Synthesis and Tribological characteristics of a nano CuO particle-filled water-based lubricants

T. Rajmohan\textsuperscript{1} D. Hemanth kumar\textsuperscript{2} R. Nivithetha\textsuperscript{3} Elamburthi\textsuperscript{4} V.V. Kalyan Chakravarthy\textsuperscript{5}

Department of Mechanical Engineering
Sri Chandrasekharendra Saraswathi Viswa Maha Vidyalaya University,
Enathur, Kanchipuram – 631561, India

rajmohanscsvmv@yahoo.com\textsuperscript{1} hemanthdeena@gmail.com\textsuperscript{2} kalyanchakravarthy@kanchiuniv.ac.in\textsuperscript{5}

Abstract. The oil-based lubricating system tends to produce high cutting temperatures owning to the low cooling capability of oil lubricants. The addition of lubricating additives in nanoscale could increase the tribological and lubrication performance of the water-based lubricants. In this work, nano CuO particle-filled water-based lubricants as cutting fluids were developed using ultrasonication process. The Thermophysical Properties of synthesized nano filled water-based lubricant was tested and analyzed. The tribological characteristics were fairly investigated using four-ball and pin on disc apparatus testing units. The results indicated that nano CuO filled water-based lubricant shows enhanced tribological performance in terms of coefficient of friction (COF) and wear scar diameter (WSD) compared with base coolant. The superior performance of CuO filled water-based lubricant was credited to the detail that CuO nanoparticle additives arrived the rubbing interface and made a tribo-thin layer of CuO. Water-based lubricant showed the highest surface deformation compared to nano-based lubricants which indicate that the damage was due to adhesive wear.

Key Words: Nano CuO particles; Wear Scar; Tribology; water-based lubricants; ultrasonication.

1. Introduction

The entire purpose of international standard 14001 is to guard environment in balance with socio-economic requirements. The materials selection, energy utilize, solid waste, liquid residues, and gaseous filtrates are the environmental stressors in different stages of product life cycle. The work pieces, tools, metalworking fluids, cleaning fluids and coatings are eliminated as wastes to the environment in manufacturing process [1]. The sustainable products, processes, and systems are the functional elements of sustainable manufacturing. The reduced material utilization, minimizing energy consumption and waste-free manufacturing processes are the major challenges to the industry to manufacture sustainable products [2]. The manufacturing process consists of several fundamentals such as Material, energy, data, machining, lubrication and chips [3]. The employ of cutting fluids in machining process is the most significant environmental exposure [4]. It has been approximated that the utilization of cutting fluid can account for more than 10-15 % of machining costs [5].
In 1868 researchers have used water as cutting fluid in machining and observed that speeds have increased by 30–40%. The quality, productivity and cost of the product mainly depend on performance of machining operations. In machining the various properties of parameters affecting the cutting performances are cutting fluids work piece, cutting tool, machining conditions and machine tool [6]. The appropriate function of cutting fluid must not only develop the performance of machining, but also complete the needs such as non-toxic, non-harmful to health for operators, not a fire hazard, not smoke and easy disposal [7]. The cutting fluids are classified into cutting oils, soluble oils, synthetic fluids and semi-synthetic fluids. Mineral based cutting fluids are even though reasonably priced the application is restricted due to the limited resource, poor biodegradability and the accessibility of mineral oil is highly dependent on political considerations. Generally the cutting fluids are diluted with water, such that about 95 % of the cutting fluid, by volume, is water [8]. The remaining 5 % is a mixture of oil, emulsifiers, and additives [9]. The additives are utilized to minimize the corrosion, to limit the acidity, to manage the microbial growth, to get better the lubricity, and to avoid the foaming. Some of these additives are toxic and harmful to human health, wildlife and environment [10].

Tao Lv et al [11] found that the cutting fluids of high thermal conductivity were needed to attain a better machining performance. One of the most active methods to improve the cooling ability of lubrication is to use water-based cutting fluids [12-13]. But, water itself could not form real lubricating films in the impression area since of its low viscosity and lubricity [13], which thus directed to a weak load-carrying capacity and high friction. Nevertheless, recent studies [14] have confirmed that the addition of lubricating additives in nanoscale, such as SiO2, Al2O3, CuO, TiO2, and MoS2, could progress the tribological properties of the base lubricants. Wang et al. [15] reported that the addition of SiO2 nanoparticles into deionized water could improve its tribological performance and extreme pressure properties significantly. Setti et al. [16] showed that Al2O3 nanoparticle based water-lubricant led to a significant reduction in the tangential forces and grinding temperatures compared with the base lubricant.

2 Experimental details

2.1 Preparation of nano CuO filled water-based lubricants

Copper oxide (CuO) nano particles of 40-80nm in diameter (purchased M/s US Nano Research., USA) was used as additives. Lauryl sodium sulfate (SDS, purchased from Ganapathy traders, India) was engaged as a surface-active agent in the research of water-based lubricants. Polyethylene glycol 300 (PEG300) was firstly diffused into purified water at a mass ratio of 3:2 at ambient temperature to prepare base lubricant [11]. CuO nanoparticles in powder was then directly added into this base lubricant (water PEG solution) at weight ratios of 0.5% and 1% and SDS was consecutively plunged at a concentration of 10 wt% of the CuO nano particles content. Consequently, the CuO nano particles was ultrasonically dispersed in water bath for 1 h by means of an ultrasonic unit of 20KW. For comparison, water-based lubricants without CuO nano particles was separately formulated using the same process. The synthesized water-based lubricants are highly steady without precipitation and stratification after 40 days of aging, as shown Figure. 1.

![Figure 1. Samples of Lubricant prepared](image-url)
2.2 Rheological and physical properties of water based lubricants

The properties of nano CuO filled water lubricants were tested and the results were shown in Table 1. The viscosity of the base-lubricant and the nano-lubricants are measured using a Redwood Viscometer with ASTM D-445 standards.

**Table 1.** Properties of water based lubricants

| Properties                      | 0.5 % nano CuO+Water | 1% wt nano CuO+Water | Water based lubricant without additive |
|---------------------------------|-----------------------|-----------------------|----------------------------------------|
| Flash point (°C) [ASTM D92]     | 493                   | 476                   | 422                                    |
| Thermal Conductivity Watt/mK    | 0.736                 | 0.924                 | 0.607                                  |
| Viscosity @100°C (cSt) [ASTM D445] | 1.649                 | 1.649                 | 1.03                                   |
| Fire point                      | 517                   | 521                   | 473                                    |

Three trials are conducted for each sample and average is taken for tabulation. Flash and fire points are measured by standard methods using a Clevel and open cup flash and fire point apparatus in accordance with ASTM D-92. Transient hot wire liquid thermal conductivity method was used for determination of thermal conductivity under ASTM D7896. Three trials are conducted for each test and average is taken for tabulation.

2.3 Friction and wear tests

a. Four-ball tester

The friction and wear performances of water-based lubricant using nano CuO as additives were performed using the four-ball testing on TR30L 1AS Ducom India, as shown in Figure 2.
The steel balls used in four-ball tests were 12.7 mm in diameter and made of AISI high chromium steel, which is having hardness of 65 HRC [17-18]. The tests were conducted at normal load of 400 N, rotational speed of 1200 rpm and room temperature of 25 °C for 30 minutes. Prior to testing, the balls were ultrasonically cleaned in acetone for 15 min. The wear scar diameters (WSDs) of the balls after testing were measured by using CCD camera 100X system. Each test was repeated three times and average values of coefficient of friction (COF) and wear scar diameter (WSD) were recorded.

b. Pin-On-Disc Tribometer

The tribological studies have been conducted using a pin-on-disc tribometer in accordance with ASTM G 99-05 standards. The pin material used is aluminium alloy (Al-86%, Si-12% and other elements-2%) and the disc is of steel (EN-32) with a hardness of 65 HRC. The layout of the Pin on disc tribometer is shown in figure 3.

![Figure 3. Schematic layout of Pin on Disc Tribometer](image)

The diameter and length of the pin are 8 mm and 10 mm respectively. After the Machining operation of the aluminium pin, its sliding surface is polished using emery paper of 800 grit size; the same polishing method is also adopted for steel disc. The surfaces are then cleaned by acetone and heptanes respectively. The operating conditions for the test is shown in Table 2.

| Table 2. Operating conditions for friction and wear test |
|----------------------------------|
| **Four ball wear test** | Normal load-400N  |
| | Rotational speed-1200rpm  |
| | Temperature-25°C  |
| | Time -30sec  |
| **Pin on disc test apparatus** | Load-5-50N  |
| | Rotational speed-100-1500rpm  |
| | Temperature-120°C  |
| | Time -300sec  |
Water based lubricant is supplied at the sliding interface in small quantity between aluminium alloy pin and steel disc on the pin-on-disc tribometer in order to keep boundary/thin film lubrication conditions. Coefficient of friction is measured directly by an electronic display.

3. Results and discussions

3.1 Properties of water based lubricants

Significant enhancement in the properties was observed in nano CuO filled water based lubricants due to the better heat yielding capability of nano fluid. Viscosity, flash and fire point of nano CuO filled water based lubricants were improved up to 40% compared to base lubricant. The thermal conductivity of nano CuO filled water lubricant is enhanced up to 50%. The increase in thermal conductivity of the nano fluid is due to dynamic interaction of the flow field and the nano CuO.

3.2 Tribological properties of nano CuO filled water-based lubricant

Figure 4, 5 shows the effect of nano CuO concentration on the tribological performance of water-based lubricants. It is noticed that the least COF and WSD were attained with 1wt% nano CuO particles filled lubricant, which confirmed a COF reduction of 15.8% and wear reduction of 10.4% in comparison with the base water lubricant. As seen in Figures 4 and 5, the COF curves of the nano CuO filled water lubricant are more constant in contrast with that of the base lubricant, and the worn surfaces of the balls shown in Fig. 4 are smoother as well. These may be credited to the fact that CuO nanoparticles acted as ball bearings during the sliding [19], which could diffuse the stress between the friction pairs, and so resulted in lesser COF and WSD. Meanwhile, the CuO nanoparticles might serve as the spacers to fill the furrows and pits on the worn surfaces which prevented the interface from direct contact, and hence led to lower COF and WSD too [20].

![Figure 4. Effect of Lubricants on COF at 10N load](image1)

![Figure 5. Effect of Lubricants on COF at 5N load](image2)
3.3 Analysis of Worn Surfaces by CCD and SEM

The worn scar surface investigation is significant for ruling the sharp failures that occurred due to the effect of friction and wear between the contact surfaces. The SEM analysis of the stationary steel balls and Pins of the Pin of Disc tribometer are used in this study in higher load conditions is illustrated in Figures 6 and 7 respectively.

![Figure 6. Surface Morphology of Ball employed in Four Ball Tribometer using CCD](image1)

![Figure 7. Surface Morphology of Pin employed in Pin on Disc using SEM](image2)

The worn scar surface areas of the stationary ball for base water lubricant was higher than nano CuO filled water based lubricants. Water based lubricant showed the highest surface deformation compared to nano based lubricants which indicates that the damage was due to adhesive wear. Apart from this, the circular, tiny and steady scuffs on the ball characterize abrasive wear[21] It is seen that CuO nano particles were easy to formulate up the nanosized furrows and pits, and provided as spacers to effectively prevent the contact of the friction peak. Temporarily, the CuO nanoparticles might act as
rolling elements between the moving parts, which helped to reduce the friction at the contacting surface[20]. Furthermore, because of the high contact pressure and rotating speed, a smooth protecting film which consists CuO would form on the rubbing interface[22]. This film could not only bear the load but also separate the rubbing surfaces, which thus resulted in lower friction with the reduced adhesion of work piece materials[11]. Therefore, the tribological characteristics of nano filled water based lubricant were much better than base lubricant.

4. Conclusions

In this project, a comparative performance analysis of nano CuO filled water-based lubricant under different weight ratios with base lubricant was systematically examined through tribological experiments. The major conclusions drawn from the present investigation as follows

- Nano CuO filled water based lubricant was successfully synthesized through ultrasonication process.
- Rheological and physical properties of water based lubricants was tested. The significant enhancement in the properties was observed in nano CuO filled water based lubricants up to 50% due to the better heat yielding capability of nano fluid.
- The friction and wear performances of water-based lubricant using nano CuO as additives were performed using the four-ball testing and pin on disc apparatus.
- The promising results were obtained from the experiments that the 1 wt% CuO filled water lubricant showed up a COF reduction of 18.8 and wear reduction of 17.6% in comparison with the base water lubricant
- Water based lubricant showed the highest surface deformation compared to nano based lubricants which indicates that the damage was due to adhesive wear.
- The CuO nanoparticles might act as rolling elements between the moving parts, which helped to reduce the friction at the contacting surface. Furthermore, because of the high contact pressure and rotating speed, a smooth protecting film which consists CuO would form on the rubbing interface.

In conclusion, CuO nanoparticles could effectively progress the tribological properties performances of the water-base lubricant. It is understood that this novel water-based lubricant suggests an efficient approach and capable industrial application for metal cutting.

References

[1] Goindi, G.S. and Sarkar, P., (2017). Dry machining: a step towards sustainable machining—challenges and future directions. *Journal of Cleaner Production*, 165, pp.1557-1571.
[2] Pusavec, F., Deshpande, A., Yang, S., M'Saoubi, R., Kopac, J., Dillon Jr, O.W. and Jawahir, I.S., (2015). Sustainable machining of high temperature Nickel alloy–Inconel 718: part 2–chip breakability and optimization. *Journal of Cleaner Production*, 87, pp.941-952.
[3] Rajemi, M.F., Mativenga, P.T. and Aramcharoen, A., (2010). Sustainable machining: selection of optimum turning conditions based on minimum energy considerations. *Journal of Cleaner Production*, 18(10-11), pp.1059-1065.
[4] Pervaz, S., Kannan, S. and Kishawy, H.A., (2018). An extensive review of the water consumption and cutting fluid based sustainability concerns in the metal cutting sector. *Journal of Cleaner Production*, 197, pp.134-153.
[5] Debnath, S., Reddy, M.M. and Yi, Q.S., (2014). Environmental friendly cutting fluids and cooling techniques in machining: a review. *Journal of Cleaner Production*, 83, pp.33-47.
[6] Srikan, R.R. and Ramana, V.S.N.V., (2015). Performance evaluation of vegetable emulsifier based green cutting fluid in turning of American Iron and Steel Institute (AISI) 1040 steel—a initiative towards sustainable manufacturing. *Journal of Cleaner Production*, 108, pp.104-109.
[7] Amiril, S.A.S., Rahim, E.A. and Syahrullaill, S., (2017). A review on ionic liquids as sustainable lubricants in manufacturing and engineering: Recent research, performance, and applications. *Journal of Cleaner Production, 168*, pp.1571-1589.

[8] Padmini, R., Krishna, P.V. and Mohana Rao, G.K., (2016). Experimental evaluation of nanomolybdenum disulphide and nano-boric acid suspensions in vegetable oils as prospective cutting fluids during turning of AISI 1040 steel. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 230*(5), pp.493-505.

[9] Mia, M., Gupta, M.K., Singh, G., Królczyk, G. and Pimenov, D.Y., (2018). An approach to cleaner production for machining hardened steel using different cooling-lubrication conditions. *Journal of Cleaner Production, 187*, pp.1069-1081.

[10] Ghosh, S. and Rao, P.V., (2015). Application of sustainable techniques in metal cutting for enhanced machinability: a review. *Journal of Cleaner Production, 100*, pp.17-34.

[11] Tao, Lv., Shuiquan Huang., Xiaodong Hu., Yaliang Ma., Xuefeng Xu. (2018) Tribological and machining characteristics of a minimum quantity lubrication (MQL) technology using GO/SiO$_2$ hybrid nanoparticle water-based lubricants as cutting fluids. *Int J Adv Manuf Technol 96*, 2931–2942. https://doi.org/10.1007/s00170-018-1725-3

[12] Itoigawa, F., Childs, T.H.C., Nakamura, T. and Belluco, W., (2006). Effects and mechanisms in minimal quantity lubrication machining of an aluminum alloy. *Wear, 260*(3), pp.339-344.

[13] Mao, C., Zhang, J., Huang, Y., Zou, H., Huang, X. and Zhou, Z., (2013). Investigation on the effect of nanofluid parameters on MQL grinding. *Materials and Manufacturing Processes, 28*(4), pp.436-442.

[14] Sharma, A.K., Tiwari, A.K. and Dixit, A.R., (2015). Improved machining performance with nanoparticle enriched cutting fluids under minimum quantity lubrication (MQL) technique: a review. *Materials Today: Proceedings, 2*(4-5), pp.3545-3551.

[15] Wang, J.H., Song, M., Li, J.L. and Wang, X.B., (2011). The preparation and tribological properties of water-soluble nano-silica particles. *Tribology, 31*(2), pp.118-123.

[16] Setti, D., Sinha, M.K., Ghosh, S. and Rao, P.V., (2015). Performance evaluation of Ti–6Al–4V grinding using chip shaping and coefficient of friction under the influence of nanofluids. *International Journal of Machine Tools and Manufacture, 88*, pp.237-248.

[17] Peña-Parás, L., Taha-Tijerina, J., Garza, L., Maldonado-Cortés, D., Michalczewski, R. and Lapray, C., (2015). Effect of CuO and Al2O3 nanoparticle additives on the tribological behavior of fully formulated oils. *Wear, 332*, pp.1256-1261.

[18] Cozza, R.C., (2014). Influence of the normal force, abrasive slurry concentration and abrasive wear modes on the coefficient of friction in ball-cratering wear tests. *Tribology International, 70*, pp.52-62.

[19] Gupta, B., Kumar, N., Panda, K., Dash, S. and Tyagi, A.K., (2016). Energy efficient reduced graphene oxide additives: Mechanism of effective lubrication and antiwear properties. *Scientific reports, 6*, p.18372.

[20] Sayuti, M., Sarhan, A.A. and Salem, F., (2014). Novel uses of SiO$_2$ nano-lubrication system in hard turning process of hardened steel AISI4140 for less tool wear, surface roughness and oil consumption. *Journal of Cleaner Production, 67*, pp.265-276.

[21] Song, H.J. and Li, N., (2011). Frictional behavior of oxide graphene nanosheets as water-base lubricant additive. *Applied Physics A, 105*(4), pp.827-832.

[22] Peng, D.X., Kang, Y., Hwang, R.M., Shyr, S.S. and Chang, Y.P., (2009). Tribological properties of diamond and SiO$_2$ nanoparticles added in paraffin. *Tribology international, 42*(6), pp.911-917.