International Journal of Heat and Mass Transfer 108 (2017) 79–89

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Review

# Recent progress on the application of nanofluids in minimum quantity lubrication machining: A review

Nor Azwadi Che Sidik *, Syahrullail Samion, Javad Ghaderian, Muhammad Noor Afiq Witri Muhammad Yazid

*Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia*

ARTICLE INFO

*Article history:*
Received 10 August 2016
Received in revised form 29 November 2016
Accepted 30 November 2016

*Keywords:*
Nanofluid
Machining process
Lubricant
Solid lubricant
MQL

ABSTRACT

This paper reviews recent progress and applications of nanofluids in machining processes. In addition to reviewing the various conventional and advanced cooling techniques during machining, the paper also discusses the preparation methods, factors for enhancing thermal conductivity and properties of nanofluids. In line with fast development of nanofluid in machining process, the purpose of this paper is to review recent progress on the application of nanoparticles in lubricants especially for MQL technique. The conclusions and important summaries were also presented according to the data collected.



**Contents**



## 1. Introduction

The last few decades have witnessed a vast research on the new types of heat transfer fluids, namely nanofluids. Nanofluid is a fluid which contains nanometer-sized solid particles. Nanofluid was introduced by Choi [1] and it has been proven to provide efficient heat transfer compared to conventional fluids.

A nanofluid can be produced by dispersing a typical size of less than 100 nm of metallic or non-metallic nanoparticles or nanofibers in a base liquid [2–6]. The preparation of nanofluids is the key step to improve the thermal conductivity of fluids. Two kinds of methods have been employed in producing nanofluids. One is a single-step method and the other is a two-step method [7]. Nanoparticles, the additives of nanofluids, play an important role in changing the thermal transport properties of nanofluids. At present, various types of nanoparticles, such as metallic nanoparticles and ceramic nanoparticles, have been used in nanofluid preparation [8–10]. Table 1 shows the summary of preparation method of various nanofluids.

The presence of nanoparticles in the base fluids contributes better flow of mixing and higher thermal conductivity compared to pure fluid. A novel study by Masuda [32] revealed that the dispersion of $\gamma$-$A1_2O_3$ particles at 4.3 vol.% can increase the effective

* Corresponding author.
*E-mail address:* azwadi@mail.fkm.utm.my (N.A.C. Sidik).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.11.105
0017-9310/

**Table 1**
Summary of preparation method of nanofluids (adapted from ref. [11]).

| Authors | Nanofluid | Dispersing equipment | Stabilizers/pH control |
|---|---|---|---|
| Duangthongsuk and Wongwises[12] | $TiO_2$/Water | Ultrasonic vibrator for 3–4 h | CTAB/– |
| Lotfi et al.[13] | MWNTs (MWNTs)/water | Ultrasonic bath for 60 min and magnetic stirrer for 3 h | COOH functional groups/– |
| Zhu et al .[14] | $Al_2O_3$/Water | Ultrasonic bath for least 1 h | SDBS 0.1 wt.%/pH = 8.0–9.0 |
| Phuoc et al. [15] | MWNTs/water | Ultrasonic processor for 10 min and magnetic stirrer for 20 min (repeated two times | Chitosan/– |
| Kumeresan and Velraj [16] | MWNTs/water-ethylene glycol (EG) mixture | Magnetic stirrer for 30 min, followed by ultrasonication for 90 min | SDBS 0.1 vol.%/– |
| Teng et al. [17] | Carbon/water | Magnetic stirrer for 1 h, homogenizer for 30 min, and ultrasonic liquid processor for 30 min (repeated five times) | Water-soluble chitosan/– |
| Ding et al. [18] | MWCNTs/water | Ultrasonic bath for 24 h, high shear homogenizer for 30 min | Gum Arabic (GA) pH = 6 |
| Peng et al. [19] | Cu/R113 (refrigerant-based) | Ultrasonic processor for 1 h | SDS, CTAB Span-80/– |
| Yousefi et al. [20] | MWCNTs/water | Ultrasonic disruptor for 30 min | Triton X100/pH = 3.5, 6.5, and 9.5 |
| Raveshi et al. [21] | $A1_2O_3$/water-Eg mixture | Ultrasonic bath for 4 h and magnetic stirrer for 5 h | SDBS/– |
| Li et al. [22] | CuO/water | Ultrasonic cleanser for at least 1 h | TX-10, CTAB, and SDBS/pH = 9.5 |
| Nieh et al. [23] | $A1_2O_3$ and $TiO_2$/water-EG mixture | Magnetic stirrer for 1.5 h, homogenizer for 30 min, and ultrasonic liquid processor for 30 min (repeated five times) | Water-soluble chitosan/– |
| Li et al. [24] | Cu/water | Ultrasonic bath for a least 15 min | SDBS 0.02 wt.%./pH = 8.5–9.5 |
| Hwang et al. [25] | Multiwalled carbon nanotubes (MWNCTs)/water | Ultrasonic disruptor for 2 h | SDS/– |
| Ho et al. [26] | $Al_2O_3$/water | Ultrasonic bath for at least 2 h | –/pH = 3 |
| Kathiravan et al. [27] | Cu/water | Ultrasonic bath for about 10 h | SDS/– |
| Yousefi ei al. [28] | $Al_2O_3$/water | Ultrasonic disruptor for 30 min | Triton X-100/– |
| Byrne et al. [29] | CuO/water | High intensity ultrasonic processor for 7–8 h | CTAB/– |
| Wang et al. [30] | Single-walled carbon nanotubes (SWNTs)/ heavy water ($D_2O$) | Ultrasonicated for 24 h | Trixon X-100/– |
| Dong et al. [31] | CuPc-U (unsulfonated and hydrophobic) and CuPc-S (surface sulfonated and hydrophilic)/(water-$NaNO_3$ mixture) | Ultrasonic bath for 30 min | Trixon X-100/– |

thermal conductivity of water by almost 30%. Since then, many studies have been carried out to investigate the enhancement of thermal conductivity with different nanoparticle volume fractions, materials and dimensions in several base fluids. Most of the findings show that thermal conductivity of nanofluid is higher than the base fluids [33–37]. Among them, Lee et al. [38] demonstrated that oxide ceramic nanofluids consisting of CuO or $Al_2O_3$ nanoparticles in water or ethylene-glycol exhibit enhanced thermal conductivity. For example, using $Al_2O_3$ nanoparticles having mean diameter of 13 nm at 4.3% volume fraction increased the thermal conductivity of water under stationary conditions by 30% [39]. On the other hand, larger particles with an average diameter of 40 nm led an increase of less than 10% [39]. Vajjha and Das [40] investigated the thermal conductivity enhancement of three different nanofluids CuO, $ZnO_2$ and $Al_2O_3$ nanofluids. Also, thermal conductivity increases with increasing temperature and volume concentration. A model was proposed by Murshed et al. [41] to predict the thermal conductivity theoretically under dynamic and static processes taking into account the effect of Brownian motion, particle size, nanolayer and particle surface. They concluded that thermal conductivity is due to both static and dynamic mechanisms. In a different study, Hong et al. [42] reported a nonlinear model of thermal conductivity enhancement of 18% at volume fraction of 0.05 vol.% using Fe-ethylene glycol nanofluid. Eastman et al. [43] compared the thermal conductivity between Cu-ethylene glycol nanofluid and pure ethylene glycol. The result indicated 40% increase in thermal conductivity of Cu-ethylene nanofluid at volume fraction of 0.3 vol.%. Liu et al. [44] recorded 23.8% thermal conductivity enhancement of Cu-water nanofluid using chemical reduction method. The enhancement of thermal conductivity as reported by various researchers is presented in Table 2 (adapted from Table 1 [45]).

Since its first introduction to actual engineering applications, nanofluid has been successfully applied to enhance heat transfer in many branches of engineering. In mechanical engineering, concern is apparent on determining the mechanisms of heat transfer involved in the operation of an equipment. For instance in heat exchanger devices, efforts have been made to enhance heat transfer of heat exchangers, reduce the heat transfer time and finally improve energy utilization efficiency using nanofluid [74–82].

An electrical engineer is interested to know the efficient methods of heat dissipation of devices so that they can operate within safe operating temperatures. The rapid miniaturization of a computing device while improving its performance put a challenge on the cooling strategy. In a study by Sohel et al. [83], they devised a copper made of mini-channel heat sink with $Al_2O_3$–$H_2O$ nanofluid as heat transfer fluid. They found that by using nanofluid, the thermal entropy generation rate was reduced around 11.50% compared to the pure water. In another study, Khaleduzzaman et al. [84] utilized $TiO_2$–water nanofluid in a water block heat sink in electronic device. In an earlier research, Roberts and Walker [85] compared the performance of nanofluid and distilled water as liquid cooling systems for computational processing units (CPUs). An enhancement of up to 18% in the convective heat transfer coefficients was reported.

In the field of automotive engineering, Zhang et al. [86] tested the effect of the addition of nanographite in heavy-duty diesel engine coolant. They found that the cooling capability increased by 15% when 3 vol.% of nanographite was added to the coolant. The effect of nanofluid coolant in a truck engine has been studied by Saripella et al. [87]. 50/50 mixture of ethylene-glycol and water was used as the base fluid and 2 vol.% and 4 vol.% of CuO particles were added to investigate the effect on engine's temperature, pump's speed, and power. The authors inferred that the addition