ICMIEE20-049

Effects of Nano-fluids Assisted MQL in Machining Processes: A Review

Mst. Nazma Sultana, Prianka B. Zaman, N.R.Dhar
Department of Industrial and Production Engineering, Bangladesh University of Engineering & Technology, Dhaka, BANGLADESH

ABSTRACT

Nano-fluids are liquid colloidal suspensions of nanoparticles or nanotubes or Nano fibers of metals or nonmetals, metallic oxides or ceramics having Nano scale dimension 1~100nm in a base fluid such as low viscous water and refrigerant or high viscous oils or ethylene glycol or a mixture of various fluids. In recent decades researchers are highly motivated to use Nano-fluids as a novel cutting fluids due to its some attractive properties such as high thermal conductivity, better wetting and spreading ability, suitable rheological properties with changing nanoparticles size, shape and mixing contribution. It has already been reported by many researchers that the main challenge of applying Minimum quantity lubrication (MQL) in machining processes is its lower cooling effect which has already been reduced remarkably by using nanoparticles as additives in base oils and this paper is an effort of authors to represent the successful implications of Nano-fluids assisted MQL in different machining processes in terms of cutting temperature, surface roughness, tool wear, cutting forces, power consumption and productivity. It is tried to point out the benefits of Nano-fluids assisted MQL in various machining processes such as turning, milling, drilling and grinding in a systematic organized way. Moreover recent challenges of using Nano-fluids are also pointed out with specific research gaps as a direction of future researchers.

Keywords: Cutting fluids, Nanoparticles, Nano-fluids, Minimum quantity lubrication, Machining.

1. Introduction

Machining plays a vital role in manufacturing process for reforming any work material into its required shape and size. Turning, milling, drilling and grinding are very common conventional machining processes and are highly adapted by any production or manufacturing industry. In conventional machining processes, cutting tools or inserts come in direct contact with work specimen to remove excess metals or chips which flow over the rake face of cutting tools. Excess heat generation in machining processes deteriorates the surface quality, reduces tool life and increases tool wear especially at higher speed with higher feed rate [1]. This problem becomes more critical for difficult to cut metals (Ni-based alloy, titanium, tool steels, hardened and forged steels etc.). But, in modern manufacturing industry such type of tough to cut metals and alloys are highly used for producing gears, bearing, shafts, automobiles and aerospace parts. Not only is that higher productivity with better surface quality and lower cost another prerequisite. For achieving those goals different techniques, such as textured and coated tools, cooling and lubrication are tried to adapt. In flood cooling, excessive use of cutting fluids increases the cost of manufacturing as well as this technique has a detrimental effect on personnel health and environment. Researchers have already published that almost 17% cost of manufacturing is related to cutting fluid use and disposal [2]. So it is a great concern of manufacturing world to reduce the use of cutting fluids. Many researchers have already reported minimum quantity lubrication (MQL) as an alternative which uses almost 10,000 times less volume cutting fluids[3] than flood cooling but provides promising machining performances [4]. The selection of proper cutting fluid in MQL is another concern because sometimes MQL cannot fulfill the requirements of proper cooling. A minute amount of cutting fluids is sprayed as mist in MQL which easily evaporates at higher temperature before cooling [5]. In that case an alternative novel class of cutting fluids is synthesized by mixing nanoparticles into conventional fluids. The another reason of choosing nanoparticles as additives or performance enhancement agents is its higher thermal conductivity, better physio-thermal and rheological properties than micro or mili –sized particles[6]. The main aim of this review is to summarize the characteristics, challenges and preparation principle of nanofluids with its recent applications in different machining operations for researchers' to acquire knowledge about the benefits of nanofluids in a short time and easier way.

2. Nanofluids, its characteristics and preparation

Nanofluids can be defined as homogeneous colloidal suspensions of nanoparticles such as metals (Al, Cu, Ag, Fe, Zn, Au), nonmetals (graphite, GnP, CNT, carbon onion, ND, MWCNT) metallic/nonmetallic oxides (Al_2O_3, CuO, SiO_2, Fe_3O_4, Fe_2O_3, TiO_2, ZnO, ZrO_2, GO) or ceramic (SiC) and some others (hBn, MoS_2) in a base fluid [7]. In comparison to other bulk materials nanoparticles have some salient features such as-

- High thermal conductivity and higher heat transfer capability.
- Brownian movement of nanoparticles due to thermal effects.
- High viscosity and surface tension.
- High specific surface area.
- Higher tendency to agglomerate.

* Corresponding author. Tel.: +88-01941055289
E-mail addresses: nazma.kuet@yahoo.com

- Better wettability.
- Reduced pumping power and reduced tendency of clogging.
- Adjustable properties such as: wettability, anti-friction ability, anti-wear mechanism, thermal conductivity, dynamic viscosity can be varied by changing nanoparticles size, shape, concentration on base fluid, stability time, sonication time, type of dispersants or surfactants, preparation techniques and so on.

Besides the positive characteristics of nanofluids, high agglomeration tendency of nanoparticles due to clamping for van der waals force between particles and weak Brownian motion is one of the major challenges. For reducing this agglomeration tendency surfactants/dispersants (SDS, SDBS, CTAB, PVP, Tween 20, Polysorbate 80, lecithin) are commonly used. Surfactants acts as coating material on the nanoparticle surface which reduces the attraction of intermolecular particles. But at higher temperature (>60^{O}C) nanofluids start to sediment due to fracture of surfactants [8]. Moreover special attention must be provided to select the surfactant type and percent concentration. Higher concentration of surfactants increases the possibility of foam generation, reduces the thermal conductivity and fluid contamination. The basic components of nanofluids are graphically presented in Fig.1.

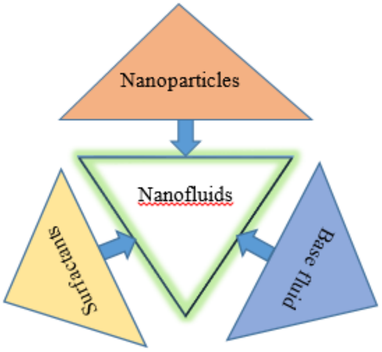

Fig.1 Basic components of Nanofluids.

In a broad sense synthesis/ preparation of nanofluids can be done in two ways-single/one step preparation and two step preparation. One step preparation method is generally tried to follow when high dispersion of nanoparticles with less sedimentation is the main concern. Generally two step preparation approach is followed due to its less complexity and higher flexibility. Moreover this approach is also economical than single step method. In two step method first nanoparticles are transferred into powder form and then they are dispersed into base fluids represented in Fig.2. But the main drawback of this approach is lower stability of nanofluids due to quick agglomeration tendency of nanoparticles. Many researchers have already tried to improve this drawback by different ways such as PH control, addition of surfactants/dispersants, surface modification, addition of ionic liquids, ultrasonic agitation, formation of carboxyl groups etc [8].

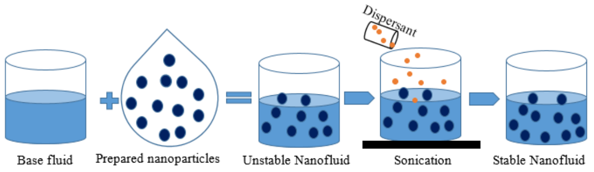

Fig. 2 Two-step preparation method of Nanofluids

3. Effects of nanofluids in machining processes

Many researchers have already published their research works on effective cooling and lubricating performances of nanofluids in different machining processes. Some review results are summarized in Table 1 to Table 4. The effects of nanofluids over dry and conventional cooling in milling are shown in Fig. 3.

Table 1 Effects of nanofluids assisted MQL in turning.

Ref.	Work materials, nanoparticles (size), base fluids , surfactants	Effects on turning performances
[9]	**W/P**: AISI 420 steel **NFs**: GnP **Size**: 5nm **BF:** Ester based cutting oil **Surfactants:** not mentioned	GnP assisted MQL provided better surface quality.
[10,11]	**W/P** : Ti-6Al-4V **NFs**: GO **Size**: 50nm **BF:** Mineral oil (25%) + saponified oil (25%) +water (50%) **Surfactants:** not mentioned	0.3 wt. % showed the best performance on tool wear and 0.5%wt. provided minimum cutting force.
[12]	**W/P** : Inconel 625 **NFs**: hBN **Size**: 65-75 nm **BF:** Plantocut 10 SR Ester based cutting oil **Surfactants:** not mentioned	Concentration of nanoparticles has a great impact on turning performances. 0.5 % hBN assisted nanofluid MQL provided less tool wear and roughness.
[13]	**W/P** :AA 7075-T6 **NFs**: Ag **BF**: Ethylene glycol **Surfactants**: Not mentioned	34%, increased surface quality by 21% and reduced friction coefficient and temperature by 18% and 74%.
[14]	**W/P**: Ni based alloy Incoloy 800H, **NFs** : Al_2O_3 **Size**:Not mentioned **BF**: Coconut oil **Surfactants**: Not mentioned	Provided better turning performances.
[15]	**W/P**: AISI 4340 steel **NFs**: CuO, ZnO Fe_2O_3 Al_2O_3 **Size**: 20-80, 30-50, 10-20, 30-70 nm	Among those four nanofluids CuO Nanofluid related MQL outperformed than others. Better

Table 1 (continue……..)

Ref.	Work materials, nanoparticles (size), base fluids , surfactants	Effects on turning performances
	BF: Radiator coolant + Distilled water **Surfactants**:Not mentioned	machined surface, shorter chips with less tool chip contact length, less tool wear and minimum residual stress were observed in CuO nanofluid assisted MQL.
[16]	**W/P**: A286 super alloy **NFs**: SiO_2, CuO **Size:** 20, 40 nm **BF**: Deionized water **Surfactants**: SDS	The presence of surfactants into nanofluids increased stability.
[17,18]	**W/P**: AISI 1040 steel **NFs**: MoS_2 **Size:** 45 nm **BF**: Coconut oil, sesame oil and canola oil **Surfactants**: not mentioned	Reduced cutting temperature, tool wear, cutting force and roughness more.
[19,20]	**W/P**: ASTM F 2063 NiTi, Inconel 718 **NF:**Al_2O_3 **Size**: 50nm **BF:** Solcut oil **Surfactants**:SDBS	Reduced cutting force 6-10% and tool wear by 4.2-34.5% than dry turning.
[21]	**W/P**: AISI 316SS **NFs**: TiO_2 **Size**: 20 nm **BF:** water **Surfactants**: Not mentioned	Both tool temperature and chip temperature were reduced highly at 0.03% concentration TiO_2 assisted MQL.

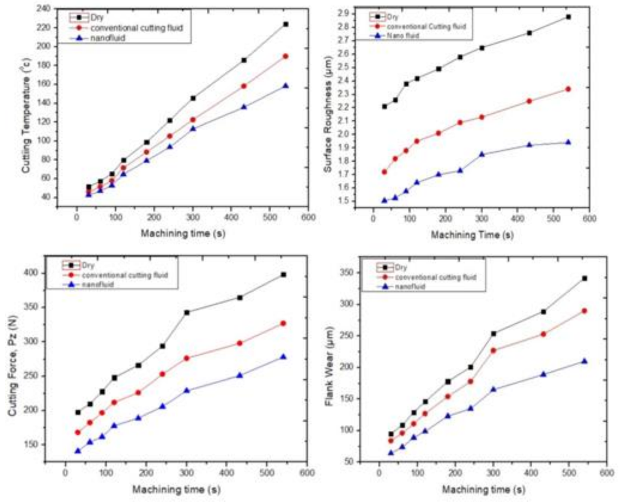

Fig. 3 Effects of nanofluids in turning for improving machinability over dry and conventional cooling [22].

Table 2 Effects of nanofluids assisted MQL in grinding

Ref.	Work materials, nanoparticles (size), base fluids , surfactants	Effects on grinding performances
[23]	**W/P**: Ni based alloy GH 4169 **NFs**: Al_2O_3, ZrO_2, ND, CNT, MoS_2, SiO_2 **Size**: 50nm **BF:** Palm oil **Surfactants:** Span 80 and polysorbate 80; SDS	Provided lowest sliding friction, grinding force, roughness but highest G ratio. NDs provided highest sliding friction but lower roughness.
[24]	**W/P**: Ni based alloy GH 4169 **NFs**: hybrid CNT/MoS_2 **Size**: 30nm **BF:** Palm oil **Surfactants:** SDS	Pure MoS_2 assisted MQL provided lower roughness and force ratio than CNT assisted MQL.
[25,26]	**W/P**: Ni based alloy GH 4169 **NFs:** Hybrid Al_2O_3/SiC **Size**: 30, 50, 70 nm **BF**: Bluebe LB 1 synthetic lipid **Surfactants**: SDS	Size ratio of nanoparticles has a great effect on grinding performance. At 30:70 size ratio of hybrid Al_2O_3/SiC provided better grinding effect and surface quality.
[27]	**W/P**: AISI 1045, Ni based alloy GH 4169 **NFs**: hybrid MoS_2/CNT , MoS_2 **Size**: 50 nm **BF**: Liquid paraffin, palm oil, rapeseed oil and soybean oil **Surfactants**: SDS	2% volume MoS_2 nanofluid provided lower roughness and force ratio than CNT based nanofluid. 8%mass fraction of hybrid MoS_2/CNT nanofluids delivered the highest positive effects on grinding.
[28]	**W/P**: Ti-6Al-4V **NFs**: Al_2O_3 **Size**: 30, 50, 70 nm **BF:** KS-1008 synthetic lipid **Surfactants**: SDS	Better lubricating performances with protective film layer was formed.
[29]	**W/P**: Ni based alloy GH 4169 **NFs** :MoS_2, **Size**: 50nm **BF**: Castor and soybean oil mix **Surfactants**: Tween 20, span 20	MoS_2 enhanced cooling property by proper mixing with base oil that accelerates the liquid film formation of outer layer of nanoparticles.

Table 2 (continue……..)

Ref.	Work materials, nanoparticles (size), base fluids , surfactants	Effects on grinding performances
[30]	**W/P** : Inconel 718 **NFs**: Ag, ZnO **Size**: 10nm and 25 nm **NF**: Deionized water **Surfactants**: SDS	Ag showed better cooling properties and ZnO showed better lubricating properties.
[31]	**W/P** :Ti6Al4V-ELI **NFs**: GO, graphite and MoS_2 **Size:** 3-8nm **BF**: canon oil, olive oil and soybean oil **Surfactants**: SDS	Grapheme had shown superior tribological potential owing to its unique characteristics viz. highest thermal conductivity (~5000 W/m.K), interlayer shear ability, chemical inertness and superoleophilic nature. 1.5% wt. of grapheme and graphite provided better results.
[32]	**W/P**: Silicon nitride ceramics **NFs**: Al_2O_3, ZnO, B_4C, WS_2, MoS_2**,** hBN **Size:** 50, 25, 50, 90, 70 nm **BF**: Distilled water **Surfactants**: SDBS, SDS	MoS_2, WS_2 and hBN provided superior grinding performance than oxide (Al_2O_3, ZnO) and carbide (B_4C) due to their lamellar structure. Similarly hybrid MoS_2-WS_2/MoS_2-hBN provided better lubrication properties in grinding.
[33]	**W/P**: Ni based alloy Inconel **NF:**Al_2O_3 **Size**: 30-50nm **BF:** Sunflower oil and ricebran oil **Surfactants**:: Polysorbate 80	Experimental results manifested the effect of base fluid type and nanoparticles concentration on nanofluid performances. In this manner Al_2O_3 Nanoparticles with sunflower oil performed better than ricebran oil. 1% wt. NPS in base oil provided better results in terms of G-ratio, surface temperature, grinding force, specific energy except surface roughness.
[34]	**W/P** : Inconel 738 **NFs**: copper coated with silver **Size**: 7nm **BF:** Distilled water **Surfactants**:: Tween 20	Due to antibacterial property of copper and silver, this novel nanofluids was proven as environment friendly cutting fluid. Not only that copper nanofluids assisted MQL improved almost 60% both wheel loading and surface roughness than dry grinding.

Table 3 Effects of nanofluids assisted MQL in milling

Ref.	Work materials, nanoparticles (size), base fluids , surfactants	Effects on milling performances
[35]	**W/P** : Al 6061-T6 **NFs**: MoS_2 **Size**: 20-60 nm **BF:** Ecocut HSG 905S **Surfactants:** not mentioned	MoS_2 Nanofluid assisted MQL enhanced the surface quality by its rolling, sliding and polishing effects.
[36]	**W/P** : Al 6061-T6 **NFs**: SiO_2 **Size**: 5-15 nm **BF:** Ecocut SSN 332 **Surfactants:** not mentioned	0.2% concentration nanofluids raised up the growth of protective layer due to breaking billions of nanoparticles between tool-chip interfaces. Moreover this nanofluids assisted MQL to reduce cutting force and cutting temperature.
[37]	**W/P:** Mild steel **NFs**: TiO_2, SiO_2, Al_2O_3 **Size**: 15, 14, 13nm **BF:** water **Surfactants:** not mentioned	5 g/L water based nanofluids Al_2O_3 was found as the best coolant for reducing milling temperature followed by SiO_2. Water based nanonfluids form oxide coating while mineral based coolants form no coat.
[38]	**W/P**: Inconel 690 **NFs**: Al_2O_3 **Size**: 50nm **BF:** palm oil **Surfactants:** Polysorbate 80	1% silica deposited nanofluid increased tool life, reduced chip curvature, minimized roughness and milling force simultaneously.
[39]	**W/P**: Al 7075- T6 **NFs**: Cu coated Al_2O_3 **Size**: 20 nm **BF:** Vulcan Strub Futura 10-9402 NC coolant oil **Surfactants:** NH_3 with PEG	Reduced roughness and workpiece temperature.
[40]	**W/P**: Inconel 750 **NFs**: graphite, hBN, MoS_2 **Size**: 80 nm **BF**: Vegetable oil **Surfactants**: Not mentioned	0.5% wt. hBN increased tool life, reduced roughness, too wear, cutting force and cutting temperature than nano MoS_2 and nano graphite.

Table 4 Effects of nanofluids assisted MQL in drilling

Ref.	Work materials, nanoparticles (size), base fluids , surfactants	Effects on drilling performances
[41]	**W/P**: Heat treated AISI 4340 steel **NFs**: MoS_2, ND **Size**: 70-100 nm, 3-5 nm **BF**: Boeblube 70104 oil **Surfactants**: None	4% wt. MoS_2 reduced sdar wear, increased tool life and reduced force and BUE. Above 1% concentration ND reduced tool life
[42]	**W/P**: Forged steel **NFs**: CNO **Size**: 5-10 nm **BF**: Mineral oil **Surfactants**: None	Reduced cutting force, roughness and tool wear.
[43]	**W/P**: Al 6061 alloy **NFs**: ND **Size**: 30 nm **BF**: vegetable oil and paraffin oil **Surfactants**: None	Ball bearing effects of spherical shaped nanofluids reduced chips and burrs. ND also reduced thrust force, torque and wear.
[44]	**W/P**: Aluminum 6063 **NFs**: Al_2O_3 **Size**: 20 nm **BF**: Soybean oil **Surfactants**: None	1.5% wt. Al_2O_3 with soybean oil possess better cooling and lubrication.

4. Conclusions and future scope of work

After reviewing the above results some points are found out which are listed below:

- At higher temperature lubrication property of GnP is poorer than soluble oil.
- Anti-friction and anti-wear properties of nanofluids can be enhanced by increasing the concentration of NPs into base fluids.
- Symmetric shaped or spherical shaped NPs are better for higher surface quality due to its rolling/sliding mechanism.
- Lamellar structured (MoS_2) NPs provides better lubrication than spherical shaped (Al_2O_3) oxides.
- Nanofluids reduced the direct contact between tool and W/P by film or coating formation.
- Ball bearing effect of NPs reduces chips and burr formation.
- Heat transfer of Nano fluids depend on the dynamic viscosity, thermal conductivity, Brownian motion and specific surface area of NPs.
- Higher percentage saturated fatty acid containing vegetable oil provides better cooling effect with NPs.
- Size ratio of NPs is a crucial factor in hybrid nanofluids formation.
- Optimum level of surfactant concentration plays a vital role of changing nanofluids property. Some other challenging factors are shown in Fig. 4.
- More research works are needed to find out the optimum mix ratio of Nps into base oil, optimum size ratio and optimum surfactant concentration. Very limited research Hybrid nanofluids are found so it may be a vast area of research for future researchers.

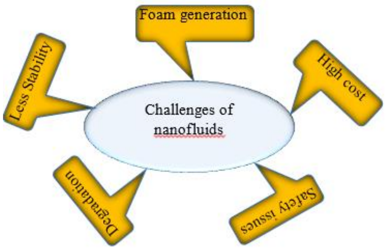

Fig. 4 Possible challenges of nanofluids

5. References

[1] Sultana, M.N., Dhar, N.R. and Zaman, P.B. A Review on Different Cooling/Lubrication Techniques in Metal Cutting. *American Journal of Mechanics and Applications*, vol. 7, pp. 71-87, 2019.

[2] Amiril, S.A.S., Rahim, E.A. and Syahrullail, S., A review on ionic liquids as sustainable lubricants in manufacturing and engineering: Recent research, performance, and applications, *Journal of Cleaner Production*, vol. 168, pp.1571-1589, 2017.

[3] Carou, D., Rubio, E.M. and Davim, J.P., A note on the use of the minimum quantity lubrication (MQL) system in turning. *Industrial Lubrication and Tribology*, vol. 3, pp. 256-261, 1571-15892015.

[4] Zaman, P.B., Sultana, N. and Dhar, N.R. Quantifying the effects of cooling condition, tool type and cutting parameters on machinability of turning AISI 4140 steel using full factorial DOE. *Journal of Production Systems and Manufacturing Science*, vol. 1, pp.23-39, 2020.

[5] Pereira, O., Català Calderon, P., Rodríguez, A., Ostra, T., Vivancos Calvet, J., Rivero, A. and López de Lacalle, L.N., The use of hybrid CO_2+ MQL in machining operations. *Procedia engineering*, vo. 132, pp.492-499, 2015.

[6] Sharma, A.K., Tiwari, A.K. and Dixit, A.R., Mechanism of nanoparticles functioning and effects in machining processes: a review. *Materials Today: Proceedings*, vol. (4-5), pp.3539-3544, 2015.

[7] Michaelides E.E., Characteristics of Nanofluids. In: Nanofluidics. Springer, Cham, 2014.

[8] Bakthavatchalam, B., Habib, K., Saidur, R., Saha, B.B. and Irshad, K., Comprehensive study on nanofluid and ionanofluid for heat transfer enhancement: A review on current and future perspective. *Journal of Molecular Liquids*, vol. 305, p. 112787, 2020.

[9] Yıldırım, Ç.V., Investigation of hard turning performance of eco-friendly cooling strategies: Cryogenic cooling and nanofluid based MQL. *Tribology International*, vol. 144, p.106127, 2020.

[10] Yi, S., Li, J., Zhu, J., Wang, X., Mo, J. and Ding, S., Investigation of machining Ti-6Al-4V with graphene oxide nanofluids: Tool wear, cutting forces and cutting vibration. *Journal of Manufacturing Processes*, vol. 49, pp.35-49, 2020.

[11] Shuang, Y., John, M. and Songlin, D., 2019. Experimental investigation on the performance and mechanism of graphene oxide nanofluids in turning Ti-6Al-4V. *Journal of Manufacturing Processes*, vol. 43, pp.164-174, 2019.

[12] Yıldırım, Ç.V., Sarıkaya, M., Kıvak, T. and Şirin, Ş., The effect of addition of hBN nanoparticles to nanofluid-MQL on tool wear patterns, tool life, roughness and temperature in turning of

Ni-based Inconel 625. *Tribology International*, vol. 134, pp.443-456, 2019.

[13] Cetin, M.H. and Korkmaz, S., Investigation of the concentration rate and aggregation behaviour of nano-silver added colloidal suspensions on wear behaviour of metallic materials by using ANOVA method. *Tribology International*, vol. 147, p.106273, 2020.

[14] Venkatesan, K., Devendiran, S., Ghazaly, N.M., Rahul, R. and Mughilan, T., 2019. Optimization of Cutting Parameters on turning of Incoloy 800H using Al_2O_3 Nanofluid in Coconut oil. *Procedia Manufacturing*, vol. 30, pp.268-275, 2019.

[15] Das, A., Pradhan, O., Patel, S.K., Das, S.R. and Biswal, B.B., Performance appraisal of various nanofluids during hard machining of AISI 4340 steel. *Journal of Manufacturing Processes*, vol. 46, pp.248-270, 2019.

[16] Musavi, S.H., Davoodi, B. and Niknam, S.A., Effects of reinforced nanoparticles with surfactant on surface quality and chip formation morphology in MQL-turning of superalloys. *Journal of Manufacturing Processes*, vol. 40, pp.128-139, 2019.

[17] 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, 2016.

[18] Rapeti, P., Pasam, V.K., Gurram, K.M.R. and Revuru, R.S., Performance evaluation of vegetable oil based nano cutting fluids in machining using grey relational analysis-A step towards sustainable manufacturing. *Journal of Cleaner Production*, vol. 172, pp.2862-2875, 2018.

[19] Khalil, A.N.M., Azmi, A.I., Murad, M.N. and Ali, M.A.M., The effect of cutting parameters on cutting force and tool wear in machining Nickel Titanium Shape Memory Alloy ASTM F2063 under Minimum Quantity Nanolubricant. *Procedia CIRP*, vol. 77, pp.227-230, 2018.

[20] Ali, M.A.M., Azmi, A.I. and Khalil, A.N.M., Specific cutting energy of Inconel 718 under dry, chilled-air and minimal quantity nanolubricants. *Procedia CIRP*, vol. 77, pp.429-432, 2018.

[21] Ukamanal, M., Mishra, P.C. and Sahoo, A.K., Temperature distribution during AISI 316 steel turning under TiO2-water based nanofluid spray environments. *Materials Today: Proceedings*, vol. 5, pp.20741-20749, 2018.

[22] Sharmin, I., Gafur, M.A. and Dhar, N.R. Preparation and evaluation of a stable CNT-water based nano cutting fluid for machining hard-to-cut material. *SN Applied Sciences*, vol. 2, pp.1-18, 2020.

[23] Wang, Y., Li, C., Zhang, Y., Li, B., Yang, M., Zhang, X., Guo, S., Liu, G. and Zhai, M., Comparative evaluation of the lubricating properties of vegetable-oil-based nanofluids between frictional test and grinding experiment. *Journal of Manufacturing Processes*, vol. 26, pp.94-104, 2017.

[24] Zhang, Y., Li, C., Jia, D., Li, B., Wang, Y., Yang, M., Hou, Y. and Zhang, X., Experimental study on the effect of nanoparticle concentration on the lubricating property of nanofluids for MQL grinding of Ni-based alloy. *Journal of Materials Processing Technology*, vol. 232, pp.100-115, 2016.

[25] Zhang, X., Li, C., Zhang, Y., Wang, Y., Li, B., Yang, M., Guo, S., Liu, G. and Zhang, N., Lubricating property of MQL grinding of Al2O3/SiC mixed nanofluid with different particle sizes and microtopography analysis by cross-correlation. *Precision Engineering*, vol. 47, pp.532-545, 2017.

[26] Gao, T., Zhang, X., Li, C., Zhang, Y., Yang, M., Jia, D., Ji, H., Zhao, Y., Li, R., Yao, P. and Zhu, L., Surface morphology evaluation of multi-angle 2D ultrasonic vibration integrated with nanofluid minimum quantity lubrication grinding. *Journal of Manufacturing Processes*, vo.51, pp.44-61, 2020.

[27] Zhang, Y., Li, C., Yang, M., Jia, D., Wang, Y., Li, B., Hou, Y., Zhang, N. and Wu, Q., Experimental evaluation of cooling performance by friction coefficient and specific friction energy in nanofluid minimum quantity lubrication grinding with different types of vegetable oil. *Journal of cleaner production*, vol. 139, pp.685-705, 2016.

[28] Zhang, J., Li, C., Zhang, Y., Yang, M., Jia, D., Liu, G., Hou, Y., Li, R., Zhang, N., Wu, Q. and Cao, H., 2018. Experimental assessment of an environmentally friendly grinding process using nanofluid minimum quantity lubrication with cryogenic air. *Journal of cleaner production*, vol. 193, pp.236-248, 2018.

[29] Jia, D., Li, C., Zhang, Y., Yang, M., Wang, Y., Guo, S. and Cao, H., Specific energy and surface roughness of minimum quantity lubrication grinding Ni-based alloy with mixed vegetable oil-based nanofluids. *Precision Engineering*, vol. 50, pp.248-262, 2017.

[30] Sinha, M.K., Madarkar, R., Ghosh, S. and Rao, P.V., Application of eco-friendly nanofluids during grinding of Inconel 718 through small quantity lubrication. *Journal of cleaner production*, vol. 141, pp.1359-1375, 2017.

[31] Singh, H., Sharma, V.S., Singh, S. and Dogra, M., Nanofluids assisted environmental friendly lubricating strategies for the surface grinding of titanium alloy: Ti6Al4V-ELI. *Journal of Manufacturing Processes*, vol.39, pp.241-249, 2019.

[32] Kumar, A., Ghosh, S. and Aravindan, S., Experimental investigations on surface grinding of silicon nitride subjected to mono and hybrid nanofluids. *Ceramics International*, vol. 45, pp.17447-17466, 2019.

[33] Virdi, R.L., Chatha, S.S. and Singh, H., Performance Evaluation of Inconel 718 under vegetable oils based nanofluids using Minimum Quantity Lubrication Grinding. *Materials Today: Proceedings*, 2020.

[34] Pashmforoush, F. and Bagherinia, R.D., Influence of water-based copper nanofluid on wheel loading and surface roughness during grinding of Inconel 738 superalloy. *Journal of Cleaner Production*, vol. 178, pp.363-372, 2018.

[35] Rahmati, B., Sarhan, A.A. and Sayuti, M., Morphology of surface generated by end milling AL6061-T6 using molybdenum disulfide (MoS_2) nanolubrication in end milling machining. *Journal of Cleaner Production*, vol.66, pp.685-691, 2014.

[36] Sayuti, M., Erh, O.M., Sarhan, A.A. and Hamdi, M., Investigation on the morphology of the machined surface in end milling of aerospace AL6061-T6 for novel uses of SiO2 nanolubrication system. *Journal of Cleaner Production*, vol. 66, pp.655-663, 2014.

[37] Okokpujie, I.P., Ohunakin, O.S., Adelekan, D.S., Bolu, C.A., Gill, J., Atiba, O.E. and Aghedo, O.A., Experimental investigation of nano-lubricants effects on temperature distribution of mild steel machining. *Procedia Manufacturing*, vol. 35, pp.1061-1066, 2019.

[38] Sen, B., Mia, M., Mandal, U.K. and Mondal, S.P., Synergistic effect of silica and pure palm oil on the machining performances of Inconel 690: A study for promoting minimum quantity nano doped-green lubricants. *Journal of Cleaner Production*, p.120755, 2020.

[39] Kulkarni, H.B., Nadakatti, M.M., Kulkarni, S.C. and Kulkarni, R.M., Investigations on effect of nanofluid based minimum quantity lubrication technique for surface milling of Al7075-T6 aerospace alloy. *Materials Today: Proceedings*, 2019.

[40] Şirin, Ş. and Kıvak, T., Performances of different eco-friendly nanofluid lubricants in the milling of Inconel X-750 superalloy. *Tribology International*, vol.137, pp.180-192, 2019.

[41] Mosleh, M., Ghaderi, M., Shirvani, K.A., Belk, J. and Grzina, D.J., Performance of cutting nanofluids in tribological testing and conventional drilling. *Journal of Manufacturing Processes*, vol. 25, pp.70-76, 2017.

[42] Agapiou, J.S., Performance evaluation of cutting fluids with carbon nano-onions as lubricant additives. *Procedia Manufacturing*, vol. 26, pp.1429-1440, 2018.

[43] Nam, J.S., Lee, P.H. and Lee, S.W., 2011. Experimental characterization of micro-drilling process using nanofluid minimum quantity lubrication. *International Journal of Machine Tools and Manufacture*, vol. 51, pp.649-652, 2011.

[44] Chatha, S.S., Pal, A. and Singh, T., Performance evaluation of aluminium 6063 drilling under the influence of nanofluid minimum quantity lubrication. *Journal of Cleaner Production*, vol. 137, pp.537-545, 2016.

NOMENCLATURE

SDS	:sodium dodecyl sulphate	ND	:nanodiamond
SDBS	:sodium dodecyl benzene sulphonate	CNT	:carbon nanotube
CTAB	:cetyl trimethyl ammonium bromide	NPs	:nanoparticles
PVP	:polyvinyl pyrrolidone	BF	:base fluid
PEG	:polyethylene glycol	W/P	:workpiece