Recent Advances and Applications of Carbon Nanotubes (CNTs) in Machining Processes: A Review

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Review

Recent Advances and Applications of Carbon Nanotubes (CNTs) in Machining Processes: A Review

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Abstract: Recently, there has been much scholarly research on the applications of CNTs in various fields which can be attributed to their outstanding properties. For that matter, machining processes as the backbone of manufacturing technologies have also benefited greatly from the introduction of CNTs. However, there is a lack of papers that provide a holistic overview on potential applications, which impedes focused and robust research in their application. In this work, after providing an outline of the methods used in increasing the productivity of machining processes, we will review the ways in which CNTs, known for their remarkable mechanical, chemical, electrical, and thermal characteristics, enhance the productivity of machining processes. We emphasize fit-for-purpose applications to determine the fate of CNTs use in machining processes. We examine the applications of CNTs in enhancing the mechanical characteristics of cutting tools, which include increased wear resistance, strength, and thermal conductivity, thereby extending tool life and performance. Additionally, this work highlights the application of nanofluids in MQL systems, where CNTs play a crucial role in reducing friction and enhancing thermal management, leading to reduced lubricant usage while maintaining cooling and lubrication effectiveness.

Keywords: CNTs; MQL; lubrication; cutting fluid; machining process

1. Introduction

To obtain the desired shape, machining operations use a cutting tool to remove material from the work-piece via shear deformation. Considerable stress and strain are typically present throughout the cutting process, as well as an inevitable amount of accumulated cutting heat, which causes the tool matrix to wear out quickly and prevents the workpiece from being cut with high performance [1,2]. Approximately 20% of the total energy input throughout the metal-cutting process is utilized to overcome sliding friction at the tool's rake and flank faces. The amount the energy may vary depending on different factors such as the feed rate, workpiece material, cutting speed, depth of cut, tool material, and coating. The heat generated by the energy input needed to overcome sliding friction can additionally have an adverse effect on tool life, surface quality, and productivity. Nonetheless, the energy value needs to be assessed experimentally based on specific cutting instances and tool–work-piece combinations since it can vary considerably for each combination [3–7].

For that matter, recently, an increase in research that investigates environmental factors throughout the machining operations and their implications on environmental issues, machining costs, and productivity in a more holistic sense has been reported. For industry to achieve a sustainable machining process in the real sense, it is essential to build energy and resource-efficient manufacturing processes. The industry's use of high-strength materials makes it difficult to attain an eco-efficiency target since a trade-off between consumed energy and economical productivity must be reached. Despite their precision, novel processes are more expensive and often have low production rates. Therefore, seeking novel fit-for-purpose materials and hybrid processes is of utmost importance [8–10].

Due to their distinct mechanical, chemical, electrical, and thermal characteristics, the application of CNTs has drawn much attention in various fields other than machining processes. Figure 1 shows the number of documents related to the application of CNTs. With diameters generally in the nanoscale range and lengths ranging from several micrometers to millimeters, CNTs have a high aspect ratio. CNTs are excellent candidates for usage as reinforcing materials in cutting tools and machining applications due to their distinctive shape and great mechanical strength. The outstanding mechanical qualities of CNTs make them an excellent choice for machining, among other benefits. CNTs are very stiff and durable, and their tensile strength is 100 times greater than that of steel. CNTs can enhance the mechanical characteristics of cutting tools and raise their resistance to wear, distortion, and failure during the machining process [11–13].

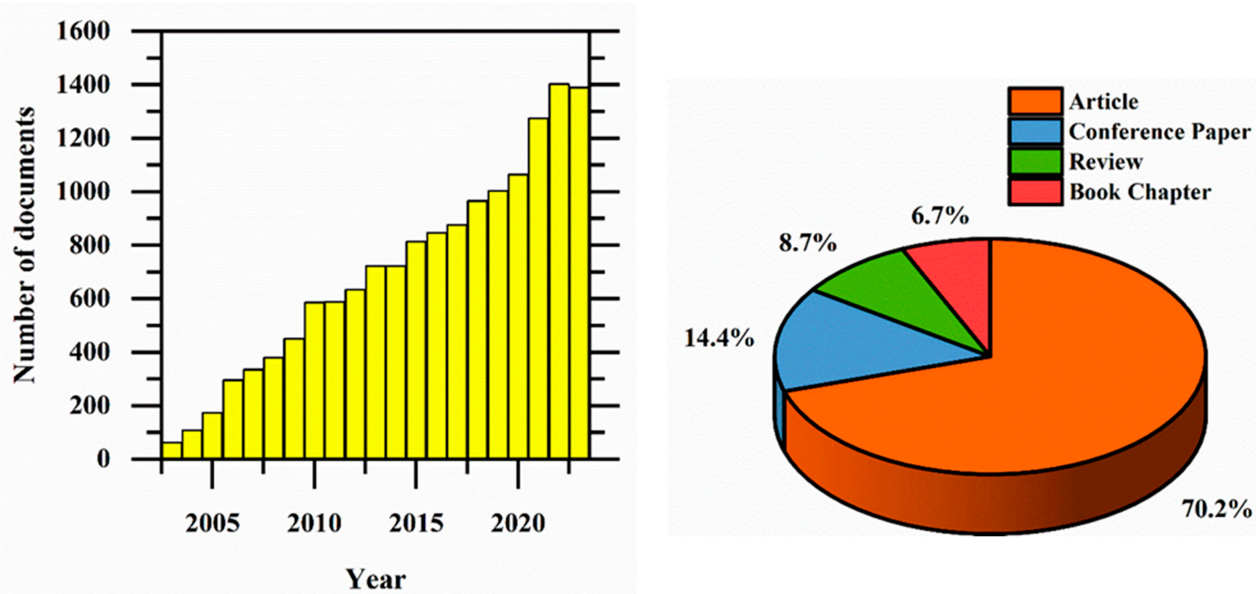

Figure 1. The number of documents (limited to articles, conference papers, reviews, and book chapters) related to the application of CNTs published from 2000 to 2023, obtained from the Scopus database (with keywords of "cnts AND application "searched in "TITLE-ABS-KEY" on 12 April 2024).

CNTs possess superior heat conductivity in addition to outstanding mechanical properties. Due to the high temperatures that can be produced during cutting operations, this property makes them ideal for use in machining applications. Table 1 shows the review articles related to various applications of CNTs in machining processes, limited to journal reviews. The improved thermal conductivity of cutting tools leads to improved heat dissipation and lowers the possibility of thermal damage to the workpiece and cutting tool. The electrical conductivity of CNTs is another benefit of CNTs in machining. In ECM, where the material is removed from a workpiece using an electrical current, this feature can be utilized. The electrical conductivity of the electrode used in ECM may be enhanced by adding CNTs, which results in quicker and more effective machining [14–16].

High aspect ratio CNTs, which can provide stable lubricant suspensions that enhance the lubricant's lubricity and thermal conductivity, can also be one of the solutions to overcome the challenges in MQL machining. The amount of lubricant needed for MQL machining can be decreased while still obtaining the needed cooling and lubricating effects by introducing CNTs into the lubricant [17–20].

Table 1. Review articles related to various applications of CNTs in machining processes.

Category	Author(s)	Primary Focus of the Review	Publication Year	Ref.
Cutting tool	Sidorenko et al.	Nanocomposites for machining tools including CNTs-doped nanocomposites	2017	[21]
Cutting tool	Soni et al.	CNTs and CNTs-reinforced nanocomposite fabrication, mechanical properties, and applications	2020	[22]
Cutting tool	Dabees et al.	Different techniques for coating cutting tools, including CNTs-coated tools	2022	[23]
Cutting fluid	Said et al.	General preparation methods and applications of various nanocutting fluids, including some CNTs-based ones in MQL	2019	[24]
Cutting fluid	Chinchanikar et al.	Thermophysical, tribological, and wetting characteristics of nanofluids, including CNTs-based ones and hybrids in MQL	2021	[25]
Cutting fluid	Kadirgama	Application of nanofluids in machining and their influence on cutting force, surface roughness, tool life, tool wear, and morphology	2021	[26]
Cutting fluid	Cui et al.	Carbon-group nanolubricants in MQL and NMQL	2022	[27]
Cutting fluid	Amin et al.	Application of nanofluids in various processes	2022	[28]
Cutting fluid	Dubey and Sharma	Hybrid nanofluids in turning, milling, drilling, grinding, and tribological behavior	2023	[29]
Cutting fluid	Wang et al.	Nanofluid preparation, characteristics, applications, and performance, including CNTs-based ones	2024	[30]
Novel tech	Chaudhurya and Samantarayb	Role of CNTs in EDM and highlighting the research gap in application of CNTs in various EDM configurations	2017	[31]
Novel tech	Porwal and Kumar	Overview of CNTs-based EDM and corresponding applications as dielectric, electrode, or both	2021	[32]

Despite the potential advantages of using CNTs in machining, the cost of CNTs, which can be many orders of magnitude greater than conventional cutting-tool materials, is one of the main difficulties. Furthermore, the synthesizing and processing of CNTs can be difficult and call for specialized tools and methods. Additionally, according to Table 1, there are few reviews on CNTs-based EDM, while none of the reviews on application of CNTs in nanofluids focuses on CNTs-based nanofluids; there is a lack of comprehensive reviews on other applications of CNTs in machining processes. For this reason, due to the importance of CNTs, the large number of scholarly research articles, and an absence of a comprehensive overview focusing solely on CNT application in this field calls for a comprehensive overview. In this work, we review current advances, fit-for-purpose applications, and prospective applications of CNTs concern productivity enhancement of machining processes.

2. Overview of CNT Applications in Cutting Processes

The most prevalent methods for achieving this goal are effective techniques for reducing friction and prolonging tool life. They may be reached through focusing on the cutting process itself and improving the outputs of the machining process by employing the cutting fluid or lubricant, via the advancement of cutting tools, which emphasizes advances in cutting tools such as tool coating and tool surface texturing [11], via tool condition monitoring, or via novel machining methods. Tool wear is defined as the deformation or degradation of a cutting tool's sharp edge caused by interactions with the workpiece while machining. The assessment of tool life using the tool wear data gathered from previous trials is the foundation for tool life prediction and tool-changing practices. Cutting-tool failure causes an increase in cost and upkeep time as well as a loss in production rate in the industry. The TCMs decrease downtime and boost productivity. The monitoring process assists with (a) preventing damage to the tool and workpiece, (b) increasing productivity and product quality, and (c) monitoring the tool wear [33,34]. Figure 2 shows the main paths for the productivity optimization of the machining process while the reviews in Table 1 indicate the primary focus of studies on CNTs-enhanced machining are on cutting fluids.

Figure 2. The main paths for productivity optimization of machining processes according to the literature.

2.1. Advances in Cutting Tools

An efficient, precise, and cost-effective machining operation is guaranteed by several essential qualities in good cutting tools. These characteristics include hardness, which enables the instrument to retain its sharpness and withstand abrasion. High toughness is crucial for effectively absorbing energy and withstanding fracture when subjected to impacts and shocks, particularly in intermittent cutting processes such as milling. Ensuring high wear resistance is essential for preserving the tool's sharpness and form over an extended duration, which in turn minimizes the need for tool replacements and enhances productivity. The tool's heat resistance allows it to endure high temperatures created during cutting without experiencing a loss in hardness or suffering thermal degradation. This ensures that the tool maintains its performance and longevity. Ensuring chemical stability is also crucial in order to avoid any interaction between the tool material and the workpiece material or the cutting environment, since this might result in tool wear and degradation [23].

High edge retention enables the tool to keep a sharp cutting edge for long durations, resulting in superior surface polish and dimensional accuracy. The high thermal conductivity of a material aids in the efficient dissipation of heat produced during cutting, hence minimizing thermal wear to both the cutting tool and the workpiece. A decreased friction coefficient between the tool and the workpiece results in reduced cutting forces, heat generation, and tool wear, hence facilitating smoother cutting operations. The tool material should also possess the characteristics of being readily manufacturable and malleable into the necessary tool form without incurring excessive expenses or complications. Moreover, the underlying material must be capable of being used with several types of coatings, such as PVD or CVD coatings, that improve hardness, resistance to wear, and thermal stability [21,22].

Manufacturing cutting tools follows these main steps: material selection [35,36], material preparation, sintering [36], forging, annealing, precision shaping, and post-treatment processes [37–39]. Each intended application demand for different kinds of materials and also introduction of nanoparticles can be carried out through a variety of methods that aid proper dispersion of the nanoparticles into the tool matrix [40]. For further information on the strategies recommended to address the challenges of each step, please refer to the cited reviews. CNTs exhibit a mean elastic modulus of 1000–2000 GPa, while MWCNTs exhibit a mean bending strength of 6–22 GPa and a tensile strength of 11–63 GPa. MWCNTs may effectively enhance the strength of cemented carbides. Furthermore, CNTs are used to enhance the efficiency of diamond tools. Introducing CNTs into a Ni-coating during the fabrication of electroplated diamond tools significantly enhances the hardness and yield strength of the nickel matrix [21].

The toughness enhancement mechanism for a CNTs-reinforced cBN cutting tool was investigated by Kong et al. [41]. Figure 3 shows the toughness enhancement mechanism for a CNTs-reinforced cBN cutting tool. As shown in Figure 3a, CNTs are elongated and fixated at either side of the fissure, facilitating bridging, and it was reported that when a propagating fracture reaches CNTs, a significant angle between the crack tip and the CNTs, coupled with insufficient stress for crack propagation to compromise the CNTs, results in the crack bypassing the CNTs and advancing ahead. For that matter, as CNTs link the two surfaces of the substrate like a bridge, increased external force next to the crack point will lead to CNTs fracture (see Figure 3b). Bridging and tension fractures require a significant amount of energy, efficiently impeding crack propagation and enhancing the fracture toughness of tool materials (see Figure 3c). This occurs due to the significantly greater elastic modulus of the CNTs compared to that of the matrix. In simpler terms, as the crack tip meets an obstruction, the CNTs will exert a pinning effect like a nail's connection between superior and inferior surfaces of the substrate. At this point, the crack will bypass the CNTs and advances ahead. Due to the need in bypassing the CNTs because of their elevated elastic modulus, the crack trajectory is semi-elliptical, resulting in crack deflection. This mechanism not only extends the fracture route but also generates several new surfaces during crack propagation, which expends much additional energy and increases the toughness of the tool material.

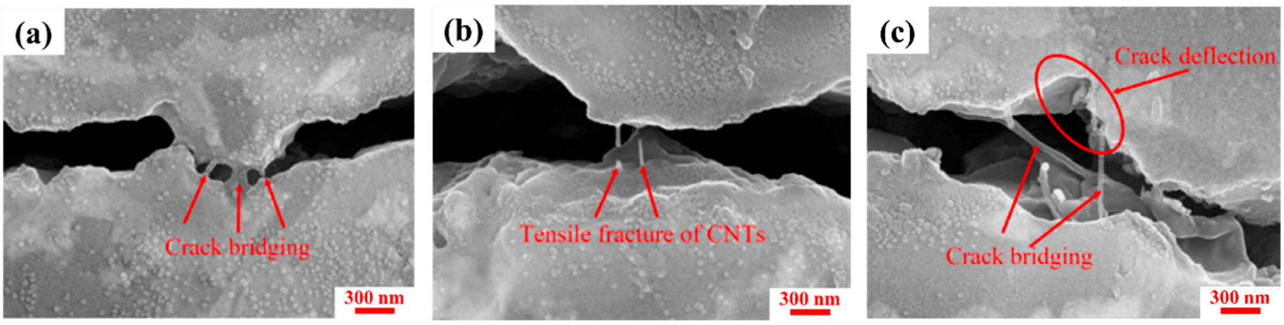

Figure 3. Toughness enhancement mechanism in a CNTs-reinforced cBN cutting tool (**a**) crack bridging (**b**) crack propagation (**c**) crack bridging and crack deflection [41].

2.2. Advances in Cutting Fluids and Lubrications

Heat is generated at numerous contact areas during metal cutting operations due to friction, and this has a huge impact on the machining process' productivity concerning tool stability, surface texture, and product precision, as well as from an economic and environmental standpoint. To lessen the severity of high temperatures at various zones where the cutting tool contacts with the workpiece, a variety of cooling strategies have been employed. Water was initially used as a coolant because of its good cooling potential to reduce heat during machining processes. However, it faced some drawbacks such corrosion and product moisture during machining operations [42]. Through time, as technology developed and because of its low health risks and environmental friendliness, dry machining gained popularity. However, it was impossible to replace the previous cooling systems as it was inefficient while processing harder materials at greater cutting speeds. The concept of MQL was introduced in workshops for cooling and lubrication in the latter part of the nineteenth century, delivering outstanding outcomes that bridge the gap between traditional cooling methods and dry machining [43,44]. Figure 4 shows the three main environmentally friendly lubrication techniques, while both MQL and cryogenic cooling machining have greatly benefited from CNTs as nanofluid additives.

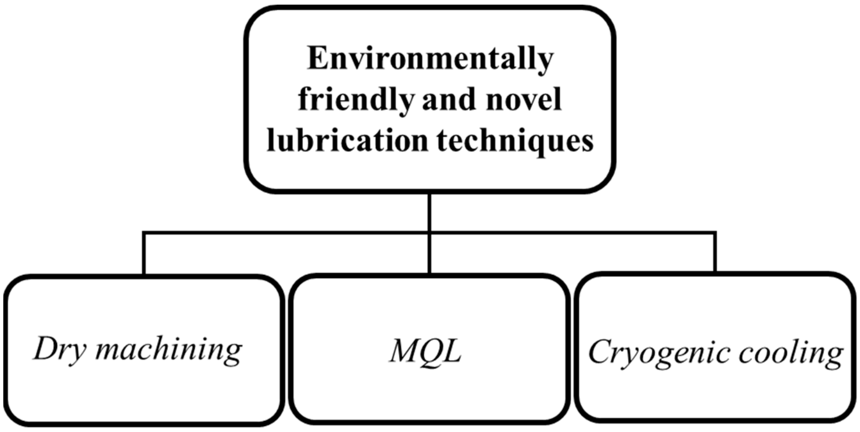

Figure 4. The three main environmentally friendly lubrication techniques.

2.2.1. Types of Cutting Fluids

Choosing the right cutting fluid is crucial because it can influence the performance of machining performance. The choice is dependent on factors like the type of metal cutting process being used, type of work-piece being used, and the material of the cutting tool. For instance, in processing titanium and nickel-based alloys, respectively, fluids with chlorine and sulfur additives should not be utilized. In general, high-lubricity cutting fluids are typically utilized in LSM, like screw cutting on challenging materials, while high-cooling cutting fluids are typically employed in HSM [45]. The four principal types of cutting fluids include cutting oils, soluble oils (emulsions), synthetic (chemical) fluids, and semi-synthetic (semi-chemical) fluids. Cutting oils, also known as neat oils or straight cutting oils, are derived from petroleum, plants, or animals. They are typically used in cutting operations that require low temperatures and slow speeds. [46].

In essence, soluble oils consist of oil droplets dispersed in water, formed by mixing oil with water and an emulsifier, which enhances the stability of the emulsion. This type of cutting fluid contains an emulsifier, a base oil, and various additives designed to improve its performance. The emulsifier plays a critical role by ensuring that the oil remains evenly distributed in water, preventing the oil and water components from separating. These additives may include anti-rust agents or biocides to extend the fluid's life and improve its effectiveness in reducing friction and wear during machining processes. Additives include neutralizing agents, lubricating additives including anti-wear, biocides, fungicides, and foam inhibitors, among others. The base oil may be vegetable or mineral oil. To create a stable emulsion, emulsifiers should spread the oil in the water [46–48]. Vegetable oils provide superior lubricity, a greater flash point, and a superior boiling point, which reduces misting losses. Despite having a lower thermal and oxidative stability, vegetable oils have a greater viscosity [48].

Rust, bacterial development, and evaporation losses can all be brought about by the water in emulsions. Under conditions of EP, chemicals based on phosphorus, chlorine, and sulfur are utilized as additions. Between the cutting fluid and the metal surface, EP interacts chemically to create a solid lubricating layer. As a result, this film has strong anti-weld characteristics and low shear strength. Therefore, EP additives can significantly minimize friction and wear. Higher cutting rates during machining might be accomplished because of the emulsions' technical capability to reduce heat [48,49]. Additionally, it can be diluted with water to minimize the expense, fire danger, and oil misting rate. The growth of fungus and bacteria, due to a greater risk particularly regarding public health and shortened useful life of cutting fluids, is the main disadvantage of emulsions. Therefore, it becomes important to utilize chemical additives to inhibit bacterial development in cutting fluids. However, the use of these additives brings additional risks, as they can be harmful to both the operators handling them and the environment. Consequently, while these additives are crucial for maintaining the effectiveness and safety of cutting fluids, they require careful handling and disposal to minimize their negative impacts [49–52].

Said et al. [53] carried out a review on nanofluids as cutting fluids. The nanoparticle additives in their review include Al_2O_3, MoS_2, TiO_2, CNTs, graphene nanoplatelets, ZnO, and CuO, among other additives. Vajjha and Das discovered that including nanoparticles of CuO, Al_2O_3, and ZnO_2 at 40 wt% enhanced the thermal conductivities of the nanofluids by 60%, 69%, and 48.5%, respectively. In addition to metallic oxides, nanoparticles of other compounds have also been explored to enhance the physical and mechanical characteristics of nanofluids. Graphene oxide is a type of nanomaterial that is composed of two-dimensional sheets. This material is hydrophilic and can be dispersed in water to form stable colloidal suspensions. The thermal conductivity of graphene oxide nanosheets is quite high, varying from 600 to 5000 W m^{-1} K^{-1}. These properties make graphene oxide an appropriate material for integration into cutting fluids used in metal-cutting processes, which aids temperature decrease by 50% with the application of a coolant comprising a graphene oxide nanosheet suspension. They also presented a temperature distribution and cooling efficacy model and carried out experimental analysis using 0.1 and 0.5% graphene oxide nanosheet-doped cutting fluid in the turning process of Ti6Al4V [54]. In another study, Yi et al. [55] applied a graphene oxide-doped cutting fluid in the drilling process of Ti6Al4V. Their results indicated a 17.21% decrease in cutting force, less thermal cracks, 15.1% less surface roughness, and formation of spiral chips rather than discontinuous chips when using the graphene oxide-doped fluid compared to the conventional ones. However, a variety of nanoparticles or their combination are used as additives in cutting fluids that enhance their performance, but for a robust comparison further studies are required to assess the efficiency of additives under similar operating parameters and settings. In the following sections of this review, the applications of CNTs-based cutting fluids are reviewed.

2.2.2. MQL

In recent years, several green-cutting lubricating technologies have been introduced for their cost-effectiveness, environmental conservation, and sustainable production. These include self-lubricating tools, dry cutting, and MQL. Cutting fluid is not used in the process of dry cutting [56]. When using a self-lubricating tool, friction and wear are reduced by the tool itself. MQL refers to a technique where a minimal amount of lubricant oil (typically < 100 mL/h) is combined with compressed gas to form a fine oil mist. This mist is then sprayed at high velocity into the cutting zone. The outcome is effective lubrication of the cutting area, which significantly reduces manufacturing costs [57]. Additionally, adjusting the parameters of the tool, an essential part of the turning system, can further enhance machining performance. However, challenges arise during machining material that is difficult to cut, including nickel-based alloys and others. The high levels of friction generated during the cutting process with these materials can compromise both the quality and efficiency of the machining operation [58–60]. This technological issue may be successfully resolved by the NMQL method, which can minimize friction by employing nanoparticles as an additive phase. Figure 5 shows the lubrication condition under (a) flooding and (b) MQL techniques.

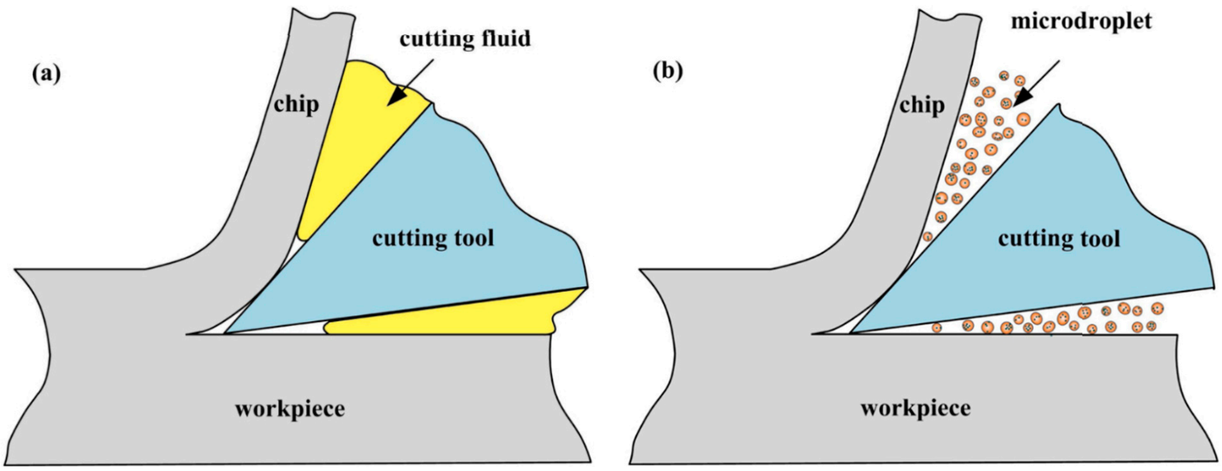

Figure 5. Lubrication condition under (**a**) flooding and (**b**) MQL techniques [61].

There are generally two ways used to manufacture the nanofluids: the one-step approach and the two-step approach. The synthesis of nanofluid in a single step entails integrating the production and distribution of nanoparticles in the base fluid, while the two stages happen simultaneously. The issues with collecting and storing nanoparticles are resolved in this manner [61]. Additionally, it is also possible to halt metal nanoparticle oxidation in the air while doing so. In the two-step method, a predefined quantity of nanoparticles is added to the base fluid. Following this, an appropriate surface dispersant in accordance with the characteristics of the nanoparticles is selected to aid in evenly distributing the nanoparticles throughout the fluid. To further improve this dispersion and ensure the nanoparticles remain evenly distributed and stable, ultrasonic vibration is employed. This technique helps to break up any clumps of nanoparticles, facilitating a more homogeneous mixture and enhancing the fluid's overall performance characteristics. The two-step approach is quite popular and rather easy to utilize. Dispersants and ultrasonic vibrations are used to avoid particle agglomeration [62]. Figure 6 shows a schematic of the second approach to nanofluid fabrication.

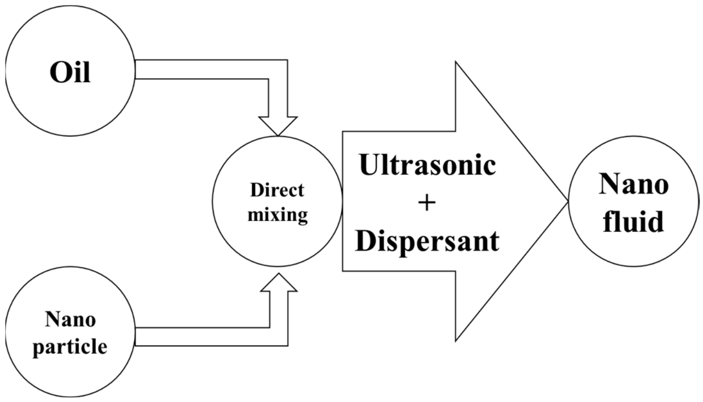

Figure 6. A schematic of the second approach to nanofluid fabrication.

3. Recent Advances in CNTs Applications for Typical Machining Processes

3.1. CNTs-Reinforced Cutting Tools

Due to their outstanding mechanical, thermal, and electrical properties such as their superior tensile strength, high Young's modulus, and wide aspect ratio, CNTs are highly sought-after for use as reinforcement in tool materials. Because of these properties, CNTs are the best additive phase for boosting strength and toughness. Nonetheless, the non-uniform dispersion of CNTs in the metal matrix can lead to uneven tool wear and inconsistent tool performance, and many technologies like ball milling have been used to improve the dispersion of CNTs [40,63].

The low strength and hardness of cBN tools cause frequent tool wear and chipping during machining. MWCNTs have the ability to significantly enhance the strength of cemented carbides. The addition of less than 0.5% MWCNTs to nano-WC-7%Co cemented carbide enhances its mechanical characteristics and increases the "hardness-to-toughness" ratio. Applying a layer of WC CNTs before use results in a more uniform structure, improves the bonding between the matrix and nanotubes, and decreases the presence of empty spaces in the nano-WC-10%Co cement. In addition, SiC coatings may be used to inhibit nanotube oxidation [64]. The addition of SiC-coated MWCNTs, up to a maximum of 5%, to a silicon carbide ceramic matrix results in a substantial enhancement in both hardness and toughness, while also preserving elasticity, owing to the bridging action of the MWCNTs [65]. The incorporation of CNTs into Ni-coating during the electroplating process of diamond tool production significantly enhances the hardness and yield strength of the nickel matrix. Calculations suggest that enhancing the mechanical qualities leads to a 1.3-fold increase in diamond retention. Testing has shown that tools with a Ni-CNTs binder have superior resistance to wear and better retention of diamond compared to tools with a nickel binder. These results are supported by a significant 8-fold improvement in tool longevity observed during the process of drilling holes in fused silica and machining the edges of white plate glass [66].

Kong et al. [41] fabricated CNTs-reinforced cBN tools via SPS in order to overcome this problem. In addition to speeding up the material densification process and enhancing the sintering impact of cBN, the addition of uniformly dispersed CNTs improved the discharge properties of the composite powders during SPS sintering. Figure 7 shows the influence of CNTs content on flexural strength, hardness, and fracture toughness of CNTs-reinforced cBN tools. The fracture toughness and flexural strength of the CNTs-reinforced cutting tool (0.5 wt%), influenced by the effects adding CNTs (see Section 2.1), are 7.16 MPa·m1/2 and 635 MPa, respectively, representing increases of 13.7% and 75.4% compared to the non-reinforced tool. The relationship flank wear and cutting length for a CNTs-reinforced (0.5 wt% CNTs) and non-reinforced cutting tool along with rake- and flank-face wear morphology can be found in Figure 8. It can be observed that the reinforced tool exhibits superior flank and rake wear resistance, leading to an increase of 33.3% in effective cutting distance of 45 carbon steel.

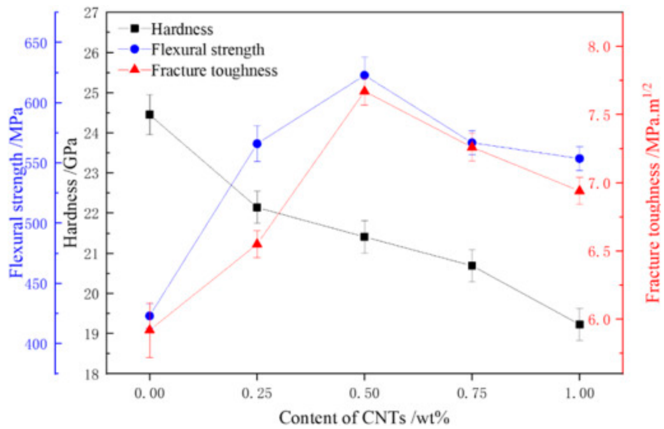

Figure 7. Influence of CNTs content on flexural strength, hardness, and fracture toughness of an CNTs-reinforced cBN tool at 1500 °C sintering temperature [41].

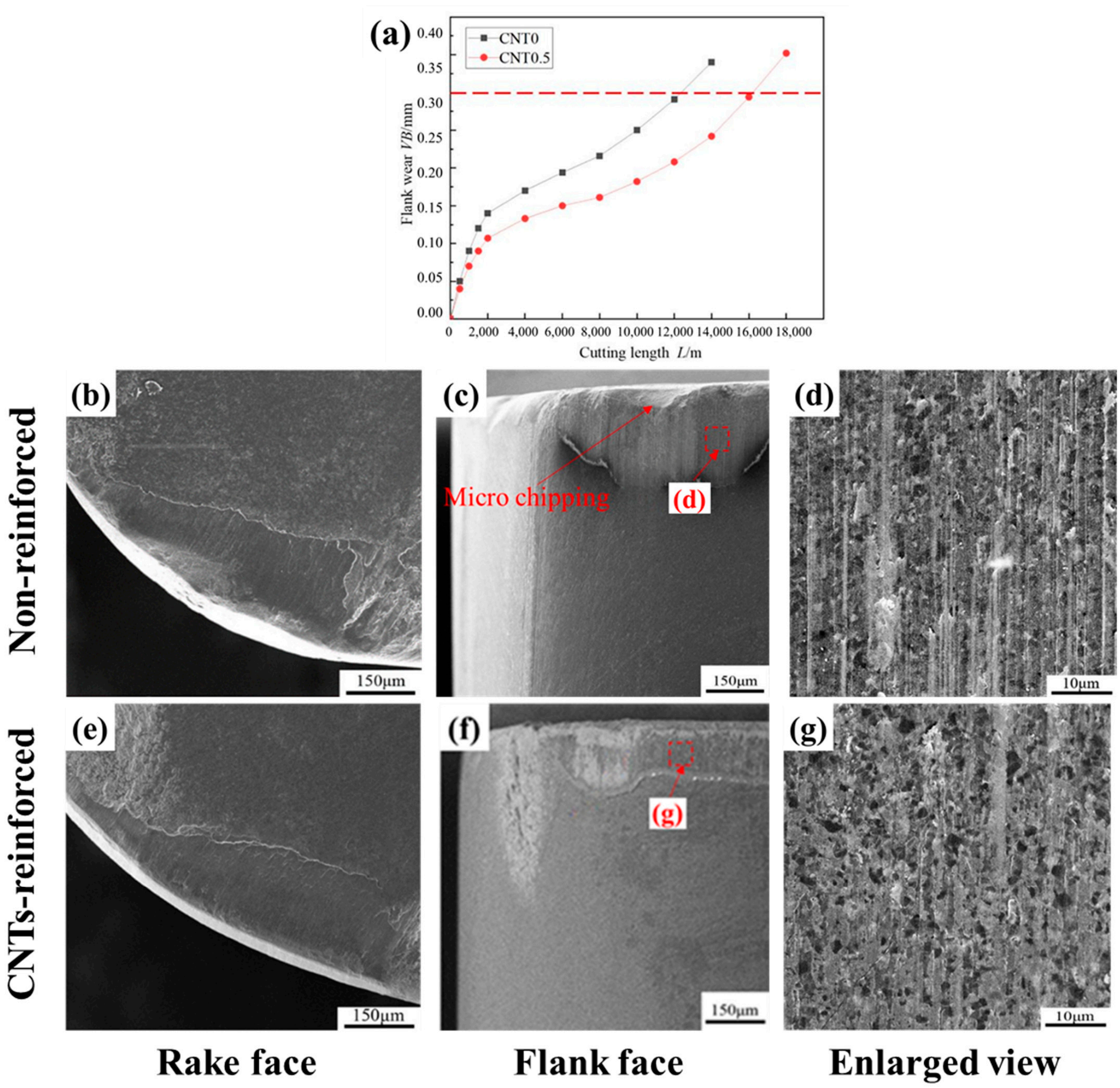

Figure 8. (**a**) The relationship between flank wear and cutting length for a CNTs-reinforced (0.5 wt% CNTs) and non-reinforced cutting tool along with rake face (**b**,**e**) and flank face wear (**c**,**f**) morphology, and an enlarged view of the highlighted part in the 2nd column (**d**,**g**) [41].

CNTs-based tool materials have been developed by Zu et al. [67] using hot pressing sintering technology at 1600 °C and 40 MPa, with CNTs serving as the reinforcement phase. The resulting material demonstrated significantly improved fracture toughness (7.0 ± 0.4 MPa.m^{-2}) compared to the original material. Sun et al. [68] also prepared cBN/CNTs tools using high temperature and high pressure technology and introducing 1 wt% CNTs, which resulted in optimal mechanical properties, including a 28.9% rise in fracture toughness and a 26.3% rise in flexural strength compared to the matrix without CNTs.

Sarkar et al. [69] studied the metal-cutting performance of an monolithic alumina tool by incorporating MWCNTs. A 0.3 vol% nanocomposite of MWCNTs-Al_2O_3 was prepared through hot-pressing at 1550°C exposed to 2.5 MPa uniaxial pressure for 1 h in static argon. The resulting specimen showed improved fracture toughness (+23%), flexural strength (+10%), hardness (+7.5%), and thermal conductivity (+30%) when compared to pure Al_2O_3. Sidorenko et al. [70] investigated the influence of CNTs addition to metal binders for cutting tools. Incorporating MWCNTs decreases the sizes of the structural components of the binder, hence improving the strength and performance of the binder. More precisely, the addition of 0.1% MWCNTs reduces the size of the Cu-based phase grains by a factor of 5.3 and the size of the Fe-based phase grains by a factor of 1.75 (measured in linear size, see Figure 9a for without CNTs and Figure 9b for with CNTs).

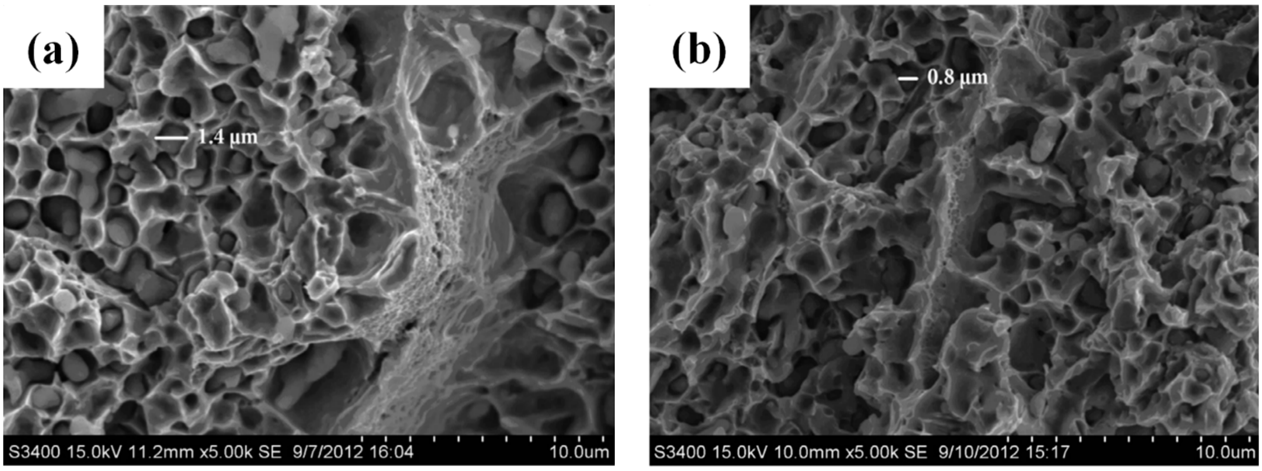

Figure 9. Fracture microstructure of binders (**a**) without CNTs and (**b**) with CNTs [70].

This leads to a small rise in the hardness and Young's modulus of the Cu-based phase, and a corresponding increase of 20% and 7% in the hardness and Young's modulus of the Fe-based phase. The incorporation of MWCNTs results in a 5% increase in the total elastic modulus of the binder. Significantly, the plastic characteristics of the composite binder improve notably, with a 20% rise in flow stress and a 60% rise in plastic extension. Nevertheless, the mechanical characteristics are very responsive to the presence of residual porosity: a greater concentration of MWCNTs results in heightened porosity and a substantial decline in the strength of the binder. Table 2 shows a summary of the effects of CNTs addition on mechanical properties of the metallic matrix.

Table 2. A summary of the effects of CNTs addition on mechanical properties of the metallic matrix: tensile strength (σ), plastic extension (δ), residual porosity (Φ), hardness (HR), and bending strength (σb) [70].

Binder	E (GPa)	σ (MPa)	δ (%)	Φ (%)	HR (HRB)	σb (MPa)
V21	147	504	0.032	4	98 ± 1	990 ± 30
V21 + 0.1% MWCNT	160	602	0.059	7	102 ± 1	1050 ± 20

Borkar et al. [71] reported that using pulsed electrode deposition for CNTs coatings led to a significant improvement in wear resistance in comparison to pure nickel coatings. Hirata et al. [72] conducted a study on the sliding friction characteristics of CNTs on different substrates such as silicon, cemented carbide, and silicon nitride. They found that the substrates with surface porosity exhibited better lubricating and adhesion qualities when coated with CNTs. Figure 10 shows variations in the friction coefficients–sliding distance. Friction coefficients observed in this experiment vary between a steel ball and a smooth silicon substrate with or without CNTs. Despite enhanced adherence of CNTs on the porous silicon substrate, friction on its surface rises even with a CNTs covering. The central region of the worn track sustained significant damage, leading to increased friction due to the grinding of the porous silicon surface compromised by etching. The emphasis is on substrate materials with suitable surface characteristics in terms of porosity and mechanical strength. Cemented carbide (WC-Co alloy) was later used as a substrate material characterized by its porous structure and robust mechanical strength, suitable for cutting tools. Furthermore, cobalt functions as a catalyst. CNTs were grown and included as a binder in the WC-Co, allowing for their deposition without the need for additional catalysts on the surface prior to deposition.

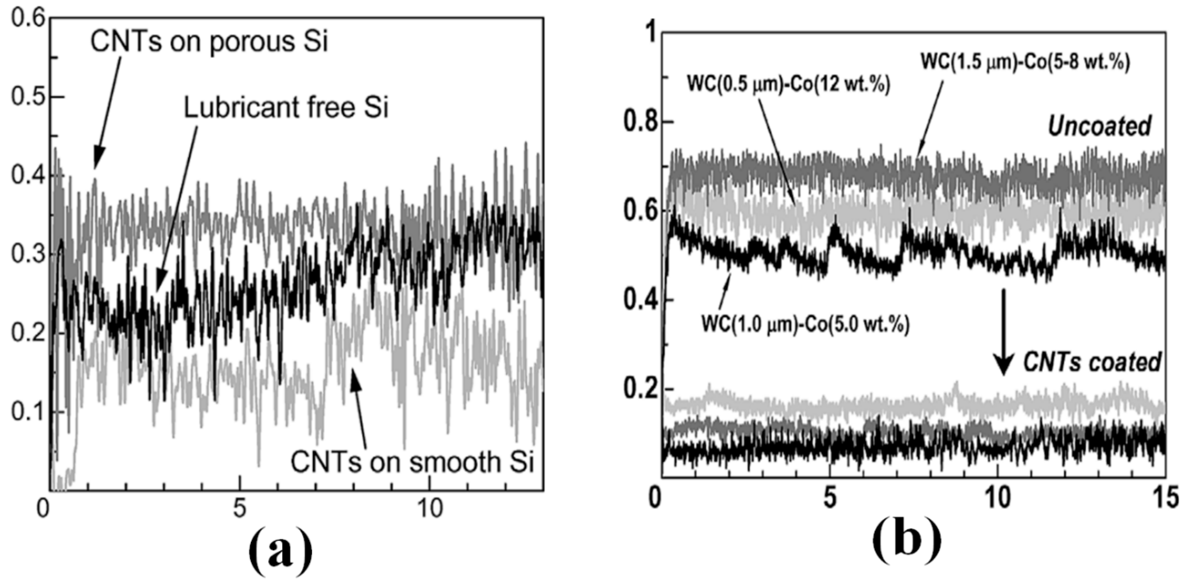

Figure 10. Variations in friction coefficients–sliding distance in a vacuum for (**a**) CNTs coated on smooth and porous silicon (**b**) amongst a stainless steel ball for uncoated substrate and CNTs-coated cemented carbides [72].

Despite the importance, there are only few studies investigating the cutting performance of CNTs-based cutting tools, while the performance of the fabricated tool can be studied by understanding the characteristics of the CNTs metal composites. For further information on CNTs-enforced composites, please refer to the following reviews [22,73–75].

3.2. CNTs-Based Nanofluids

Until now, to comprehend the interaction of nanoparticles within solid materials, researchers have pinpointed four primary effects. One notable effect pertains to spherical or nearly spherical nanoparticles functioning as miniature ball bearings on surfaces experiencing friction. These nanoparticles enable a ball-bearing effect, wherein rolling friction takes the place of sliding friction, thereby diminishing the coefficient of friction. This modification considerably bolsters the anti-friction properties of the material, as evidenced by the rolling effect observed in nanofluids. Such findings exhibit the capacity of nanoparticles to enhance lubrication and decrease wear in mechanical systems. Figure 11a shows the rolling effect, one of the four tribological effects of nanoparticles. For the second effect, certain nanoparticles, such as graphene, possess inherent solid lubrication properties, which enable them to create a more compact and smoother friction film on the work surface during sliding and peeling processes. This characteristic of graphene nanoparticles effectively reduces surface irregularities and enhances the durability of the friction film. Consequently, these particles result in a reduction in overall friction and wear, leading to improved performance and longevity of mechanical systems in which they are utilized. Figure 11b shows the film-formation effect, another one of the four tribological effects of nanoparticles. To form a deposited film, some nanoparticles in the lubricant will move toward the surface because of certain factors, thereby compensating for the loss of mass and assist in decreasing wear. Figure 11c shows the filing effect, the third proposed effect of the four. In the rolling process, the high temperature can melt the surface and the addition of nanoparticles results in ultra-smooth surfaces and a polishing effect. For that matter, some hard nanoparticle materials serve as a method for precision polishing in and of themselves. When used for polishing, these nanoparticles reduce the surface roughness and increase the contact area between surfaces. This expanded contact zone naturally leads to a reduction in the friction coefficient. Moreover, the use of these nanoparticles decreases the compressive stress on the contact surface, which enhances the bearing capacity of the lubricant. These improvements collectively contribute to more efficient operation and extended durability of mechanical components. Figure 11d shows the polishing effect (last proposed effect of the four) [17,61,62,76].

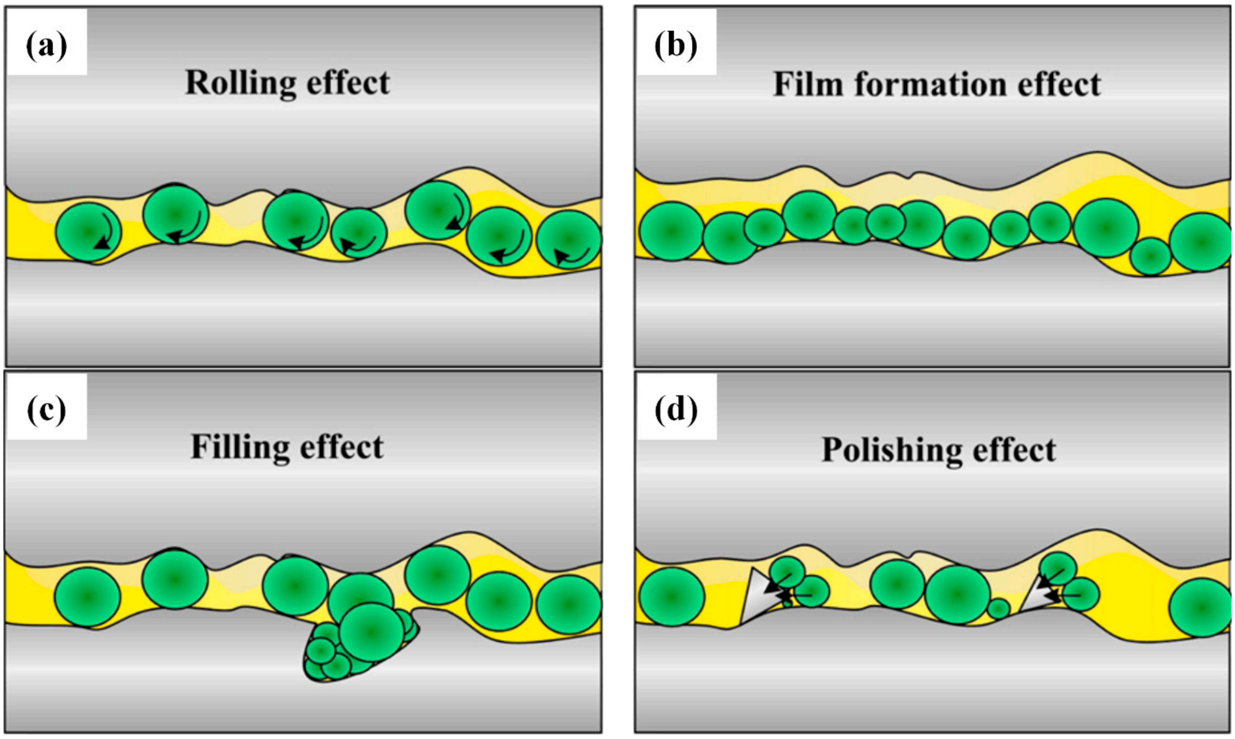

Figure 11. Tribological effects of nanoparticles [61].

CNTs possess a circular tube structure with high strength and modulus characteristics. Hence, the rolling effect is apparent. When nanofluids contain a minimal amount of CNTs, nanoparticles exist as "independent microtubules" in the turning zone. Due to their great strength and hardness, CNTs will not grind into hard film under heavy loads; as a result, they may lower the sliding friction force of the friction zone and enhance the lubricating effect of nanofluids [17]. Hegab et al. [77] conducted a study on the effects of two types of nanocutting fluids on tool performance and chip morphology during the turning of Inconel 718. In their investigation, both nanofluids demonstrated better results compared to the tests performed without any nanoadditives. The study revealed significant changes in the modes of tool wear and improvements in the intensity of wear progression when using nanofluids. Additionally, the collected chips were analyzed to understand the effects of adding nanoadditives on chip morphology. The results indicated that the MWCNTs nanofluid showed better performance than the Al_2O_3 nanofluid.

In other studies, Soltani et al. [78] examined the effects of temperature and particle concentration on the dynamic viscosity of a MgO-MWCNT/ethylene glycol hybrid nanofluid. The experiments were conducted in the solid volume fraction range of 0 to 1.0% under temperatures ranging from 30 to 60 °C. The results showed that the hybrid nanofluid behaves as a Newtonian fluid for all solid volume fractions and temperatures considered. Furthermore, the measurements indicated that the dynamic viscosity increased with increasing solid volume fraction and decreased with rising temperature. The relative viscosity revealed that when the solid volume fraction increased from 0.1 to 1%, the dynamic viscosity increased up to 168%. Jamil et al. [79] compared the influence of cryogenic CO_2 and hybrid nanofluid-based MQL techniques for turning Ti–6Al–4V. The hybrid nanofluid used was Al_2O_3 with MWCNTs dispersed in vegetable oil. The results demonstrated that the hybrid nanoadditives lowered the average surface roughness by 8.72%, cutting force by 11.8%, and augmented the tool life by 23% when compared to cryogenic cooling. Nonetheless, the cryogenic approach demonstrated an 11.2% decrease in cutting temperature as compared to the MQL-hybrid nanofluids, regardless of the cutting speed and feed rate being low or high. Semisynthetic cutting fluid Castrol Clearedge 6519 was utilized as the baseline cutting fluid by Samuel et al. [80] at a 12.5% dilution. Cutting fluids containing 0.5% by weight of SWCNTs and MWCNTs were made. In terms of providing lubrication, MWCNTs outperformed SWCNTs due to the intrinsic slipperiness of the nested nanotubes within the structure of the MWCNTs. The enhancements achieved by including around 0.2% by weight of graphene platelets are comparable to those achieved via incorporating roughly 0.5% by weight of the SWCNTs or MWCNTs. Figure 12 shows the thermal conductivity, kinematic viscosity, cutting force, and cutting temperature increase for different wt% of graphene platelets and CNTs.

Sharma et al. [81] examined the effectiveness of using MWCNTs-enriched cutting fluid in the process of machining AISI D2 steel material. The author observed a significant enhancement in the surface finish and a decrease in the temperature of the tool. For turning operations on Ti–6Al–4V workpieces, Sahu et al. [82] evaluated the effectiveness of nanofluid, which uses MWCNTs distributed in distilled water and SDS as a surfactant. Three distinct settings were used for the turning operations: dry, with traditional cutting fluid, and with nanofluid. Gravity feed was used to apply the nanofluid to the tool tip, with a maximum flow rate of 1 L/h. While rotating at the ideal cutting settings of 150 m/min, 0.1 mm/rev, and 1 mm depth of cut, a variety of machining reactions were examined, including cutting force, surface quality, and tool wear. Later, at a low cutting speed of 90 m/min, the nanofluid's machining capability was verified. Through a decrease of 34% in tool wear, a mean 28% decline in cutting forces, and a 7% decrease in surface roughness at a cutting speed of 150 m/min, the data showed that the nanofluid performed better than the standard cutting fluid.

In the investigations carried out by Dongkun et al. [83], MoS_2, CNTs, and ZrO_2 nanoparticles were employed as additives in grinding fluids. The specific grinding energy of the MoS_2 nanoparticle jet MQL was 32.7 J/mm^3, which was 8.22% and 10.39% lower than that of the other two nanoparticles, according to a comparison of the surface roughness values and specific grinding energies of the three nanoparticles. Furthermore, the ideal surface quality was obtained using MoS_2 nanoparticle jet MQL.

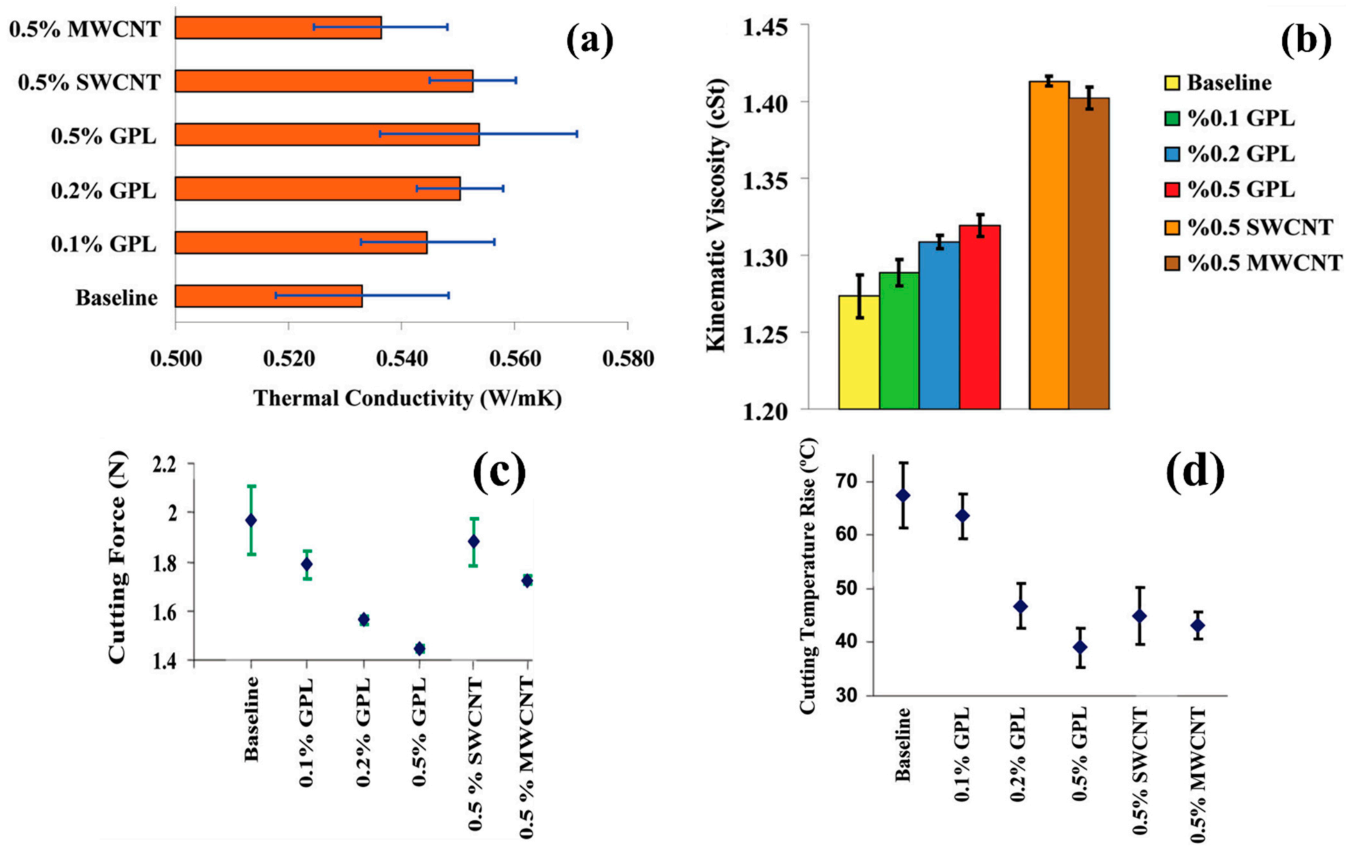

Figure 12. (**a**) The thermal conductivity, (**b**) kinematic viscosity, (**c**) cutting force and (**d**) cutting temperature increase at different wt% of graphene platelets and CNTs [80].

Prabhu et al. [84] investigated the surface properties of AISI D2 tool steel material during the grinding process utilizing MWCNTs. The surface roughness was assessed in the grinding process by using a surface roughness meter TR200 and an AFM, both with and without the presence of MWCNT lubricating mixes. The findings demonstrated that the use of CNTs led to a significant enhancement in the surface properties, transitioning from a microscale to a nanoscale level. The machined surface exhibited a range of surface roughness, with values ranging from 0.2 to 1.15 μm. This measurement was taken across a scanning area of 8 μm × 8 μm. The parameters used include a current of 0 amps, a pulse on duration of 8 μs, and a pulse off time of 7 μs. The roughness value obtained for the specimen using this parameter is 0.678 μm. It is noteworthy to mention that the preparation of nanofluids for the grinding process involved the combination of MWCNTs with SAE20W40 oil. An analysis was conducted on the surface roughness and microfractures using an AISI D3 tool. Experimental findings using a Taguchi DoE by Prabhu et al. [85] demonstrated an improvement in the surface quality of the machined workpiece from a microscale to a nanoscale. Furthermore, a regression analysis was used to construct an empirical model for predicting output parameters in the grinding process. The findings were then compared empirically for both cases, with and without the use of nanofluids.

Sharma et al. [86] used Al_2O_3 mixed nanofluid to create a hybrid nanofluid by adding MWCNTs at concentrations of 0.25, 0.75, and 1.25 vol%. The researchers used RSM to tune the cutting fluid and machining input variables, including cutting velocity, feed rate, depth of cut, and nanoparticle concentration, in order to enhance the response parameters. The findings indicated that augmenting the nanoparticle concentration in the cutting fluid led to a decrease in wear, and the hybrid nanofluid exhibited the least amount of wear. The use of Al-MWCNTs hybrid nanofluid as a cutting fluid resulted in the lowest reported values for cutting force, thrust force, feed force, and surface roughness. The lowest coefficient of friction was observed while using a 1.25 vol% Al-MWCNTs hybrid nanofluid, which was lower than that of the basic fluid. The utilization of NMQL in conjunction with a single type of nanoparticle has several drawbacks, including the grinding of materials that are known as hard to cut. Hybrid nanoparticles combine the characteristics of many types of nanoparticles, resulting in enhanced lubrication and heat transfer capabilities compared to single nanoparticle enhancements. Figure 13 shows characteristics of Al_2O_3-doped and Al-MWCNTs-doped cutting fluids.

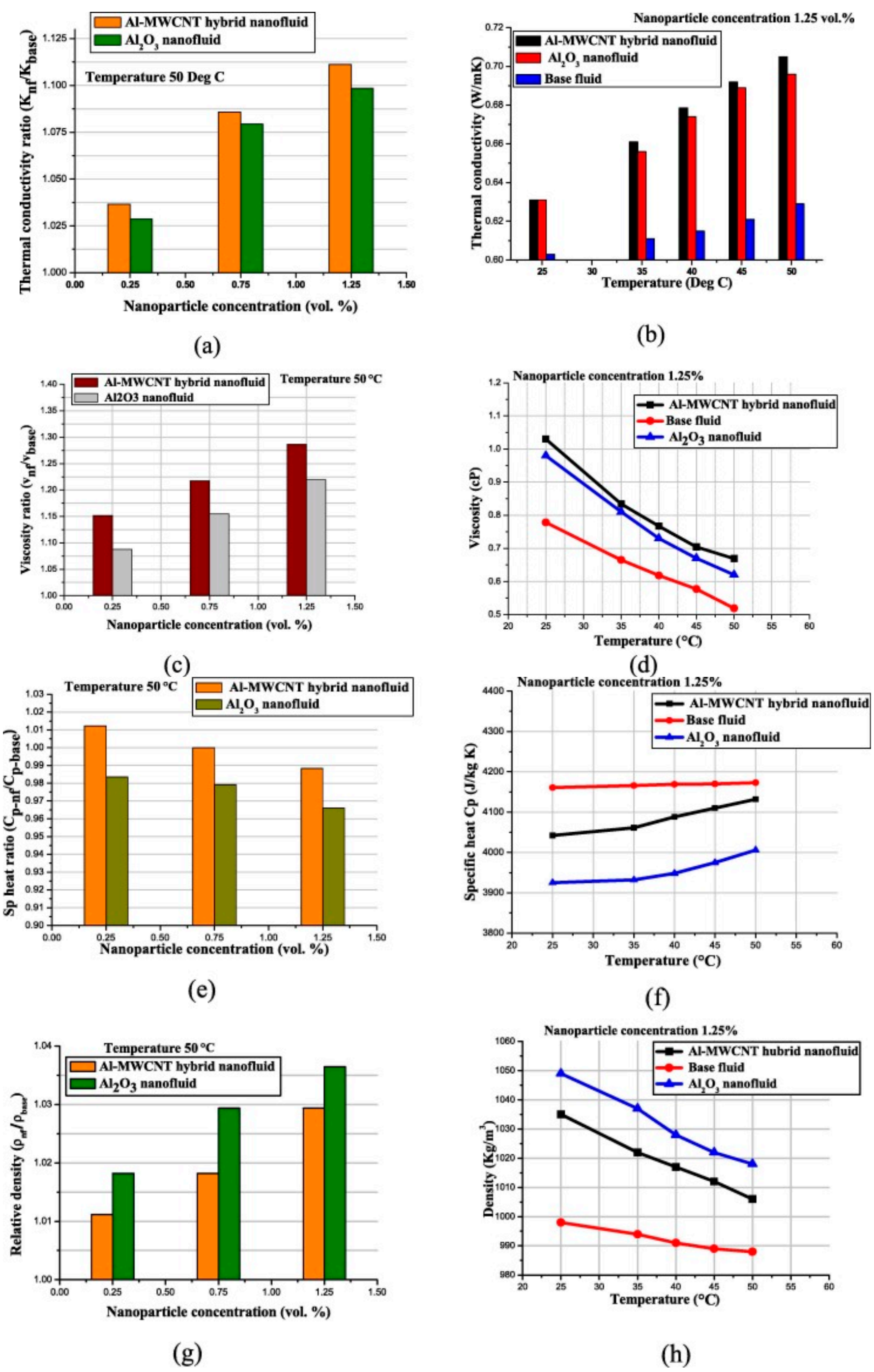

Figure 13. (**a**) Thermal conductivity as a function of nanoparticle concentration and (**b**) temperature, (**c**) viscosity as a function of nanoparticles concentration and (**d**) temperature, (**e**) specific heat as a function of nanoparticle concentration and (**f**) temperature, (**g**) density as a function of nanoparticle concentration and (**h**) temperature [86].

Zhang et al. [87] conducted a study to ascertain if hybrid nanoparticles exhibit superior lubricating performance compared to pure nanoparticles. An investigation was conducted on a hybrid nanofluid composed of MoS_2 nanoparticles, which exhibit excellent lubricating properties, and CNTs, which have a high heat conductivity coefficient. An analysis was conducted on the impact of hybrid nanofluid on grinding force, coefficient of friction, and workpiece surface quality in the context of grinding Ni-based alloy. The results indicated that the MoS_2/CNTs hybrid nanoparticles exhibit superior lubricating performance compared with single nanoparticles. The ideal ratio for combining MoS_2 and CNTs was reported as 2:1, and the optimum concentration of the nanofluid was 6 wt%. A brief summary of the application CNTs in nanofluids reported in the literature is presented in Table 1.

In an ELID, Prabhu and Vinayagam [88], via incorporating SWCNTs into the water-soluble fluid, tried to achieve superior machining at nanoscale-level surface finish. As measured by a Hommel surface roughness tester, the results of the experiment demonstrated that the utilization of a metal-bonded diamond grinding wheel with ELID and CNTs nanofluids decreased the surface roughness of glass materials from 1.788 to 0.722 µm. By utilizing CNTs nanofluid, the surface roughness and microcracks decreased from 0.3758 µm and 2.88 nm, respectively, in the absence of nanofluid, to 0.1791 µm and 1.58 nm, as determined by AFM. A significant enhancement in surface finish and microcracks is shown by these results. Table 3 provides a brief summary of the application of CNTs in nanofluids and corresponding workpiece, and the research findings reported in the literature.

Table 3. A brief summary of the application CNTs in nanofluids reported in the literature.

Nanoparticle	Fluid	Workpiece	Findings	Ref.
MWCNTs + Al_2O_3	Rapeseed oil	Inconel-718	The tribological performance of MWCNTs is better when two kinds of nanoparticles are used at the same time.	[77]
MgO + MWCNTs	Ethylene glycol	-	Newtonian fluid behavior for all solid volume fractions and temperatures. Dynamic viscosity increases with temperature decline and solid volume fraction.	[78]
MWCNTs + Al_2O_3	Deionized water	Ti–6Al–4V	Compared with low-temperature cooling, the hybrid nanoadditives reduced the average surface roughness by 8.72%, 11.8% of the cutting force, and 23% of the tool life.	[79]
MWCNTs	SAE-20W40 oil	AISI D2	Decline in cutting zone temperature, improved surface quality.	[81]
MWCNTs	Distilled water	Ti–6Al–4V	34% decrease in tool wear, a mean 28% drop in cutting forces, and a 7% decrease in surface roughness, better performance than nanofluid traditional cutting fluid.	[82]
CNTs	Colza oil	Hardened Steel 45	Specific grinding energy decreased, as did the surface roughness of the workpiece.	[83]
MWCNTs	SAE-20W40 oil	AISI D2	Improved the surface characteristics from microscale to nanoscale level.	[84]
CNTs	SAE-20W40 oil	AISI D3	Elevation of surface finish of workpiece to nanoscale level and increased flash and fire point of fluid.	[85]
MWCNTs	5 vol% vegetable oil + distilled water	AISI 304	Improved surface roughness.	[86]
MoS_2 + CNTs	Synthetic lipid	Ni-based alloy	Evaluated by specific grinding force, MRR of workpiece, surface roughness, morphology of grinding debris, and contact angle.	[87]
SWCNTs	Water-soluble oil	Glass	High level of surface finish because of in-grinding by the ELID technique	[88]
MWCNTs	Semisynthetic Castrol Clearedge 6519 @ 12.5% dilution	1018 steel	MWCNTs and SWCNTs solutions were made. MWCNTs outperformed SWCNTs in lubrication.	[80]
Modified CNTs	Water and surfactant	-	Thermal conductivity elevates with both higher concentrations and elevated temperatures.	[89]

Table 3. *Cont.*

Nanoparticle	Fluid	Workpiece	Findings	Ref.
CNTs	Soybean oil	Hardened Steel 45	Grinding fluids with of 1, 2, and 3 vol% concentrations were made; 2 vol% concentration of CNTs delivered optimal cooling effects.	[90]
MWCNTs	Coconut oil	Martensitic Stainless Steel	Cutting temperature and surface roughness improvement.	[91]
MWCNTs + Al_2O_3	Oil mist	100 Cr6 hardened steel	Decline in minimum tangential grinding force by 61.5%	[92]
CNTs	Coconut oil, Azadirachta indica, Cymbopogon citratus, Centella asiatica, jaggery syrup, and pure emulsifier (TEA, TN 80 and TN 85)	AISI 1040	Cutting force (−33%), cutting temperature (−29%), surface roughness (−34%), tool wear (−39%)	[93]
CNTs	Palm oil	nickel-based alloy GH4169	Increase in viscosity and thermal conductivity of nanofluids. The 2 vol.% had the lowest contact angle, thereby providing superior lubrication	[94]
MWCNTs	-	AISI 4140	Finite element analysis for cutting temperature.	[95]

To further elucidate the influence of CNTs on thermal conductivity increment, Xing et al. [89] performed an experimental study by adding various CNTs to deionized water. The results indicate that the thermal conductivities of CNTs- nanofluids surpass those of the base fluid. Furthermore, both the concentration and temperature of the nanofluids contribute to a rise in thermal conductivities. CNTs-nanofluids exhibit maximal thermal conductivity enhancements of 8.1%, 16.2%, and 5.0%, respectively, for short-SWCNTs, long-SWCNTs, and MWCNTs when the CNTs concentration is 0.48 vol% at 60 °C. Furthermore, the thermal conductivity values of the long-SWCNTs nanofluid are the highest due to their exceptional surface area and high aspect ratio. Under the experimental conditions, the enhancements in thermal conductivity for these nanofluids are nearly linear with the concentration of CNTs and the operating temperature. A straightforward linear correlation has been established between concentration, temperature, and effective thermal conductivities for all three varieties of CNTs- nanofluids.

4. Recent Advances in CNTs Applications for Other Machining Techniques

4.1. EDM

EDM is a non-conventional machining process that employs electrical sparks to shape hard materials into complex geometries. In this process, an electrically charged electrode creates a spark between itself and the workpiece, melting or vaporizing the material without direct contact, thus avoiding mechanical stress. This operation is conducted in a dielectric fluid that helps control the sparks, cools the process, and flushes away debris. EDM is particularly effective for detailed and precise machining of conductive materials and is utilized extensively in mold-making, die production, and intricate part fabrication. The technique allows for high precision and a smooth surface finish, which often eliminates the need for additional processing [96,97]. EDM's limitations include its restriction to conductive materials, relatively slow MRR, and high operational costs due to significant power consumption and electrode wear. Additionally, the use of flammable dielectric fluids introduces environmental and safety concerns. The process can also leave a recast layer and microcracks on the machined surface, potentially requiring further treatment to improve the part's mechanical properties [32,98]. Figure 14 shows a schematic of an RC electrical circuit micro-EDM.

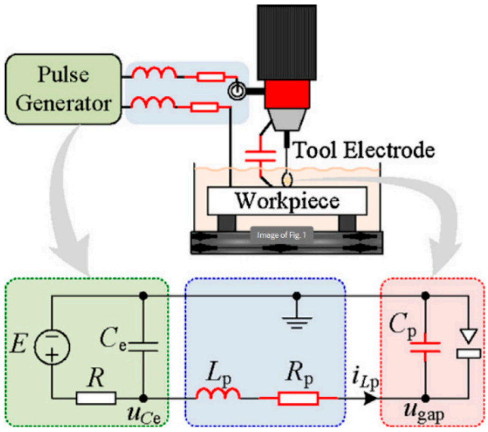

Figure 14. A schematic of an RC electrical circuit micro-EDM [99].

The density of CNTs is slightly lighter than other powders, but its thermal conductivity is much higher and specific heat is comparable. These properties promote uniform heat distribution, preventing thermal-induced instability. Mai et al. [96] fabricated CNTs via CVD and placed them in kerosene with a homogenizer cutting CNTs into 1–3 µm lengths to separate them. Experimental results showed that 0.4 and 1.2 g/L CNTs powder concentrations had the shortest machining time (72 min), while the EDM process with kerosene dielectric had the longest machining time (210 min), indicating a 66% reduction in machining time with CNTs powder mixed in the dielectric. Enhanced surface finish and elevated surface roughness was also reported. SEM images of machined surfaces can be observed in Figure 15 (without CNTs in Figure 15a and with CNTs in Figure 15b).

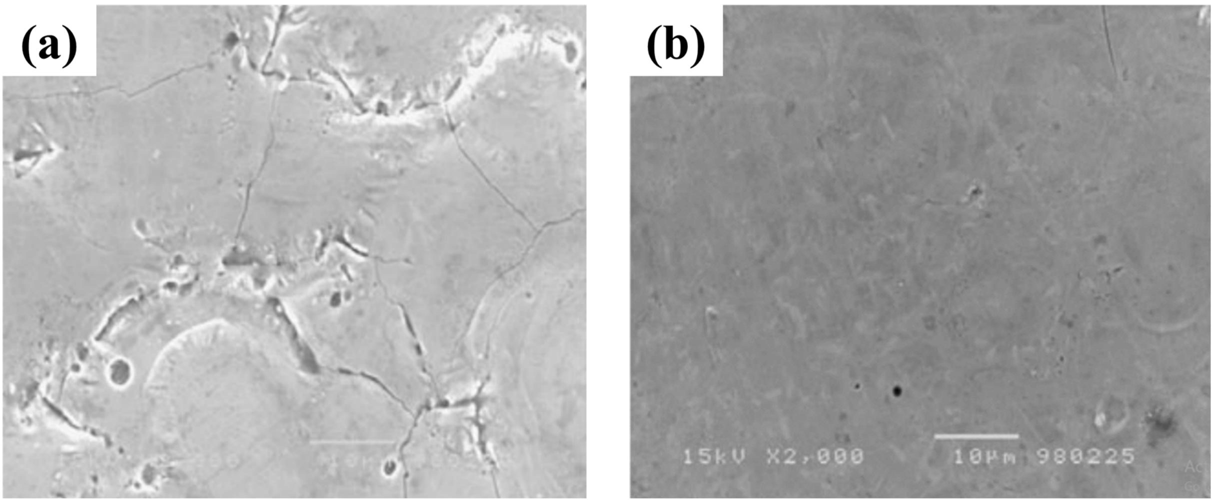

Figure 15. Machined surfaces using EDM (**a**) without CNTs and (**b**) in the presence of CNTs [31].

Copper plating was used by Suzuki et al. [100] to create Cu-based MWCNTs composite-coated electrodes. To enhance the dispersion of CNTs inside the matrix, they explored rotation and ultrasonic with two concentrations of CNTs. They reported improved average wear rate, enhanced CNTs dispersion via ultrasonication, and reduction in crater sizes caused by EDM after introduction of CNTs. Sari et al. [101] investigated the electrode wear rates, MRR, white layer thickness, and surface roughness using DoE with and without MWCNTs. The factors considered were interval time, pulse on time and peak current with corresponding three levels. They reported a smaller thickness for the recast layer, and superior electrode wear and MRR due to addition of CNTs, while there was a low pulse of energy. Prabhu et al. [102] experimentally examined AISI D2 tool steel machining for surface analysis using EDM with SWCNTs mixed in kerosene dielectric medium and copper tool electrode. They studied pulse-on duration, pulse-off duration, and pulse current as process parameters. Surface roughness and microcracks were analyzed using a surface roughness meter and SEM. The results showed that low pulse energy produced a better surface finish, and the workpiece with CNTs had fewer microcracks and a better surface finish. Table 4 shows a brief summary of application of CNTs in EDM.

Table 4. A brief summary of CNTs application in EDM.

Electrode	Dielectric	Work-Piece	Findings	Ref.
Cu (Φ20–Φ55)	Kerosene + CNTs	NAK80 steel	Shortened machining duration, enhanced surface finish, and elevated surface roughness.	[96]
Cu-based MWCNTs composite coated	-	Stainless steel	Improved average wear rate; enhanced CNTs dispersion via ultrasonication; reduced crater size after introduction of CNTs.	[100]
Cu (Φ4.9 mm)	Kerosene + MWCNTs	-	Smaller thickness for recast layer, superior electrode wear, and MRR.	[101]
Cylindrical copper rod	Kerosene + SWCNTs	AISI D2 Tool steel	A neuro-fuzzy optimization model used for surface roughness and MRR.	[102]
Cu	Kerosene + CNTs	Austenitic stainless steel	DoE considering pulse-on-time and powder concentration factors, enhanced surface finish, and MRR.	[103]
Cu	Kerosene + SWCNTs	Cold work steel	Development of full-factorial and DoE to assess the optimal CNTs concentration; enhanced surface finish.	[104]

The study conducted by Ahsan et al. [103] involved incorporating CNTs into a kerosene-based dielectric to enhance the machining performance of austenitic stainless steel during EDM with copper as the electrode. The researchers employed DoE with pulse-on time and powder concentration factors, and assessed their effects on the MRR and surface roughness. The findings revealed that the addition of CNTs powder not only increased the MRR but also improved the surface finish, which is in conformity with previous research. Specifically, the lowest surface roughness value of 8.61 μm was observed with a CNTs powder concentration of 0.3 mg/L, compared to 9.97 μm without CNTs. Conversely, the highest surface roughness value of 30.38 μm was noted in the absence of CNTs, which decreased to 29.4 μm with the addition of 0.3 mg/L of CNTs powder, highlighting the beneficial impact of CNTs in reducing surface roughness. Atefi et al. [104] developed DoE and full-factorial in optimization of EDM. The relevant model was derived once statistical analysis of the experimental data was completed.

According to the experimental findings, surface roughness reduced by around 15% and about 1 μm when CNTs were dispersed in a dielectric with 0.1 vol%. Carbon nanotubes were also mixed with a 0.2 vol% dielectric to reduce surface roughness by around 1.4 μm and roughly 20%.

4.2. ECM

ECM is one of the novel machining technologies that benefits greatly from CNTs. ECM is a method of metal removal via anodic dissolution, in which a specialized tool functions as the cathode and the workpiece acting as the anode. By conducting a direct current between the anode and cathode while both are immersed in an electrolytic solution, the process is carried out. The dissolution of metal ions from the workpiece into the electrolyte occurs as electricity travels through the circuit, thereby causing the workpiece to assume the intended form. The absence of thermal, mechanical, or residual stresses on the workpiece is among the key advantages of ECM. This is recognizing that the process is non-contact: removal of materials via chemical processes as opposed to employing physical force [105].

Due to this attribute, ECM is well-suited to produce components that necessitate exceptional material integrity but are susceptible to degradation when subjected to thermal or mechanical stress. Surfaces of superior quality and precise dimensions can be manufactured using ECM without requiring supplementary surface treatment procedures. The surfaces produced exhibit a high degree of smoothness and frequently lack burrs, rendering them advantageous for applications that require minimal additional processing steps. ECM's precision in machining difficult-to-machine materials and intricate geometries renders it indispensable in industries such as aerospace, medical implants, and die manufacturing [106,107]. ECM can efficiently accomplish intricate features and deep cavities that are difficult to attain using conventional machining methods. However, ECM functionality is limited to electrically conductive materials along with other factors that are not a subject of this review. This constraint renders it unsuitable for processing non-metallic materials, which could potentially be more effectively machined utilizing alternative non-conventional methods [16,105,108].

4.3. Other Machining Techniques

Novel technologies for machining cutting process seek to increase the method's efficiency by reduction of cutting pressures, cutting temperatures, and cutting time duration. High-speed machining [109], five-axis machining [110], electrical discharge machining [111], abrasive jet machining [112], grinding [113,114], laser machining [115,116], ultrasonic machining [117], and hybrid machining [118,119] are some of the novel technologies for machining processes. Machining technologies can be categorized into contactless, with contact, or a hybrid of the processes, in terms of physical contact between workpiece and the cutting tool. Contact machining processes involve physical interaction between the tool and the workpiece, which can lead to wear on the tool.

Examples of contact processes include turning, where the cutting tool shapes the rotating workpiece; milling, which involves cutting tools that remove material through rotary cutting; drilling, where a drill bit penetrates the material to create holes; grinding, which achieves fine surface finishes and precise dimensions using an abrasive wheel; broaching and gear cutting, where multi-toothed tools cut predetermined shapes by contacting and passing over the material [12,52,79,92]. HSM, a contacting-type process, is a type of machining that employs high spindle speeds and feed rates to remove material from a workpiece with greater speed than traditional machining techniques. HSM may be used on a variety of materials, including metals, polymers, and composites, and is commonly utilized for milling, drilling, and turning processes. The utilization of cutting tools with a great number of teeth and shallow cutting depths, which enable an increased chip load and a faster MRR, is the core element of HSM. High spindle speeds and feed rates additionally decrease cutting forces and enhance the workpiece's surface finish. HSM may be carried out on both CNC and manual machines, and to obtain the appropriate results, it needs specific equipment and cutting techniques. Reduced machining times, increased productivity, and cheaper production costs are just a few advantages of HSM, which makes it a desirable alternative for multiple industries including aerospace, automotive, and medical device production. The performance of HSM has recently been the subject of investigation, especially for hard-to-cut materials like titanium and Inconel. Although CNTs might not directly contribute to enhancement of productivity, they indirectly contribute via improvements in cutting tools and lubrication techniques. For instance, some of the problems with HSM of these materials have been resolved owing to improvements in tooling materials and coatings as well as new cutting techniques, which are already improved or can be further improved with a suitable design and strategy of introducing CNTs [109,120,121].

In contrast, contactless machining processes do not involve direct physical contact between the tool and the workpiece, reducing tool wear and allowing for machining of hard or brittle materials. Examples of contactless processes include EDM, which was briefly discussed in Section 4.1; laser cutting, which uses a laser beam to cut or engrave materials without physical contact; waterjet cutting, which uses high-pressure water to cut through material without contact; plasma cutting, which utilizes an ionized gas stream to cut through conductive metals; ultrasonic machining, which uses ultrasonic vibrations of a tool to remove material from a brittle workpiece; and ECM, which was briefly discussed in Section 4.2 [111,122].

Advanced machining processes may combine contact and contactless techniques. Electrochemical grinding blends ECM and mechanical grinding, reducing tool wear and achieving high surface quality. Laser-assisted machining preheats the workpiece contactless using a laser, while traditional tools complete the machining under contact conditions [123,124]. In this regard, CNTs, attributed to their outstanding properties, can contribute in either one or several ways by enhancing various properties, as previously mentioned: improving the cutting tool, better lubrication for contacting machining processes, and improving conductivity, together with the other discussed properties for non-contacting processes. And, finally, a combination of enhancements in hybridized processes, making room for further research in the field to better elucidate the interplay among the multitude of parameters.

5. Challenges in Application of CNTs in Machining

5.1. Challenges in CNTs-Reinforced Cutting Tools

While CNTs can potentially enhance the wear resistance of cutting tools, there are challenges associated with their consistent distribution and integration. These challenges include the complexity and cost of incorporating CNTs into cutting tool materials using techniques such as chemical vapor deposition [125], ball milling [40], and sintering [126]. Additionally, the high material and processing costs of CNTs-reinforced tools make them more expensive than conventional tools, limiting their widespread adoption in the industry. Scaling up production while maintaining quality and performance consistency is also challenging and optimizing the process of fabrication for cutting tools with certain geometries may not be feasible. Overcoming these technical and economic hurdles is crucial for the successful commercialization of CNTs-reinforced cutting tools.

5.2. Challenges in CNTs-Based Nanofluids

As CNTs tend to agglomerate, achieving stable dispersion of CNTs within the fluid is problematic. This agglomeration can lead to settling and uneven distribution, diminishing the effectiveness of the nanofluids [87,127]. CNTs often necessitate surface modifications, such as functionalization, to improve their compatibility with the base fluid. However, these modifications may alter the intrinsic properties of CNTs, which could impact their performance. Moreover, the introduction of CNTs into fluids can significantly affect the fluid's viscosity [128], which can be detrimental in systems that require low viscosity, such as in microchannels or narrow passages of heat exchangers [129]. Additionally, the cost and scalability of producing and integrating CNTs into fluids pose significant challenges. The processes involved in synthesizing, purifying, functionalizing, and dispersing CNTs on an industrial scale are complex and expensive, which can limit the commercial application of CNTs-based nanofluids [26,30]. Furthermore, while CNTs are expected to significantly enhance the thermal conductivity of fluids, the actual extent of this enhancement can be inconsistent and often falls short of theoretical predictions when scaled from laboratory experiments to practical applications.

5.3. Challenges in Application of CNTs in Other Machining Techniques

The challenges can vary depending on the process type. In contacting processes, the challenges in cutting tool and lubrication persists while in non-contacting processes, novel challenges are brought about. For instance, despite the benefits, integrating them into the electrodes presents challenges. One of the main difficulties lies in maintaining the structural integrity of the electrode while enhancing its conductivity and thermal stability. Achieving a uniform distribution of CNTs within the electrode material is crucial for consistent performance, yet CNTs tend to agglomerate, leading to uneven machining results. Although CNTs can potentially increase the wear resistance of EDM electrodes, consistently maintaining these properties in a practical manufacturing environment is challenging. Additionally, utilizing the superior electrical and thermal conductivities of CNTs effectively within the EDM process can be difficult, as the electrodes must be designed to avoid overheating or excessive electrical discharge that could damage the workpiece or machining equipment [14,126,130].

In ECM, there is a primary need for uniform dispersion within the electrolyte. CNTs tend to clump, resulting in uneven material removal. Their incorporation can also alter the electrochemical dynamics between the tool and the workpiece, which may change the efficiency and outcomes of the machining process. Moreover, maintaining the stability of CNTs in the electrolyte is critical, as any settling or aggregation reduces their effectiveness [15,16,124]. Addressing these challenges requires an interdisciplinary approach, combining insights from material science, electrochemistry, and engineering to fully harness the potential of CNTs in ECM while effectively managing their complexities.

6. Final Remarks and Outlook

CNTs have attracted significant attention due to their remarkable properties, which have been utilized in machining processes. However, there is a scarcity of review papers that offer a comprehensive overview of the potential applications of CNTs in these fields. This review highlights the significant enhancements that CNTs offer in machining processes, particularly in fit-for-purpose applications. Furthermore, due to the existence of reviews on the preparation and characterization methods for CNTs-reinforced composites and CNTs that include nanofluid, repeating the same content was avoided to keep this review short. The discussion emphasized the integration of CNTs in cutting tools and lubrication systems, which has resulted in improved wear resistance, thermal management, and reduced lubricant consumption. Table 5 depicts a summary of challenges and advantages.

- The use of CNTs in cutting tools has extended tool life and improved the efficiency of machining operations by reducing the energy required to overcome friction and enhancing cutting precision. Despite the promising enhancements, the adoption of CNTs in industrial settings is hindered by high costs and technical challenges related to their manufacturing and integration. Furthermore, there are many research articles on CNTs-reinforced composites that further incentivize the application of CNTs-reinforced cutting tools.
- The use of CNTs in cutting fluids results in decreasing cutting zone temperature, grinding force, cutting force, and tool wear, along with increased thermal conductivity in correlation with temperature and concentration. For certain wt% of CNTs, lower contact angle and superior lubrication were reported.
- The review pointed out the need for comprehensive studies focused on the long-term operational benefits and cost-effectiveness of integrating CNTs into mainstream machining processes.
- Future research should aim to optimize fabrication techniques to reduce costs and enhance the dispersal quality of CNTs in composite materials. Additionally, further empirical studies are needed to quantify the improvements in tool life and machining efficiency under various operational conditions. By addressing these challenges, the machining industry can fully leverage the unique properties of CNTs to advance toward more sustainable and efficient manufacturing practices.

Table 5. Summary of challenges and advantages of CNTs application in machining processes.

Summary of Challenges and Advantages			
Process Type	**Application Category**	**Advantages**	**Challenges**
Contacting	Cutting tools	▪ Reinforcement phase ▪ Improved discharge during SPS ▪ Improved fracture toughness ▪ Improved flexural strength ▪ Improved hardness and thermal conductivity	▪ Complexity and cost of incorporating into cutting tools ▪ Material cost ▪ Upscaling while maintaining the performance ▪ Agglomeration
	Cutting fluid	▪ Decline in cutting zone temperature ▪ Improved surface quality and MRR ▪ Specific grinding energy decline ▪ Improved tool wear and lubrication	▪ Dispersion, agglomeration and stability in the cutting fluid ▪ Estimation of thermal conductivity enhancement ▪ Synthesizing, purifying, functionalizing
Non-contacting	EDM	▪ Shortened machining duration ▪ Enhanced surface finish ▪ Reduction in crater size ▪ Superior electrode wear and MRR ▪ Smaller thickness for recast layer	▪ CNTs integration into electrodes ▪ Maintaining the structural integrity of the electrode while enhancing its conductivity and thermal stability ▪ Agglomeration ▪ Uneven machining results ▪ Overheating or excessive electrical discharge

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Nomenclature and Abbreviations

Atomic force microscope	AFM
Computer numerical control	CNC
Carbon nanotubes	CNTs
Cubic boron nitride	cBN
Design of Experiments	DoE
Electrochemical machining	ECM
Electrical discharge machining	EDM
Electrolytic in-process Dressing	ELID
Extreme pressure	EP
High-speed machining	HSM
Low-speed machining	LSM
Minimum quantity lubrication	MQL
Material removal rate	MRR
Multi-walled carbon nanotubes	MWCNTs
Nano-fluid minimum quantity lubrication	NMQL
Response surface methodology	RSM
Scanning electron microscopy	SEM
Sodium dodecyl sulfate	SDS
Spark plasma sintering	SPS
Single-walled carbon nanotubes	SWCNTs
Tool condition monitoring systems	TCMs

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