Performance evaluation of using water and bio oil-based nanocutting fluids under minimum quantity lubrication with compressed cold air during milling operations of steel

1B Sugiantoro, 2Sakuri and 1Sutarno

1Mechanical Engineering Department, 2Industrial Engineering Department
STT Wiworotomo Purwokerto, Indonesia
Semingkir Street 1th, Purwokerto, Central Java, 53352

biotech.machining@gmail.com

Abstract. The process machining of metal occurs increasing friction force and high temperature, consequently will affect the wear of tool and product quality. The cooling method contributes significantly to reduce heat, friction force and surface roughness of workpiece. The cooling method that used must develop to aim environmental machining process with minimum quantity lubrications (MQL) and dry cutting, but the dry cutting has limited performance because of low lubrications. The MQL using nanofluid base natural oil/water is major challenge in cooling method. In this study in order to aim high performance of cooling, the bionanofluid formed from high thermal conductivity of nanoparticles (50 nm) emulsifier by water and bio oil as base fluid in MQL process by injection of low temperature of air. To improve the cooling performance, it used cool air as injection pressure, designed by utilizing the evaporative process refrigerant flow with the counter flow direction. The experimental results show the lowest roughness was obtained from Titanium Dioxide TiO2 with palm oil-based fluid, followed Aluminum Oxide (Al2O3) based on coconut oil occurring, the last CuO in a water-based fluid. TiO2 most dispersing compared to others and correlates to cooling performance, it can be candidates for coolants for machining.

1. Introduction

The process of forming workpiece with machining occurs in the friction and high temperature, consequently will affect the wear of chisels and product quality. The solution to reduce the frictional force, wear and improve surface workpiece, is the cooling method. According to the last development of cooling technology is use of nanocutting based natural fluid with purpose for safe the ecologic and operator health [1]. The optimization of the milling process, the highest quality products and lowest roughness were achieved by the use of vegetable oil based fluids with minimum quantity lubrications (MQL) [2] with purpose for friendly environment [3, 4].

Nanofluids formed from base fluid (dispersants) and particles under dimension of 100 nm (disperse), nanofluid (suspense) can be perfectly dispersed and are permanent due to the effect of motion of Brownian [5]. Mixing Al2O3 (2.5% weight) improves convective properties up to 79% [6]. The choice of mixing is based on the fundamental nature of nanoparticles, dispersing nanoparticles with the appropriate base fluid will improve the thermo-physical properties especially the thermal
conductivity that impacts on the convective properties of nanofluid [7, 8]. The application of nanofluid based 50 nm coconut oil, can reduce significant friction between tools and the workpiece surface. The coconut oil has heat and stable oxidation properties in the machining process [9], the use of coconut oil with 0.5% weight of Al₂O₃ performs better and is capable of reducing cutting temperature [10], Al₂O₃ and TRIM E709 emulsifier reduce heat generated and improve surface finish [11]. The cooling by the MQL method with nanofluids below 1.5% Al₂O₃ coconut oil-based, reduces machining force [12, 13], with ingredients added Molybdenum Sulfide with 0.5% volume MoS₂ reduces force [14].

The biocutting fluid for machining process influenced by fiber content [15]. The nanofluid characteristics influenced by the time of mixing process, temperature, variation of these two factors will affect the characteristics and performance of nanofluid [16]. The formation of nanofluid to obtain a stable suspension, permanent (durable), free agglomeration (sedimentation) in order to avoid chemical changes, temperature and rotation speed affect the time of synthesis. The ratio of nanoparticle masses per 100 mL (% v/v) is described by equation (1).

\[
\varphi = \frac{V_{np}}{V_{bf} + V_{np}} = \frac{V_{np}/V_{np}}{100 \text{ mL suspension}} \times 100
\]  

(1)

where: np (nano particle), bf (base fluid), \(\varphi\); Indicates volume fraction.

The cooling performance of bionanofluid in process machining generalized in MQL system. The MQL methods are always developed to improve performance to increase quality and precision high hardness material. The different MQL processes used in the study compared to other MQL methods, is the use of low-temperature air to pressure bionanofluid in mist formations. The cold air used is obtained by lowering the air of the compressor by utilizing the evaporation process of refrigeration system with the Freon R 32 with counter flow heat exchange. Evaluation of performance of bionanofluid under MQL process using Taguchi method with four factors machining parameters (spindle speed, feed rate, depth of cut and bionanofluid), each in three levels. The most optimum process and best nanofluid performance can be seen from its ability to reduce process temperature, power consumption, chatter/vibration and surface roughness of the results as requirement ASTM 2009 in N5 classification.

In this study the effects of changes in thermal conductivity of nanoparticles and nanofluid, and the degree of dispersion will be tested on the milling process. The effect of these two properties on the cooling performance of the milling operation on steel will be analyzed for each type of nanofluid used by looking at temperature, power consumption, vibration, and especially on the machining surface roughness of the milling process.

2. Methodology
This section explains the methodology of the proposed method.

2.1 Materials
Materials used in this research are:
- a. Nanoparticles: CuO; Al₂O₃, and TiO₂ (powder dimensions according to MSDS: 50 nm)
- b. Basic fluid: Water and bio oil (coconut oil and palm oil).
- c. Metals: Steel ST 60 and Stainless Steel 304.
- d. Tool: Nachi (HSS) end mill 8 mm, 4 flute.

2.2 Design experiment of bionanofluid formation
The determination parameters process formulating nanofluid using three factors and levels can be seen in table 1. The use of nanofluids made with fiber-containing materials can facilitate decomposition reactions [17]. The addition of nanoparticle elements with high thermal conductivity properties will improve heat transfer capability. The process of making nanofluid aims to produce a nanofluid capable of minimizing the style, the cultivation of the carving and producing high quality machining. CuO can
be well ionized if reacted with waterbase [18], Cu dispersing and stable in water [19]. TiO₂ using palm oil base fluid dispersing well, and Al₂O₃ coconut oil base fluid.

Table 1. Factors and levels of formatting of nanofluid (CuO/Al₂O₃/TiO₂).

| Parameters                  | Level (1) | Level (2) | Level (3) |
|-----------------------------|-----------|-----------|-----------|
| Mixing time (minute)        | 60        | 120       | 180       |
| Nano Particle (% weight)(gr)| 0.5       | 1         | 1.5       |
| Temperature mixing (°C)     | 25        | 30        | 35        |

2.3 Test of the characteristics of nanofluids

The formation of nanocutting fluids by 3 factors: percentage of weight (0.5, 1.0, and 1.5% weight: base fluid), temperature variation (25°C, 30°C, 35°C), and mixing time (60, 120 and 180 minute) at rotation stirrer (50, 75, 100 rpm), using magnetic stirrer arranged with microcontroller. Test the characteristics of nanofluid to identify thermal conductivity, viscosity, density, and to know crystal structure form of nanofluid, testing by Transmission Electron Microscopy (TEM).

2.4 The principle of reducing temperature of air compressed base refrigeration system

Minimum Quantity Liquid (MQL) with cold air injection at temperature below 15°C. Portable process temperature regulator using the concept of heat exchanger with a system counter flow, when the air compressor pipe (inside) then the cooling evaporation pipe with high performance refrigerant, this process also reduces the humidity of compressed air, the illustration can be seen in figure 1.

Figure 1. Principle of heat exchange with counter flow direction.

The principle of heat-based heat exchanger by placing a pipe with air flow to be cooled by refrigeration system, to reduce air temperature until continuous at a temperature below 15°C. The exchange of heat aims to reduce the air temperature of the compressor by utilizing the evaporative process of the Freon in the refrigeration system with the flow direction of the counter flow is the most optimum direction in the heat release process. The material used as a compressor air conveyor tube of copper is positioned on the evaporative pipe. To prevent leakage and heat loss on the output side the cold air carrier pipe in isolation is fraught with the objective of minimizing loses.
A refrigeration-based temperature-reducing device can constantly supply air with constant pressure easily, efficiently and optimally. Especially for MQL the fluid used is bio oil based so that the biodegradable index is in accordance with ASTM 2009 requirements. This tool can be used almost for all types of machining process both dry cutting with cold air and MQL for all types of commercial cooling fluid (conventional).

2.5 Experimental design of the milling process under MQL with cooled air pressure

Distribution and data analysis using Taguchi method, to determine the most dominant fluid effect on the results. Performance of nanofluid in machining on milling process materials used as test specimens in this research are ST 60 steel, Stainless steel 304, with length 60 mm, and 40 mm thick, and width 60 mm, and the tools used is a cutter end mill (8 mm, 4 flute/knives). Experimental design for application of cooling performance by MQL method on each nanofluid can be seen in table 2.

Table 2. Factors and levels for the nanofluid cooling performance on milling.

| Parameter of milling Factor | Level 1 | Level 2 | Level 3 |
|-----------------------------|---------|---------|---------|
| Spindle speed (rpm) A       | 360     | 565     | 950     |
| Feed rate (mm/min) B        | 98      | 132     | 200     |
| Depth of cut (mm) C         | 0.75    | 1.0     | 1.25    |
| Cutting Condition D         | Nanofluid (mixing time 60 minutes) | Nanofluid (mixing time 120 minutes) | Nanofluid (mixing time 180 minutes) |

The cooling performance in milling operations using nanofluid CuO water base, TiO$_2$ base palm oil and Al$_2$O$_3$ base coconut oil performed by the same method on factors (D). Characteristics of quality used is Smaller-the-Better (STB). Characteristic quality where the lower the value, then the better quality. S/N value for the type of STB characteristics shown in the equation (2) [20].

$$S/N_{STB} = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} y^2 \right)$$  \hspace{1cm} (2)

Where (S/N): Identify control factor;
  - n: number of experiment,
  - y: square of mean

Achievement of process optimization will be known from power consumption, vibration, temperature/injection pressure, tool temperature. The most optimum results are based on the value of the power of spindle, lowest temperature process, lowest vibration and best roughness target as determination of optimum target condition.

3. Results and discussion

This section presents and discuss the experiment results.

3.1. Nanofluids characteristic (thermophysical properties)

The nanoparticles are mixed in order to be suspended, the perfect suspend proof is the mixture become homogeneous (minimal sediment). Thermophysical properties of nanofluids can be seen in table 3. In the cooling process with MQL the process used as the reference is the thermal conductivity value of nanofluid. The change in the K value on the particle shape and the nanofluid is taken in an average of 3 preparation samples. The result (comparative) on the rate of thermal conductivity of nanoparticles and nanofluid after forming can be seen on figure 2.

The characteristic test results show that in the water-based CuO, there was a 20% decrease in the thermal conductivity value of CuO nanoparticles after dispersed with water from 48.4 W/m.C to 39.62 W/m.C. If compared with Al2O3 the powder conductivity value after dispersed with coconut oil decreased by 15%, from 36.15 W/m.°C to 28.28 W/m.°C. While the increased conductivity value
occurs only in TiO2 nanoparticles with palm oil, after being formed into nanofluid the conductivity value increased significantly from 8.74 W/m°C to 27.56 W/m°C. The specimen with the highest conductivity value tested its crystal arrangement by Transmission Electron Microscopy (TEM) testing. The TEM images can be seen in figure 3. From figure 3(a) is the nanofluids TiO₂ (50 nm), (b) CuO on water (50 nm) and (c) vegetable oil (palm oil) with Al₂O₃.

The TEM test results on three nanofluids describe the dispersion rate of nanoparticles in the base fluid. Nanofluids with base oil of vegetable oil with TiO₂ additive material shows very good dispersion rate compared with crystal density and bonding with basic fluid is very good, while at CuO with water visible process of disperse less visible from crystal structure that loose, at Al₂O₃ with coconut oil. The level of disperse is quite good and the distribution of crystals quite good. From the comparison, the disperse will improve performance for cutting fluid [21].

**Table 3.** The result of properties of nanoparticle and nanofluid (CuO with water base fluid).

| No | Properties of Nanoparticle and Nanofluid | Measurement (CuO with water base fluid) | Measurement (TiO₂ palm oil base fluid) | Measurement (Al₂O₃) with coconut oil base fluid |
|----|-----------------------------------------|----------------------------------------|----------------------------------------|-----------------------------------------------|
| 1  | Thermal conductivity (W/m°C)            | 48.4                                   | 8.47                                   | 36.15                                         |
| 2  | Nanoparticles dimension (nm)             | 50                                     | 50                                     | 50                                            |
| 3  | Density (gr/cm²)                         | 2.93                                   | 4.15                                   | 3.64                                          |
| 4  | Cristal Structure form                   | Cubic                                  | Anatase                                | γ                                              |
| 5  | Viscosity (cp) in nanofluid              | 16.9                                   | 29.5                                   | 27.8                                          |
| 6  | Average K in nanofluids (W/m°C)          | 39.62                                  | 27.56                                  | 28.28                                         |

![Figure 2. The result (comparative) of thermal conductivity of nanoparticle and nanofluid.](image-url)
Figure 3. TEM image (a) TiO$_2$ palm oil (b) CuO in water and (c) Al$_2$O$_3$ coconut base fluid.

3.2. Set-up application of nanofluid under Minimum Quantity Lubrications (MQL) with compressed cool air in milling operations of steel

The nanofluid performance test performed on milling operations in each specimen measured process temperature (tool), vibration, power consumption and surface quality of workpiece can be seen in figure 4. The experimental design uses the Taguchi distribution to detect the most dominant fluid with the specification of the formation process against surface roughness, temperature of cutting zone, tool wear and machining characteristics (vibration, and power consumption).

Figure 4. Set-up application nanofluid in the process of milling with Minimum Quantity Lubrications (MQL) with compressed cool air.

3.3. The result of nanofluid performance in the milling process on steel

Table 4 shows parameters obtained bionanofluids under MQL in milling operations on steel.
Table 4. Parameters obtained bionanofluids under MQL in milling operations on steel.

| Parameters obtained in milling process Measurement (lowest/highest) | Bio-nanofluids formation (water/bio-oil base) |  |
|---|---|---|
| | Palm oil based | Coconut oil based | Water based |
| | nanofluids | nanofluid with | nanofluids |  |
| | Titanium | (Al₂O₃) | water fluid with (CuO) |
| | Dioxide (TiO₂) | |  |
| Lowest temperature cutting zone °C | 27.36 | 30.033 | 28.00 |
| Highest temperature cutting zone °C | 34.10 | 37.733 | 35.900 |
| Lowest Surface roughness (ra) µm | 0.34 | 2.058 | 2.388 |
| Highest Surface roughness (ra) µm | 3.2730 | 6.516 | 6.628 |
| Power consumptions (lowest) (Watt) | 363.73 | 418.733 | 388.911 |
| Power Consumptions (highest) (Watt) | 427.53 | 440.733 | 418.733 |

The graph of S/N ratio roughness the process and temperature can be seen in figure 5(a) and 5(b).

![Graph (a) S/N ratio surface roughness](image-a)

![Graph (b) S/N ratio temperature](image-b)

Figure 5. Graph (a) S/N ratio surface roughness (b) S/N ratio temperature on milling process with nanocutting fluid palm oil with Titanium Dioxide Particles (TiO₂).

The result of milling operations on steel with MQL shows that the use of nanofluid from palm oil with titanium dioxide particles (TiO₂) on stainless steel yielded roughness with the smallest value 0.534 ra, with very low temperature at the smallest temperature at 27.36° C and highest 34.10° C, temperature condition. The low cutting zone is able to reduce the wear of the tool significantly. In accordance with the graph shows that the best roughness is obtained at spindle speed 950 rpm, depth of cut 0.5 mm mixing time 60 minutes, while for the lowest temperature obtained at 180 minutes mixing, this shows that the formation of nanofluid effect on the performance. The characteristics of milling process using nanofluid (coconut oil with Al₂O₃) can be seen on figure 6(a) and figure 6(b).
The natural (coconut) oil-based nanocutting fluid aluminum oxide (Al$_2$O$_3$) applied on ST 60 material on the milling process shows the result of the smoothest roughness at 2.058 ra, and the largest at 6.516 ra, with the smallest cutting zone temperature at 30.033°C and the highest 37.733°C. With a mixing time of 120 minutes. Characteristics of milling process results with nanofluid base water with (CuO), shown in S/N Roughness ratio of Surface and Temperature in Figure 7(a) and 7(b).
The nanofluid with added ingredient (CuO) water base fluid shows the lowest roughness is 2,388 Ra and the lowest temperature is 28°C. Length of mixing is not correlated with performance, it can be seen on the graph that the best conditions occur at the time of the mixing, the number of nano particles less effect on changes in nanofluid properties. In terms of wear and tear, it can be reduced well. The wornest area is on the edge and side of the end mill chisel. In general, the wear of the tool (end milling) reduce significantly. After 9 times milling process shows that the mean wear of tool reduces significantly, positions and type of tool wears can be seen in figure 8.

The MQL using bionanofluid with cool air injections increased tool life, it is evident that at 8 mm (diameter) end mill can be used for the formation of SS 304 with a depth of cut up to 1.0 mm, at low temperatures, with minimal wear and low surface finish.

3.4 Discussion
The thermal conductivity value is added to the base of the coconut oil/palm oil fluid with Al₂O₃ the powder conductivity value after dispersed with coconut oil decreased by 15%, from 36.15 W/m.°C to 28.28 W/m.°C. While the increased conductivity value occurs only in TiO₂ nanoparticles with palm oil, after being formed into nanofluid the conductivity value increased significantly from 8.74 W/m.°C to 27.56 W/m.°C. The result is similar to the research trends [22].

The formation of nanofluid with coconut oil and palm oil shows the process temperature should be below 35°C, because above the temperature began to occur early boiling process. The addition of nanoparticles has an effect on cooling performance, because it can increase enhanced penetration but
not directly proportional to the same trend with the research [23]. Bionanocutting fluid with cold air injections can reduce the temperature at the cutting zone and friction force that occurs tool life increased, suitable at the result previous study [24-26]. The nanofluid TiO$_2$ base palm oil minimize frictions, reductions cutting wear and surface roughness as research trends [27]. The comparison of bio-oil and water base in MQL with micro additives / nano additives shows that palm oil with TiO$_2$ give the best performance than others, as previous research result [28].

4. Conclusion and future work

Nanofluids used to produce the lowest roughness obtained from nanofluid; titanium dioxide (TiO$_2$) based palm oils, In sequence Aluminum oxide (Al$_2$O$_3$) base coconut oil, and the last (CuO) base water. TiO$_2$ with palm oil as base oil can be used as a good coolant for machining process It shows that the most disperse level as shows in crystal images has an effect on cooling performance, the lowest temperature even for the hardest material that is stainless steel. The level of dispersion and thermal conductivity of nanofluid into factors affecting cooling performance in milling operations, proven titanium dioxide (TiO$_2$) based palm oils, became the best coolant in milling of SS 304 with reduce surface roughness significantly. Effect of air with cold temperature below 15°C, at pressure 1 bar is most effective as bionanofluid suppressor in MQL process.

Bionanofluid research is strategically developed in the future, because it is environmentally friendly and biodegradable. Subsequent research is indispensable in automated machining and high speed machining to obtain more complete bionanofluid performance characteristics as reference for industrial scale applications.

Acknowledgments

Thank to Ministry of Research, Technology and Higher Education of the Republic of Indonesia, which has provided funding for fundamental Research of fiscal year 2016-2017.

References
[1] Shokoohi Y, Khosrojerdi E and Shidhai B H R 2015 Machining and ecological effects of a new developed cutting fluid in combination with different cooling techniques on turning operation J. of Cleaner Prod. vol 94 pp 330-9
[2] Sugiantoro B, Rusnaldhy and Widyanto S A 2014 Optimization of parameter of milling process on quality of aluminum machinery result with taguchi method TRAK SI vol 14 no 1
[3] Shashidhara Y M and Jayaram S R 2010 Vegetable oils as a potential cutting fluid—An evolution Tribology International vol 43 pp 1073–81
[4] Ozcelika B, Kuram E, Demirbas E and Şık E 2013 Effects of vegetable based cutting fluids on the wear in drilling Sadhana vol 38 issue 4 pp 687–706
[5] Suhanan, Kamal S, Prayitno Y A K, Wiranata A and Pradecta M R 2016 Experimental study of thermophysical properties of nano fluid TiO2/TermoXT-32, Proceeding of National Symposium on Thermofluids VIII Yogyakarta, Indonesia
[6] Putra N, Maulana S, Koestoer R A and Danardono A S 2005 Measurement of coefficient of heat transfer convection of nano particle fluid suspended water (Al$_2$O$_3$) on fintube heat exchanger Journal of technology vol 2 no XIX pp 116-25
[7] Naina H K, Gupta R, Setia H and Wanchoo R K 2012 Viscosity and specific volume of TiO2/water nanofluids J. Nanofluids vol 1 no 2 pp 161–5
[8] Vasheghani M, Marzbanrad E, Zamani C, Aminy M, Raissi B, Ebadsadeh T and Barzegar-Bafrooei H 2011 Effect of Al$_2$O$_3$ phases on the enhancement of thermal conductivity and viscosity of nanofluids in engine oil Heat Mass Transf. vol 47 pp 1401–06
[9] Rao G K M, Padmini R and Krishna P V 2008 Performance evaluation of eco-friendly nano fluids in machining Recent Advances in Robotics, Aeronautical and Mechanical Engineering pp 221-9
[10] Sodavadia K P and Makwana A H 2014 Experimental investigation on the performance of coconut oil based nano fluid as lubricants during turning of AISI 304 austenitic stainless
steel International Journal of Advanced Mechanical Engineering vol 4

[11] Vasu V and Kumar K M 2011 Analysis of nanofluids as cutting fluid in grinding EN-31 Steel Nano-Micro Lett. vol 3 issue 4 p 209-14

[12] Shokoohi Y and Shekarian E 2016 Application of Nanofluids in Machining Processes - A Review Journal of Nanoscience and Technology vol 2 no 1 pp 59–63

[13] Bose P S C, Rao C S P and Jawale K 2014 Role of MQL and nano fluids on the machining of Microfer C263, 5th International & 26th All India Manufacturing Technology, Design and Research Conference (AIMTDR 2014) Guwahati, Assam, India pp 1 - 4

[14] Padmini R, Krishna V P and Rao G K M 2015 Effectiveness of vegetable oil based nanofluids as potential cutting fluids in turning AISI 1040 steel Tribology International vol 94 pp 490-501

[15] Mirjalili S A, Muirhead J C and Stringer M D 2011 Ultrasound visualizations of the spinal accessory Journal of surgical research vol 175 issue 1 pp e11-6

[16] Keblinski P, Eastman J A and Cahill D G 2005 Nanofluids for thermal transport materials Materials Today vol 8 issue 6 pp 36-44

[17] El-Nahhal I M, Zourab S M, Kodef F S, Selmane M, Genois I and Babonneau F 2012 Nanostructured copper oxide-cotton fibers: synthesis, characterization and applications Int. Nano Lett. vol 2 issue 1 pp 62-7

[18] Manimaran R, Palaniradja K, Alagumurthi N, Sendhilnathan S and Hussain J 2013 Preparation and characterization of copper oxide nanofluid for heat transfer applications Applied Nanoscience vol 4 issue 2 pp 163-7

[19] El-Maghlany W M, Hanafy A A, Hassan A A and El-Magid M A 2016 Experimental study of Cu–water nanofluid heat transfer and pressure drop in a horizontal double-tube heat exchanger Experimental Thermal and Fluid Science vol 78 pp 100–11

[20] JMP 2014 Design of experiments guide (Cary, NC, USA: SAS Institute Inc.)

[21] Prasad M M S and Srikanth R R 2013 Performance evaluation of nano graphite inclusions in cutting fluids with MQL technique in turning of AISI 1040 steel IJRET: International Journal of Research in Engineering and Technology vol 2 issue 11

[22] Baby T T and Ramaprabhu S 2011 Enhanced convective heat transfer using graphene dispersed nanofluids Nanoscale Research Letters vol 6 p 289

[23] Nam J S, Lee P-H and Lee SW 2011 Experimental characterization of micro-drilling process using nanofluid minimum quantity lubrication Int J Mach Tools Manuf. vol 51 pp 649–52

[24] Zhang S, Li J F and Wang Y W 2012 Tool life and cutting forces in end milling Inconel718 under dry and minimum quantity cooling lubrication cutting conditions Journal of Cleaner Production vol 32 pp 81–7

[25] Hadad M and Sadeghi B 2013 Minimum quantity lubrication-MQL turning of AISI 4140, steel alloy Journal of Cleaner Production vol 54 pp 332–43

[26] Rahim E A and Sasahara H 2011 A study of the effect of palm oil as MQL lubricant on high speed drilling of titanium alloys Tribology International vol 44 issue 3 pp 309–17

[27] Belluco W and Chiffre L D 2004 Performance evaluation of vegetable-based oils in drilling, austenitic stainless steel Journal of Material Processing Technology vol 148 issue 2 pp 171–6

[28] Padmini R, Krishna P V and Rao G K M 2016 Effectiveness of vegetable oil based nanofluids as potential cutting fluids in turning AISI 1040 steel Tribology International vol 94 pp 490–501