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Nano-Cutting Fluids Technology: A Review

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Abstract

Proposing nano-cutting fluids contributes to facing the heat dissipation challenge during machining difficult-to-cut materials since they offer a highly observed thermal conductivity value in comparison with the base lubricants. Thus, several nano-additives are employed to improve the cooling and lubrication functions of the used base lubricants. The nano-additives have superior thermal and wettability characteristics which could significantly enhance the resultant nano-fluid properties. These properties include the ability to withstand the high generated temperature during machining difficult-to-cut materials. Also, they would enhance the nano-fluid tribological functions since the employed nano-additives work as spacers in the workpiece-tool interface area to reduce the induced friction during machining processes. Generally, nano-cutting fluids have shown promising effects on the cutting performance characteristics through different cutting operations such as turning, milling, and grinding. In the current work, a comprehensive review study about the nano-cutting fluid technology is presented. The study discussed different aspects related to the nano-cutting fluids and their applications such as, the preparation techniques of nano-fluids, characterization of nano-fluids stability, the thermal and rheological of the resultant nano-fluid, the nano-fluids effects on improving the cutting processes performance, and nano-fluids challenges.

Keywords: Nano-fluids; Machining; Cooling; Lubrication; Nano-additives

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Introduction

Increasing the heat dissipation area is an essential requirement during the cutting processes as it could offer effective results in terms of cutting tool life, energy consumption, and production rates. The conventional technique for increasing the heat dissipation for several industrial applications has focused on increasing the heat exchanging area; however, it associates with a problem of the thermal management system size [1]. Thus, proposing new environmental cooling and lubricant systems is highly required especially in improving the cutting quality characteristics. Several environmentally conscious cooling/lubrication technologies during machining processes have been presented such as dry cutting, Minimum Quantity Lubrication (MQL), and cryogenic technology. Eliminating the cutting fluids usage can be performed using dry cutting techniques; however, dry cutting techniques are associated with some machining difficulties such as excessive tool wear and poor surface quality [2]. Kamata and Obikawa investigated another conscious technology in order to improve the machinability known as minimum quantity lubricant (MQL) and it could be penetrated into the cutting zone using an optimal amount of cutting fluid with compressed air [3]. Furthermore, the cryogenic technique is considered as another effective alternative for enhancing the machinability and dissipating the generated heat at the cutting zone as it affects the properties of the cutting tool and workpiece using a super cold medium with liquefied gasses at a temperature lower than 120K (e.g. Liquid nitrogen:LN_2) [4].

Literature Review

Proposing new nano-cutting fluids in order to face the heat dissipation challenge during cutting processes is encouraged since it offers a highly observed thermal conductivity value in comparison with the base lubricants. Additionally, it is showed that nano-fluids have superior cooling properties due to its good heat extraction capabilities [5-8]. A nanofluid can be defined as a new fluid result from the dispersion of metallic/nonmetallic nanoparticles or nanofibers with a certain size less than 100 nm into the base cutting fluid [1]. Nano-additives can be categorized into several types which are non-metallic, mixing metallic, carbon, and ceramic nanoparticles [9,10]. Various advantages of using nanofluids through different applications have been presented as follows [11]:

- High heat transfer surface between particles and fluids due to the high specific surface area of nano-fluid;
- High dispersion stability;
- Saving power consumed in intensification of pure liquid since nanofluids can offer the desired heat transfer properties;
- Surface wettability and heat transfer properties can be controlled by changing the nano-additives concentrations.

Examples of several applications which implemented the nano-fluid technology to improve its thermal, rheological, and stability properties are obtained through various literature studies such as cooling of electronics, engine cooling, solar water heating, cooling of welding, engine transmission oil, nuclear systems cooling, and nano-fluids in different cutting operations [11-14]. This article is mainly focused on presenting a comprehensive literature survey of publications which are related to techniques of nano-cutting fluids preparation (section 2), characterization of nano-cutting fluids stability (section 3), the thermal and rheological nano-cutting fluid properties (section 4), improvements of machining quality characteristics (section 5), Nano-Fluids Challenges (section 6).

Techniques of nano-cutting fluids preparation

In order to achieve optimum thermal properties during the preparation of nano-cutting fluid, two main factors need to be considered: durability and stability. Achieving lower sedimentation velocity of nano-additives is an essential requirement to ensure the nanofluid's stability. The sedimentation velocity is varied proportionally with the square of nano-additive radius according to the stokes law given in equation (1), where V_s is the sedimentation velocity, R is the nano-additive radius, μ is the base fluid viscosity, P_p is the nano additive density, and P_m is the base fluid density. However, using lower particle radius leads to decrease the sedimentation velocity, the surface energy of the nano-additives is increased which can result in nano-additives aggregation. Thus, selecting an optimal value of the nano-additive size and performing homogeneous dispersion are highly required to avoid both higher sedimentation velocity and occurring of nano-additives aggregation [1,15,16].

$$V = \frac{2R^2}{9\mu_m}(\rho_p - \rho_m)g \qquad (1)$$

There are two main techniques for nanofluids preparation: two step and single step. The two steps technique means manufacturing of nano-additives (e.g. physical vapor deposition) and dispersion of nano-additives into the base fluid are two separate steps; however, the single step technique depends on making both of them concurrently. In regards to the two steps technique, it is more suitable during dispersion of oxide particles and carbon nanotubes and show potential results for metal-nano-particles. However, this technique includes two step to disperse the nano-additives into the base fluid and it is simpler than the other technique, it associates with several problems such as nano-additives agglomeration. Thus, some methods are used to face the previously mentioned problem using ultrasound, and high shear approaches. It has been recommended that the two-step technique can fit more volume concentration values higher than 20% [17,18]. In terms of the single step technique, drying, storage, and transportation of nano-additives are included; hence, a stable and durable nanofluid can be achieved as nano-additives agglomeration and sedimentation are avoided. However, the high observed efficiency of the single step technique in terms of nanofluids' stability and durability has high observed efficiency, it cannot fit the applications with high volume concentration values [19,20]. A schematic of the nano-fluids preparation methods is provided in **Figure 1.**

It should be stated that physical vapor deposition (PVD) method has the capability to uniformly disperse the nano-additives into the base oil using two main approaches collimated beam PVD or ionized metal plasma. In spite of the previous advantage, these approached aren't effective when higher nano-additives concertation's are used.

Nano-additives dispersion into the base fluid is an important consideration which affects the thermal conductivity and viscosity of the resultant nano-cutting fluid. Dispersion of nano-additives into the base cutting fluid can be performed using an ultrasonic machine following by stirring stage using a magnetic stirrer to ensure the full desperation of nano-additives. Furthermore, the processing time for each previous step depends on the weight fraction (wt. %) of nano-additives [21,22]. The nano-additive weight concentration into the base cutting fluid can be determined using equation (2). Another two alternatives rather than the dispersion of nano-additives powder into the base fluid have been obtained namely; nano-additives synthesis using chemical precipitation or organic reduction [23].

$$\%\ \text{of weight concentration} = \frac{\text{nanoadditive weight}}{\text{nanoadditive weight} + \text{the base fluid weight}} \qquad (2)$$

Characterization of nano-cutting fluids stability

Nano-cutting fluids result from the suspension of nano-additives into the base cutting fluid can be expressed using four design parameters as follows [24]:

Nano-additives: metallic particles, non-metallic particles, and carbon tubes/graphene;Base fluid: water-based oil, organic liquids, vegetable oil, and polymeric solutions;Other additives: surfactants, anti-wear/corrosion additives, and fungicides; Scale: percentage of weight/volume concentration.

During the nano-fluid manufacturing process, these design parameters are selected depending on the required thermal,

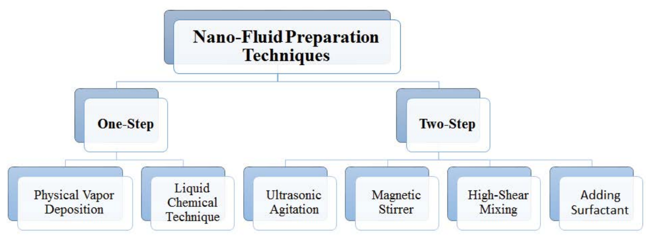

Figure 1 Nano-fluids preparation techniques.

tribo-chemical, physical, and rheological properties which need to be achieved in the resultant nanofluid as the functional requirements for each nanofluid type are different.

Dispersion of nano-additives into the base fluid is considered as a difficult challenge due to the strong van der Waals interactions which results in nano-additives agglomeration, clogging, and sedimentation. Thus, using physical or chemical treatment such as surfactants is recommended in order to achieve powerful forces on the clustered nano-additives to ensure sufficient dispersion and achieve an observed enhancement in thermal conductivity and viscosity [25-27]. Two principles have been studied in order to establish a high suspension quality for nano-additives into the base oil, namely, diffusion and zeta potential. The first principle is the diffusion principle: it ensures the nano-additives are scattered and dispersed into the liquid medium. The second principle is mainly focused on achieving higher zeta potential value which offers a repulsive force among the nano-additives [28].

Through the various literature studies [29-35], this study survey found that three main methods have been implemented to control and offer a high suspension/stability performance in order to avoid the nano-additives agglomeration, clogging, and sedimentation. The three main methods are as follow:

Surfactant: the purpose of using surfactant is modifying the nano-additives to be more hydrophilic, and increasing the nano-additives surface charges; hence, the repulsive forces between the nano-additives are increased [36,37]. Thus, the suspension of nano-additives into the base fluid can be improved; however, selecting an optimal amount of surfactant is an important factor as it can effect on the resultant electrostatic repulsion. Another limitation of this techniques is the difficulty in dealing with applications associated with a temperature above 60°c as the repulsive forces can be damaged [33]. Various examples of surfactant have been used such as; sodium dodecyl sulfate, dodecyl trimethylammonium bromide, and polyvinylpyrrolidone (PVP) [1]. PVP was thought to strongly adsorb on the surface of the ferrite nanocrystals, limiting grain growth. Generally, PVP can serve as a surface stabilizer, growth modifier, nanoparticle dispersant, and reducing agent [36].

pH control: the nano-fluid pH can control the stability and also improve the thermal conductivity as it is related to the electro-kinetic properties. Using simple chemical treatment techniques cause a conversion for the nano-additives shape which results in higher surface discharge density, electric repulsion force, and zeta potential value. Thus, agglomeration, clogging, and sedimentation effects can be decreased and high suspension quality of the resultant nanofluid can be accomplished [38,39]. It has been investigated during the dispersion of Al_2O_3 nanoparticles into the water as a base fluid that agglomeration size has been decreased at pH level of 1.7. However, an increase of agglomeration size has been noticed at a pH level of 7.66 [40]. Furthermore, another study provided the effects of pH on the electrostatic repulsion and van der Waals attraction energies (total energy) at different inter-particle distance using metal oxide nanoparticles, and it can be observed that the total energy is inversely proportional to pH values at lower levels of inter-particle distance; however, no significant effect of pH can be observed at higher levels of inter-particle distance as shown in **Figure 2** [39].

Ultrasonic vibrations: this technique aims to break down the agglomerations among nano-additives and it reveals promising results in term of the process stability. Nevertheless, optimizing the processing time is required as it can lead to fast clogging and sedimentation of nan-additives [41]. The ultrasonic disruptor is the most popular apparatus used for ultrasonic vibration to disperse the nano-additives into the base fluid. The applied mechanisms during the ultrasonic vibration include three stages to ensure fully process stability and decreasing the clogging and agglomeration size [42]; strong and irregular shock on the system wall, micro-bubbles formation, and high flow shear rate.

Many different studies presented several instrumentation techniques which employed to assess the nano-fluid suspension performance such as sediment photograph capturing [43], UV–Vis spectrophotometer [44], transmission electron microscopy, scanning electron microscopy, and light scattering [44]; however, the zeta potential analysis and analyzing the gathered data are the most popular techniques to check the process stability. **Table 1** shows the suspension stability at different zeta potential levels [45].

The thermal and rheological nano-cutting fluid properties

The nano-cutting fluids have shown promising results in improving the base cutting fluid properties; however, these improvements cannot be clearly observed without applying an adequate dispersion technique as mentioned in the previous section. These improvements are mainly focused on the thermal,

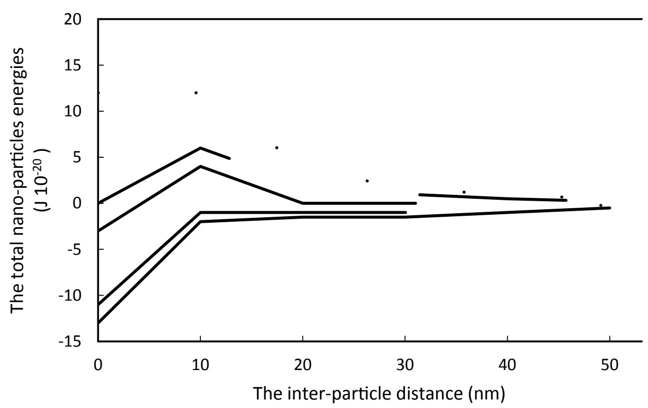

Figure 2 The inter-particle distance versus the total nano-particles energies.

Table 1 The suspension stability at different zeta potential levels.

Z potential absolute value	Stability Status
0	Little or no stability
15	Some stability but settling lightly
30	Moderate stability
45	Good stability, possible settling
60	Very good stability, little settling likely

tribological, and rheological properties. The thermal conductivity is one of the most important indications to express the system heat transfer.

Regarding the thermal properties improvements, a previous review study [23] has shown the thermal conductivity enhancements for different nanoparticles types, sizes, and volume fraction percentages using water as base fluid as shown in **Table 2**. Various analytical models have been performed to express the nano-fluid thermal conductivity. The Maxwell equation [46] shown in equation (3) can predict the thermal conductivity depending on the base fluid's thermal conductivity(K_m), the nano-additive thermal conductivity (K_p), and the nano-additive volume fraction (υ_p), while the resultant thermal conductivity is (K_e).

$$k_e = k_m + 3u_p \frac{k_p - k_m}{2k_m + k_p - u_p(k_p - k_m)} k_m \quad (3)$$

Another modified model has been obtained for calculating the nanofluid thermal conductivity as shown in equation (4) [47], where ρ_p, C_p, T, η, R are nano-additive density, nano-additive specific heat, temperature, viscosity, and nano-additive radius.

$$\frac{k_e}{k_m} = \frac{k_p + 2k_m - 2u_p(k_m - k_p)}{k_p + 2k_m + 2u_p(k_m - k_p)} + \frac{\rho_p u_p c_p}{2k_m} \sqrt{\frac{k_p T}{3\pi R \eta}} \quad (4)$$

On the other hand, the transient hot-wire method has been used in various studies to predict the thermal conductivity, and it is called transient line heat source method [48,49]. In addition, the nano-fluids have shown the promising result to enhance the heat transfer coefficient. Through investigation the effective heat transfer ratio (nano-fluid heat transfer coefficient/base fluid heat transfer coefficient) for different nano-additives types, sizes, and volume fractions [50].

Furthermore, two analytical models have been developed to predict another heat transfer indicator which the specific heat

Table 2 Literature summary the thermal conductivity enhancements for various nano-fluids (water-based).

References	Nano-additive type	Nano-additive Diameter (nm)	Volume fraction (%)	The percentage of thermal conductivity improvement (%)
[55]	Cu	100	7.5	78
[56]	CuO	36	5	60
[57]	MWCNT	100	0.6	38
[39]	CuO	23	9.7	34
[55]	TiO_2	10	5	33
[58]	Al_2O_3	13	4.3	30
[58]	Al_2O_3	13	4.3	30
[55]	TiO_2	15	5	30
[57]	MWCNT	130	0.6	28
[59]	Cu	100	0.1	24
[60]	Cu	100	2.5	22
[61]	Al_2O_3	36	10	22
[62]	Au	10	0.026	21
[63]	Al_2O_3	68	5	21
[63]	Al_2O_3	60.4	5	20
[39]	CuO	23	4.5	17
[62]	Ag	60	0.001	17
[63]	Sic	26	4.2	16
[39]	Al_2O_3	33	4.3	15
[61]	Al_2O_3	36	2	15
[64]	CuO	28.6	4	14
[39]	CuO	36	3.4	12
[39]	CuO	23.6	3.5	12
[25,36]	Al_2O_3	28	3	12
[65]	Ag	15	0.39	11
[58]	TiO_2	27	4.3	10.8
[39]	Al_2O_3	38.4	4	10
[66,67]	Al_2O_3	42	1.59	10
[64]	Al_2O_3	38.4	4	9
[68]	Al_2O_3	11	1	9
[58]	TiO_2	27	3.25	8.4
[68]	Al_2O_3	47	4	8
[55]	TiO_2	10	0.5	8
[63]	$Al2O_3$	60.4	1.8	7
[63]	MWCNT	15	1	7

is. The first model [51] is based on the nano-additive volume fraction as shown in equation (5) while the second model [52] depends on the heat capacity concept.

$$C = C_{bf}(1 - U_p) + U_P C_P \quad (5)$$

Where C_{bf} is the base fluid's specific heat, and C is the nano-fluid specific heat.

Another effective property in terms of nano-fluids dynamics is the viscosity as it is an important consideration for the heat transfer applications. Furthermore, the nanofluids rheological behavior can be obtained through investigating its effects [1]. Several analytical models have been implemented to calculate the effective nano-fluid viscosity ratio (i.e., nano-fluid viscosity/ base fluid viscosity) as shown in **Table 3**. These models vary depending on the nano-additive volume fraction and the dynamics of their interactions [32,53]. The nano-fluid rheological behavior has been classified into four main sections [54]:

- Nano-fluids which has volume fraction less than 0.1% and its viscosity associated with the Einstein model (without shear thinning);
- Nano-fluids which has volume fraction between 0.1 till 5% (no obvious shear thinning);
- Nano-fluids which has volume fraction between 5 till 10% (observed shear thinning);
- Nano-fluids which has volume fraction greater than 10% (nano-additives interpenetration).

Generally, it has been observed that nano-fluids containing spherical nanoparticles are more likely to exhibit Newtonian behavior and those containing nanotubes show non-Newtonian flow behavior. Furthermore, nano-fluids show Newtonian behavior at low shear rate values while behave as non-Newtonian fluid at high shear rate values. Also, MWCNTs nano-fluid mostly exhibits shear thinning behavior for low shear rates. However, sometimes it shows Newtonian behavior at high shear rate range. Regarding Al_2O_3 nano-fluids, they show a transition from shear thinning behavior to shear thickening as shear rate exceeds certain critical level. This critical value increases with an increase in nanoparticle concentration [55-60].

Improvements of machining quality characteristics

Recently, other researchers have focused on adding multi-walled carbon nano-tube (MWCNT) into the base fluid, and high improvement in thermal conductivity have been reported up to 150% and 200% in comparison with based fluid thermal conductivity [61-65]. In terms of the friction between the cutting tool and workpiece, it has been reported that graphite nano-particles addition into the conventional lubricant helps in reducing the induced friction coefficient [66-69]. Thus, better workpiece dimensional accuracy, good surface quality, and reduction of cutting forces could be achieved [70]. Additional study has confirmed that increasing nanoparticle concentration and decreasing nanoparticle size into the base cutting fluid have critical roles for improving the thermal conduction during the cutting processes [71].

Table 3 The nano-fluid viscosity analytical models.

Model	The effective nano-fluid viscosity ratio	Application
Einstein	$1 + \eta\, Up$	At no nano-additives interactions & U_p is less than 1%
Batchelor	$1 + \eta\, Up + (\eta\, Up)^2$	Brownian motion & interactions of nano-additives
Ward	$1 + \eta\, Up + (\eta\, Up)^2 + (\eta\, Up)^3$	Up is greater than 35%

Regarding using carbon nano-tubes as nano-additives into the conventional cutting fluids, some studies have presented promising results in terms of improving the machining quality characteristics. MQL system using nano-cutting fluid based on MWCNT has been applied through the turning of high carbon high chromium AISI D2 using tungsten carbide insert (CNMG 120408). Taguchi method has been implemented to study the effects of cutting parameters on the surface finish and cutting zone temperature. In comparison with MQL technique based on conventional cutting fluid, promising results have been observed through using the proposed technique (MQL-nanofluid) [21].

Another study has investigated the effects of MWCNT/MQL system during the high-speed milling of AISI 1050 and AISI P21. The results have been compared to dry and wet cutting. It has been observed that the MWCNTs/ nano-fluid has an important role in reducing the tool wear and improving the surface finish because of the excellent heat conductivity of MWCNTs nano-fluids [72].

In addition, the high-speed turning of AISI 4140 steel with a TiN-top coated multilayered carbide insert has been conducted using small quantity lubrication (SQL) technology. Using of 3 vol. % alumina and 1vo. l% MWCNT nano-fluid instead of soluble oil have shown significant reduction of the cutting forces and tensile residual stresses. Furthermore, improvement of surface quality has been observed due to the improvement in retention of cutting tool edges sharpness [73]. Setti et al. has concerned to control the friction behavior in the grinding processes as the contact between the abrasive grains and work-piece is highly affected the machining quality characteristics such as; the wheel wear and grinding forces. Different volume concentrations of Al_2O_3 and CuO nanoparticles have been added to water as a base fluid. The grinding process has been performed on Ti-6Al-4V under using MQL system and the previous nano-cutting fluid. The wheel morphology, surface integrity of ground surface, grinding forces, the coefficient of friction, and chip formation have been investigated. The nano-cutting fluid and MQL have obtained promising results in reduction the coefficient of friction, and tangential forces. Moreover, the short C-type chip formation has been observed; hence, it could indicate the cooling effect of the proposed lubrication system [74].

Zhang et al. studied the effects of the dispersed MoS_2 nanoparticles into vegetable oil (i.e., soybean oil) on several machining quality characteristics during grinding of 45 steel. Various lubrications strategies have been employed (i.e., flood, MQL, and dry cutting). It has been observed that lubrication property can be improved through the high nano-cutting fluid viscosity, therefore the heat transfer performance can be enhanced. On the other hand, the optimal mass concentration for MoS_2 nanoparticles into the base cutting fluid was 6 wt.% since it is an important factor to be selected in order to avoid the agglomeration of nanoparticles [75].

Discussion

Achieving sustainable machining process is an essential requirement as it offers various environmental, societal, and economical advantages; however, enhancing the machining processes performance is still required besides building a sustainable environment. Rao and Srikant have recommended that using nano-additives with vegetable oil as a base cutting fluid under using MQL system could establish the two desired objectives: enhancing the machining quality characteristics since nano-additives improve the friction and thermal behavior, and accomplishing a sustainable process as using vegetable oils provide effective environmental benefits [76]. Najiha and Rahman have investigated different wear mechanisms during end-milling of aluminum alloy AA6061 under using MQL system and water-based TiO_2 nano-cutting fluid. The investigations have been compared with other lubrication techniques (i.e., MQL with conventional cutting fluid, and flood cooling technique). The nano-cutting fluid-based method has presented promising results in terms of reducing the edge chipping and fracture due to its cooling effects which lead to decreasing the cutting zone temperature [77].

Prabhu et al. have elaborated Taguchi methodology, neural networks, and fuzzy logic techniques have been employed to analyze the effects of using CNT-nano-fluids to enhance the induced surface roughness during turning AISI D3 Tool steel. ANOVA results have revealed that the most significant parameters are the cutting speed and mass concentration of CNT. The artificial neural network and fuzzy logic techniques have presented two models used in investigating the relationship between the machining parameters and the measured surface roughness and 10.31% and 9.23% model accuracies have been determined respectively [78-83]. Recent studies have also revealed the effectiveness of using MQL-nano-fluid technique during machining Ti-6Al-4V [84-86], Inconel 718 [87], and Austempered Ductile Iron [88] as it improves the machining performance efficiency with achieving a sustainable environment.

Nano-fluids challenges

In spite of all previous superior properties of nano-fluids, there are still several challenges which face the development and implementation of the nanofluid technology. The main aspects facing this growing technology are [13];

- There is no a sufficient agreement between the results obtained in various studies;
- Poor suspension/stability characterization;
- More understanding needs to be investigated in terms of properties changes mechanisms;

In this section, various challenges which face growing the nano-cutting fluids applications have been mentioned as follows:

- Long-term stability for nano-fluid dispersion: it is one of the most important requirements needed as nanoparticles are easily aggregated due to very strong van der Waals interactions. A lot of proposed solutions have been applied and presented (e.g. using surfactant); however, the time period after preparing the nano-fluid is a critical factor as nanoparticles agglomeration can happen [56];
- The challenges of nano-fluids/nano-additives production (e.g. sedimentation, clustering, agglomeration): an effective recommendation to face these challenges has been obtained through establishing a multi-disciplinary approach which can link between the thermal, mechanical, chemical, and materials science aspects [79];
- The high cost of nano-fluids [80];
- The nano-fluids thermal behavior for turbulent flow cases: More concerns are required to investigate the convective heat transfer and thermal conductivity in cases of turbulent flows. However, few studies have obtained promising results for using nanofluids in turbulent flow cases [81-83], building general analytical models to express the flow mechanisms effects are highly required.

Conclusion

In this article, a comprehensive literature survey of publications which related to the nano-cutting fluid technology has been presented and discussed. It has been investigated that two main techniques for nano-fluids preparation are commonly used: two step and single step. The two steps technique is more suitable during dispersion of oxide particles and carbon nanotubes and it does not show potential results for metal-nano-particles; however, higher efficiency in term of nano-fluid stability can be noticed during using the single step technique. In spite of the advantage of using the single step, it can't fit the applications with high volume concentration values. Besides, three main methods have been used to control and offer a high suspension/stability performance in order to avoid the nano-additives agglomeration, clogging, and sedimentation; using a surfactant, pH control, or ultrasonic vibrations.

The nano-cutting fluids have shown promising results in improving the base cutting fluid properties; however, these improvements cannot be clearly observed without applying an adequate dispersion technique. These improvements are mainly focused on the thermal, tribological, and rheological properties as several studies have established different empirical and analytical models to express the relationship between the process parameters and these properties. In addition, the nano-cutting fluids have revealed promising results in terms of machining quality characteristics improvements (e.g. cutting forces, friction behavior, tool wear, cutting zone temperature). Despite the previous improvements due to the nanofluid technology usage, a number of challenges still face its implementation such as; long-term stability for nano-fluid dispersion, difficulties associated with the turbulent flow cases, the high cost of nano-fluids, and challenges related to nano-fluids/nano-additives production process.

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