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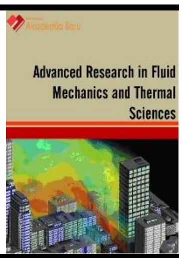

Nanofluid as an Alternative Coolant in Machining: A Review

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ABSTRACT

This review paper is concerned about the important of nanofluid in machining. It is discussed in several parts such as cutting force, surface roughness, tool life and tool wear. Various type of nanofluid is discussed in this paper with an effect on the surface roughness, force, tool life, and wear. Nanofluid plays a significant role in the increment of tool life and reducing tool wear. Nanofluid creates an artificial layer on top of the workpiece, and this reduces wear at the cutting tool. It seems that nanofluid can be the next alternative coolant in machining.

1. Introduction

Machining plays major role in the manufacturing industry because machining is used to produce desired shape, size and surface finish through the removal of excess materials in the form of small chips. In machining operations, cutting tools are used to remove the excess material to produce the desired product [1]. The machine tool gives necessary relative motion during the machining process. The temperature rises due to the direct mechanical contact between the workpiece and cutting tool during machining will reduce the tool strength. Hence it will lead to a faster tool failure and wear [2,3]. To produce at higher rate, high cutting speed is needed but it also will lead to a faster tool wear. To prevent the tool wear take place in a faster rate, the temperature should be controlled during machining. It is also important to reduce the heat produced during machining to avoid the cutting tool lose its sharpness and cause poor surface finish. The tool life also will be shortened if the excessive heat is not controlled. Thus, the usage of cutting fluid is essential to reduce the heat produced at the tool and work piece interface for a better surface finish, enhance the tool life and reduce the tool wear with a reduction in cutting force.

The cutting fluid plays important role in removing the heat generated from friction between cutting tool and workpiece which will eventually reduce temperature rise in cutting tool. Cutting tool's life span will be prolonged by lowering the heat generated at tool-workpiece interface during

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machining. The cutting fluid will dissipate the heat produced at the interface surface area and lower the friction force between the tool and workpiece. Chis deformation and high thermal load which cause tool wear to occur mainly developed by the friction force. To reduce the friction force the cutting force should be reduced during machining process and it will prolong the life span of the cutting tool [4-6]. During cutting process, the tool wear occur especially at the edge of cutting tool [7]. The wear formation at the cutting tool results in poor surface finish and product with less dimensional accuracy. Cutting fluid also helps to prevent the formation of Build-up edge (BUE) and Build-up layer (BUL) defects which causes bad appearance on the workpiece. Other than that, cutting fluid also used to wash away chips during machining.

Many researchers have conducted various researches on alternating the cutting fluid as coolant. Most of the investigation of alternating the cutting fluid is mainly focused on minimum quantity lubricant technique and there are very few research and publication about using nanofluid as coolant [8]. On the other hand, it is reported that the dispersed nanoparticle additives (TiO_2, ZnO, SiC, etc) in the based liquid exhibits higher load carrying capacity, anti-wear and friction reduction properties [9] Therefore, these features can make the nanofluid very attractive in usage of machining coolant.

The concept of nanocoolant or nanofluid is referred to dispersions of nano particle into the based liquid which is water or ethylene glycol [10,11]. Nanofluids are the next generation heat transfer fluid due to their higher thermal conductivity than those of based liquid [12-14]. From the viewpoints hybrid nanofluid show better performance in term of heat transfer rate, compare to conventional coolant for machining. Besides that, the cutting temperature could also be reduced in both work-piece and cutting tools due to its high heat transfer rate [15,16]. Therefore, the tool life and the surface integrity considered to be much improved compared with normal commercial coolant [17].

2. Cutting Force

The main objective of machining process is to obtain a good quality and cheap parts. The power consumption will rise when the cutting forces rise thus the machining costs also increase. Various researches reported that by adding the nanoparticles into coolant the cutting force reduced dramatically. Table 1 shows the percentage of reduction in cutting force when using nanofluids as cutting fluid. Through many literature reviews, it found out that the nanofluids tends to reduce the cutting force by reducing the friction between the surfaces in contact [18].

According to Padmini *et al.,* and Singh *et al.,* viscosity also plays some role which influences the reduction in cutting force [19,20]. The authors stated that the dissipation capacity of nanofluid tends to increase when the viscosity is low. If the viscosity is high, the nanofluid is able to form a consistent barrier which will separate both the surfaces in contact during machining [18,21] also agree that there will be a layer formed which act as a barrier that reducing the cutting force. Due to the barrier, the friction between the surfaces in contact and the cutting forces reduce simultaneously [19]. Reddy and Rao mentioned that the specific energy of the nanoparticles is effective in reducing the frictional forces between the tool and workpiece which leads to reduction in cutting force [22].

Raju *et al.,* and Sahu *et al.,* reported that the nanofluid improved lubricant properties leads to a high wettability and enables to lubricate the cutting zone much better while resulting in lesser frictional force [23,24]. According to Lee *et al.,* and Zhou *et al.,* nanofluids tends to reduce the cutting force due to its friction coefficient which evaluate the characteristics of a lubricant [25,26]. Khandekar *et al.,* stated that nanofluid reduce the cutting force magnitude better than conventional cutting fluid due to the enhanced cooling characterization [27].

According to Khrisna, nanofluid act as a film that reduce the coefficient friction between tool-workpiece interface which lead to reduction in cutting force [28]. Yuan *et al.,* stated that the larger surface area of diamond made the surface contact area flatter and lower the cutting force generated. They also mentioned that the larger the surface area of a nanoparticle the more effective it will be in reducing the cutting force [29].

Table 1
Reduction in cutting force when using different nanofluids

Authors	Cutting Fluid	Reduction in Cutting Force
[19]	Coconut oil (CC) + nano molybdenum disulphide (nMoS_2)	37 percentage of reduction
[20]	Alumina based fluid with graphene nano plates	9.94% reduction in cutting force
[22]	Graphite, Molybdenum disulphide (MoS_2)	20% of reduction for graphite powder and 28% reduction for MoS_2 powder.
[23]	Multi wall carbon nanotubes and distilled water with sodium dodecyl sulphate as surfactant	5 to 8 percentage reduction
[25]	Mineral oil with graphite nanoparticle	24% of reduction
[27]	Aluminum Oxide added to the conventional cutting fluid	50% of reduction
[26]	Fe_3O_4 with conventional coolant	38.4% reduction
[28]	Nano boric Acid with coconut oil	14.5% reduction than dry machining
[30]	Al_2O_3 with carbon nanotube (CNT) in vegetable oil	11.8% reduction
[24]	MWCNT nanofluid with distilled water	28% drop of cutting force
[29]	Natural777 oil based diamond nanoparticle	10.71%

3. Surface Roughness

In machining process achieving a desired surface quality is very important. The desired surface index of product quality basically called surface roughness which is a technical requirement for most of the mechanical products [31]. To achieve a fine surface roughness the friction and heat generated between the surface contacts reduced by using cutting fluids. By using nanofluid as a replacement for conventional cutting fluid, the quality of product increased by reducing the surface roughness of the product. Table 2 shows the surface roughness reduction when using different nanofluids.

Vasu and Kumar stated that the generated intensive temperature at the workpiece surface will increase the residual stress and lead to micro cracking of the work piece [32]. By adding Al_2O_3 nanoparticles the stress at workpiece surface area decreases and produces a fine surface roughness. Sharma *et al.,* stated that nano fluid produces lowest surface roughness because the nanoparticles within the nanofluid enhance the heat dissipation and improve the properties of the tool's rake face [33]. Hence it will lead to a smoother machining process and retain the tool's hardness and sharpness. Sharma *et al.,* mentioned that Multi wall carbon nanotube (MWCNT) nanoparticles act as a layer which reduces the heat generated at the cutting zone [34]. They also stated that other than providing a good surface roughness MWCNT also reduce tool wears.

Roy and Ghosh reported that the high temperature caused by the high velocities is reduced greatly by adding nanoparticles into cutting fluid due to the thermal properties of the nanoparticles [35]. According to Kadirgama *et al.,* nanofluid is considered as higher heat transfer fluid due to their improved thermal conductivity [36]. Zhou *et al.,* also share same opinion that the thermal conductivity enhancement helps to reduce the heat generated and also, act as a heat transfer medium and dissipate the heat generated at the cutting tool interphase [26]. Therefore, less burning occurs at the cutting zone and enhance the surface quality of the workpiece.

Sharma *et al.,* mentioned that the TiO_2 nanofluid enhances the wetting and lubricating properties of the rake face which retain the sharpness and hardness of the cutting tool for a longer period [33]. Gupta *et al.,* stated that graphite nanofluid produce better surface roughness than aluminum oxide nanofluid due to the better thermal conductivity properties of graphite than aluminum oxide [37]. According to them, by achieving a fine surface quality the tool wears can be reduced drastically. Jamil *et al.,* mentioned that the reduction in surface roughness is due to the better wetting properties of nanofluid at the workpiece and tool intact surface area [30].

According to Kulkarni *et al.,* and Mahadi *et al.,* the temperature reduce at the tool interface is reduce due to the rolling action of the billions of nanoparticles that contributes to the heat dissipation [38,39]. They also mentioned that thermal conductivity enhancement helps the nanofluid to perform better as heat transfer medium. Khrisna stated that the nanofluid provide a better surface roughness by reducing the coefficient friction which lead to reduction in cutting temperature [28].

Table 2
Reduction in surface roughness when using different nanofluids

Authors	Cutting Fluid	Reduction in Surface roughness
[32]	Al_2O_3 nanoparticles	20-30% surface roughness reduction
[33]	Aluminum oxide (Al_2O_3) with vegetable oil	47.8% reduction
[34]	MWCNT with SAE oil	Better surface reduction than conventional coolant
[35]	Multi wall carbon nanotube (MWCNT) with deionized water	30-35% reduction
[36]	Ethylene glycol (EG) with nanocellulose	0.251 – 0.984 μm
[40]	Titanium dioxide (TiO_2) with vegetable oil	34.7% reduction
[37]	Aluminum oxide/vegetable oil and graphite/vegetable oil	Graphite/vegetable oil give much better surface roughness than aluminum oxide/vegetable oil
[30]	Al_2O_3 with carbon nanotube (CNT) in vegetable oil	8.72% reduction
[26]	Fe_3O_4 with conventional coolant	27.75% reduction
[38]	Copper coated Al_2O_3 with distilled water	Surface roughness improved better than conventional coolant
[39]	Boric acid with vegetable oil	7.21% surface roughness enhancement
[28]	Nano boric Acid with coconut oil	24.74% enhancement than dry machining

4. Tool Life

Tool life is usually depending on tool wear [41]. The longer the tool can withstand the wear the longer the tool life span will be [42]. Tool life also can be increased by reducing the coefficient friction occurs between tool-workpiece interface area [43]. Even tough conventional coolant helps to reduce the heat generated at intact surface area, many research has been done to improve the thermal properties of the conventional coolant. Table 3 shows the tool life enhancement when using different nanofluids.

Vázquez *et al.,* mentioned that by adding the nanoparticles into the conventional cutting fluid, their thermal properties enhanced and increase the tool life [44]. Minh *et al.,* stated that the main reason for the tool life prolonged is due to the oil mist and the number of nanoparticles formed on flank face [45]. The formed oil mist and nanoparticles in the cutting zone increases to create “roller effect” which eventually reduce the cutting force and tool wear. According to Sharma *et al.,* the hybrid nanofluid able to maintain the hardness of the tool longer due to their wettability while extracting heat from the tool at high rate [46].

Lü *et al.,* reported that due to the better wettability, better lubrication, higher stability, and higher heat dissipation characterization of TiO_2 nanofluid, increases the tool life 70% more than water [47]. Jamil *et al.,* stated that the reduction in cutting temperature at tool-workpiece surface will increase the tool life. Due to the enhanced heat transfer properties of nanofluid the cutting temperature reduced drastically and prolong the tool life [30]. Eltaggaz *et al.,* mentioned that the nanofluid penetrate in between the tool-workpiece surface area to form as a film that reduce the coefficient friction [48]. They also stated that the higher the thickness of the film the more it will reduce the heat generated and prolong the tool life.

According to Singh *et al.*, the reduction in cutting force and cutting temperature leads to tool life enhancement [49]. They stated that when the heat generated at tool-workpiece interface is reduced the tool will be preserved from damaged. Muthusamy *et al.,* found significant improvement in tool life in their research when using nanofluid [50]. They stated that the improvement is due to the excellent performance of nanofluid as heat transfer medium at tool-workpiece interface.

Table 3
Tool life enhancement when using different nanofluids

Authors	Cutting Fluid	Tool life enhancement
[44]	CuO nanoparticles with mineral oil	Increase the service life of the cutting tool up to 604%
[45]	Al_2O_3 with soybean oil	Increase almost 177% of the tool life than base fluid
[46]	Al_2O_3/MWCNT hybrid nano fluid with vegetable oil	Improved the tool life much more better than base fluid and single nanofluid (Al_2O_3)
[47]	TiO_2 with deionized water	70% more tool life than water
[30]	Al_2O_3 with carbon nanotube (CNT) in vegetable oil	23% enhancement
[48]	Al_2O_3 with vegetable oil	23.5% enhancement in tool life
[49]	Graphene with vegetable oil	178-190% of tool life enhancement
[50]	Ethylene glycol based TiO_2	Tool life is 54.9 minutes.

5. Tool Wear

Tool wear is mainly dependent on cutting conditions [51]. When there is much heat generated at tool-workpiece interface area the tool tends to lose its hardness and leading to wear at faster rate [52]. The wear criteria normally set at 0.3 mm as worn tool [50]. There are a lot of wear types that occurs during machining for example notch wear, comb crack, crater wear and chipping wear [53-55]. But the major wear frequently occur is the flank wear [56]. To minimize the tool wear, many researches has been conducted on nanofluid to enhance the thermal properties. Table 4 shows the tool wears reduction when using nanofluid.

Zhou *et al.,* mentioned that the nanofluid act as a lubricant that smooth the surface of the rake face during machining process [26]. The author also reported that less adhesion occurs when using nanofluid which leads to a high resistance towards the tool wear. Jamil *et al.,* reported that the nanofluid reduce the heat from the primary shearing zone at faster rate and preventing the workpiece hardening [30]. Therefore the cutting tool can sustain longer the hardness of the workpiece and prevent the tool wear occurs at faster rate.

Sahu *et al.,* mentioned that high surface area of the MWCNT; results in high heat transfer rate that helps to tool wear reduction [24]. The author also stated that even at low particle concentration the nanofluids are better as heat transfer fluid. Eltaggaz *et al.,* stated that a mist composed nanoparticle and base fluid mist is created into tool-workpiece interface zone and forms a tribofilm [48]. The heat generated reduced significantly by the tribofilm as well as minimizing the coefficient friction that occurs at interface zone. Thus, the tool hardness able to withstand for a longer period and prevent tool wear to occur faster.

Das *et al.,* in their research work; they compared ZnO, CuO, Fe_2O_3 and Al_2O_3, nanofluids to measure the reduction in tool wear [57]. They found out that the crater wear occur more in Al_2O_3 nanofluid than CuO nanofluid due to the high percentage of oxygen presence in Al_2O_3. The presence of high percentage of oxygen in Al_2O_3 caused significant weight percentage found during machining process and leads to improper cooling thus, crater wear and flank wear take place faster. According

Das *et al.,* CuO nanofluid has superior behavior compared to the other nanofluids while Al2O3 nanofluid was last in the row [57].

Table 4
Tool wears reduction when using different nanofluids

Authors	Cutting Fluid	Tool wear type/reduction
[26]	Fe_3O_4 with conventional coolant	Crack wear on rake face, wear resistance up to 63.3%
[30]	Al_2O_3 with carbon nanotube (CNT) in vegetable oil	Flank wear occurs after 292 seconds of machining
[24]	MWCNT nanofluid with distilled water	Average flank wear occurs at cutting length of 960 mm
[48]	Al_2O_3 with vegetable oil	Up to 26.5% of flank wear reduced
[57]	ZnO, CuO, Fe_2O_3 and Al_2O_3, with distilled water	Crater wear and flank wear reduced
[50]	Ethylene glycol based TiO_2	Flank wear occurs after 940 mm cut length

6. Morphology Analysis

Figure 1 shows the nanofluid forming a thermal barrier between chip and cutting tool. According to Kadirgama *et al.*, the small chip shows the presence of less aluminum percentage proves that the nanofluid is capable to carry away the heat generated due to the superior thermal conductivity properties [36]. They also mentioned that carbon element presence in the nanofluid embedded the chip surfaces and act as a thermal barrier which reduce thermal expansion greatly.

Figure 2 shows the flank wear occurs at faster rate when using the conventional cutting coolant. Muthusamy *et al.,* found that at the 720 mm cut length the cutting tool using nanofluid still with stand the heat generated while conventional cutting fluid couldn't withstand the heat and lead to tool wear [50]. Thamizhmanii and Hasan also mentioned in their research work that flank wear is highly affected by the high heat generated on the flank wear [58]. Khandekar *et al.,* mentioned that the nanofluid has improved conduction, convection and wettability compare to the conventional cutting fluid [27]. The superior properties of the nanofluid make them to withstand the high temperature at a longer period of time [59].

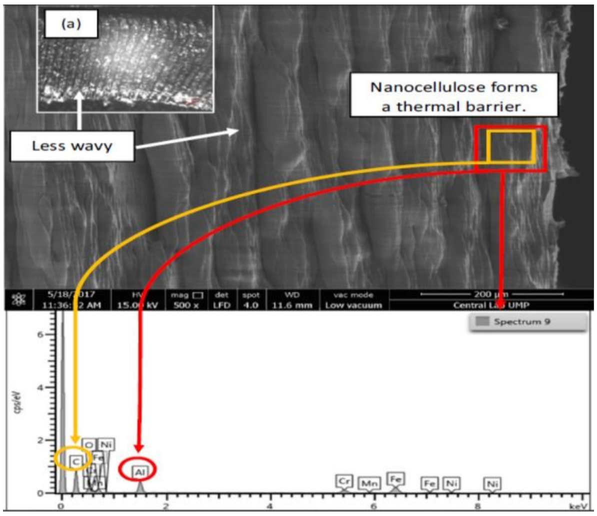

Fig. 1. Thermal barrier formed by nanofluid [36]

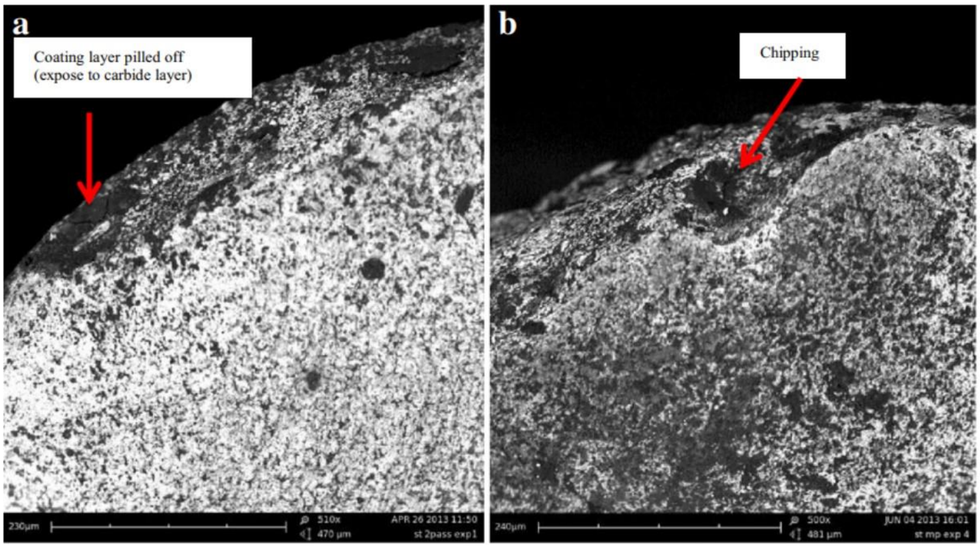

Fig. 2. SEM images after cut length of 720 mm with a) nanofluid and b) conventional cutting coolant [50]

7.Costing Analysis

The innovation and development of machining triggered research on machining with minimum energy consumption and production at lowest cost [60]. Conventional cutting fluid replaced with nanofluid is one of the steps to reduce the machining cost. Cutting fluid mainly used to and to lubricate. According to Krajnik *et al.,* limiting the usage of coolant in machining will reduces machining costs [61]. Apart from that the usage of cutting fluids range from 7-17% of the total costs of the manufactured workpiece [62]. According to Abbas *et al.,* the cost of machining 100 mm distance using conventional cutting fluid is about $ 2.170 while nanofluid cost $ 2.306 for the same distance [60]. The author also mentioned that even though nanofluid is costing a bit higher, but when comparing with the sustainability assessment the nanofluid cost lower than conventional coolant.

8. Conclusions

From the reviews, the following conclusions can be summarized

i. Nanofluid improved lubricant properties leads to a high wettability and enables to lubricate the cutting zone much better while resulting in lesser frictional force. Reduced frictional force resulting in reduction of cutting force.
ii. Nanofluid produces lowest surface roughness because the nanoparticles within the nanofluid enhance the heat transfer and improve the properties of the tool's rake face. Hence it will lead to a smoother machining process and retain the tool's hardness and sharpness.
iii. Nanofluid prolongs the tool life due to the oil mist and the number of nanoparticles formed on flank face. The formed oil mist and nanoparticles in the cutting zone increases to create a film of barrier which eventually reduce the cutting force and tool wear.
iv. Nanofluid reduces tool wear by reducing the heat from the primary shearing zone at faster rate and preventing the workpiece hardening. Thus, the cutting tool can sustain longer the hardness of the workpiece and prevent the tool wear occurs at faster rate.

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