, T.; Hausberger, A. Influence of Solid Lubricants on the Tribological Performance of Photocurable Resins for Vat Photopolymerization. *Lubricants* **2020**, *8*, 104. [CrossRef]
135. Bastwros, M.M.; Esawi, A.M.; Wifi, A. Friction and wear behavior of Al–CNT composites. *Wear* **2013**, *307*, 164–173. [CrossRef]
136. Zhang, X.; Luster, B.; Church, A.; Muratore, C.; Voevodin, A.A.; Kohli, P.; Aouadi, S.; Talapatra, S. Carbon nanotube− MoS2 composites as solid lubricants. *ACS Appl. Mater. Interfaces* **2009**, *1*, 735–739. [CrossRef]
137. Sharma, A.K.; Tiwari, A.K.; Dixit, A.R.; Singh, R.K.; Singh, M. Novel uses of alumina/graphene hybrid nanoparticle additives for improved tribological properties of lubricant in turning operation. *Tribol. Int.* **2018**, *119*, 99–111. [CrossRef]
138. Cornelio, J.A.C.; Cuervo, P.A.; Hoyos-Palacio, L.M.; Lara-Romero, J.; Toro, A. Tribological properties of carbon nanotubes as lubricant additive in oil and water for a wheel–rail system. *J. Mater. Res. Technol.* **2016**, *5*, 68–76. [CrossRef]
139. Jang, I.; Joo, H.G.; Jang, Y.H. Effects of carbon nanotubes on electrical contact resistance of a conductive Velcro system under low frequency vibration. *Tribol. Int.* **2016**, *104*, 45–56. [CrossRef]
140. Mao, F.; Wiklund, U.; Andersson, A.M.; Jansson, U. Graphene as a lubricant on Ag for electrical contact applications. *J. Mater. Sci.* **2015**, *50*, 6518–6525. [CrossRef]
141. Wu, S.; Tian, S.; Menezes, P.L.; Xiong, G. Carbon solid lubricants: Role of different dimensions. *Int. J. Adv. Manuf. Technol.* **2020**, *107*, 3875–3895. [CrossRef]
142. Muzakkir, S.; Lijesh, K.; Hirani, H. Carbon Nanotubes as Solid Lubricant Additives for Anti-wear Performance Enhancement under Mixed Lubrication Conditions. *Int. J. Mod. Eng. Res* **2015**, *5*, 25–28.
143. Chaudhuri, S.; Ghosh, A.; Chattopadhyay, S.K. Green synthetic approaches for medium ring–sized heterocycles of biological and pharmaceutical interest. In *Green Synthetic Approaches for Biologically Relevant Heterocycles*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 617–653.
144. Kolchugin, A.; Pikalova, E.Y.; Bogdanovich, N.; Bronin, D.; Pikalov, S.; Plaksin, S.; Ananyev, M.; Eremin, V. Structural, electrical and electrochemical properties of calcium-doped lanthanum nickelate. *Solid State Ion.* **2016**, *288*, 48–53. [CrossRef]
145. Ma, P.-C.; Siddiqui, N.A.; Marom, G.; Kim, J.-K. Dispersion and functionalization of carbon nanotubes for polymer-based nanocomposites: A review. *Compos. Part A Appl. Sci. Manuf.* **2010**, *41*, 1345–1367. [CrossRef]
146. Choi, H.; Shin, J.; Min, B.; Park, J.; Bae, D. Reinforcing effects of carbon nanotubes in structural aluminum matrix nanocomposites. *J. Mater. Res.* **2009**, *24*, 2610–2616. [CrossRef]
147. Ma, P.C.; Wang, S.Q.; Kim, J.-K.; Tang, B.Z. In-situ amino functionalization of carbon nanotubes using ball milling. *J. Nanosci. Nanotechnol.* **2009**, *9*, 749–753. [CrossRef]
148. Esawi, A.; Morsi, K.; Sayed, A.; Taher, M.; Lanka, S. The influence of carbon nanotube (CNT) morphology and diameter on the processing and properties of CNT-reinforced aluminium composites. *Compos. Part A Appl. Sci. Manuf.* **2011**, *42*, 234–243. [CrossRef]

149. Tserengombo, B.; Jeong, H.; Dolgor, E.; Delgado, A.; Kim, S. Effects of Functionalization in Different Conditions and Ball Milling on the Dispersion and Thermal and Electrical Conductivity of MWCNTs in Aqueous Solution. *Nanomaterials* **2021**, *11*, 1323. [CrossRef]
150. Oliver, U.C.; Sunday, A.V.; Christain, E.I.-E.I.; Elizabeth, M.M. Spark plasma sintering of aluminium composites—A review. *Int. J. Adv. Manuf. Technol.* **2021**, *112*, 1819–1839. [CrossRef]
151. Chieh, K.; Te-Tan, L.; Kuo-Hwa, T.; Kuo-Ying, C.; Ming-Shuing, C. The influences of powder mixing process on the quality of W-cu composites. *J. Trans. Can. Soc. Mech. Eng.* **2009**, *33*, 361–375.
152. Peng, T.; Chang, I. Uniformly dispersion of carbon nanotube in aluminum powders by wet shake-mixing approach. *Powder Technol.* **2015**, *284*, 32–39. [CrossRef]
153. Chung, D.D. *Composite Materials: Science and Applications*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2010.
154. Štengl, V. Preparation of graphene by using an intense cavitation field in a pressurized ultrasonic reactor. *Chem. Eur. J.* **2012**, *18*, 14047–14054. [CrossRef]
155. Simões, S.; Viana, F.; Reis, M.A.; Vieira, M.F. Aluminum and nickel matrix composites reinforced by CNTs: Dispersion/mixture by ultrasonication. *Metals* **2017**, *7*, 279. [CrossRef]
156. Thomas, S.; Pillari, L.K.; Umasankar, V.; Pious, J. Effect of sonication in enhancing the uniformity of MWCNT distribution in aluminium alloy AA2219 matrix. *Mater. Today Proc.* **2019**, *18*, 4058–4066. [CrossRef]
157. Javadi, A.; Mirdamadi, S.; Faghihisani, M.; Shakhesi, S.; Soltani, R. Well-dispersion of multi-walled carbon nanotubes in aluminum matrix composites by controlling the mixing process. *Fuller. Nanotub. Carbon Nanostruct.* **2013**, *21*, 436–447. [CrossRef]
158. Rais, L.; Sharma, D.R.; Sharma, D.V. Synthesis and structural characterization of Al-CNT metal matrix composite using physical mixing method. *IOSR J. Appl. Phys.* **2013**, *5*, 54–57. [CrossRef]