Cooling Performance of Turning M2 steel by using copper nanofluids

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Abstract

Minimum quantity Lubrication (MQL) is a technique used to reduce the utilization of cutting liquids in accomplishing a perfect and well-disposed condition. In this examination, the machinability of M2 steel which is hard-to-machine material utilized in key applications was researched under three separate cutting strategies such as dry environment, oil environment, and copper nanofluids with minimum quantity lubrication as environment. The turning tests were conducted utilizing carbide inserts on five separate cutting speed with constant feed and depth of cut. The maximum roughness value obtained with dry condition is 3.75 µm, for oil is 1.7 µm and nanofluid is 0.81 µm. The extreme flank wear values attained is 0.16 mm, 0.055 mm and 0.04 mm for dry, oil and nanofluid conditions. The reduced value of surface roughness (0.45 µm) and flank wear (0.04 mm) were obtained when the machining was performed under copper nanofluid as a coolant.

Keywords: Copper Nanofluids, Turning, Tool wear, Surface Roughness, Chip Morphology

1 Introduction

Now a day, "becoming environmentally viable" is a challenge ahead to the subtractive manufacturing sector and Minimum Quantity Lubrication (MQL) is a simple and powerful choice for reducing the environmental pollution. MQL is a system which applies minute measures of coolant to the cutting tool /work piece interface rather conventional method of applying coolants. MQL has incredible potential for helping with machining a wide range of materials. As manufacturers are attempting consistently to minimize the fabricating costs, environmental impact and enhance quality, the MQL system serves the purpose. Naresh Babu et al. [1] found that the use of nanofluid MQL results in better heat dissipation and

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thus improved surface finish and tool wear while turning D3 tool steel. It was confirmed that NFMQL was superior to dry and oil MQL in terms of cutting temperature, with 84% and 64% decrease in heat compared to dry and oil MQL, respectively. Further, the use of silver nanoparticles as a lubrication has been effective in turning die tool under MQL process.Wang et al. [2] has done a numerical simulation and experimental analysis of the turning process using a tool surface with controllable texture and noted that the texture on the tool surface can change the wetting state and spread of the oil medium and the arrangement direction of the surface has a significant influence in the cutting zone. The texture with a perpendicular cutting region gained the lowest cutting force, while the texture with parallel cutting edges and cross-textured tools increased the cutting force. Additionally, the texture vertical to the cutting region was found to be effective in removing chips and achieving optimal work area and surface quality with small chip radius. Chen et al. [3] proposed a cooling method combining MQL and internal cooling for turning nickel-based superalloy GH4169 through finite element simulation and experimental analysis and observed there was a reduction in temperature by 80°C and force by 18%. The method resulted in improved chip breaking, better surface quality and smoother surface with clear and regular texture, and a reduction in surface roughness by 24%. The surface roughness prediction model has confirmed that the cutting speed and feed rate are the crucial factors in influencing the surface roughness, whereas depth of cut and coolant flow rate has little effect on the responses. Zhang et al. [4] examined the dot textures in the face of YG8 carbide tools improved cooling environment at very fewer cutting speeds in dry cutting, but this effect decreases as cutting force increases. Under MQL conditions, the dot-surfaced tools were found to be effective in reducing cutting force, coefficient of friction and chip thickness while also refining the anti-adhesion properties. The DT-100 tool serves to be very effective among the three different dot textures tested. Moreover, the use of nano-WS_2 and Cu particles further enhance the anti-wear property and prevent the direct interaction between the chip and tool interface. Makhesana et al. [5] evaluated the effectiveness of MoS_2 and graphite based nanofluid during turning of Inconel 625. It was found that MoS_2 mixed with oil containing resulted in better surface quality and improved tool life, while dry conditions had the poor tool life and worst surface finish. Further, MoS_2 blended nanofluid pave way in reducing the temperature at the cutting region. Ibrahim et al. [6] performed a comparative examination among MQL with flooded cooling methods on temperature, flank wear and surface roughness in turning D3 steel. The authors noticed that variation in the output was obtained through MQL with the inclusion of zinc oxide as nanoparticles have helped in obtaining the positive results between the responses. Further, they concluded that nanofluid MQL minimised the wear on the tool by 9-51 % and roughness on the machined surface by 3-12% respectively. Pal et al. [7] noted that the use of 1.5 wt. % of Al_2O_3 NFMQL in drilling process of AISI 321 had the best surface quality and the lowest drill tip temperature. The SEM and EDS study showed that a reasonable decrease in the drill wear rate at 1.5 wt. % Al_2O_3 NFMQL

comparing all other drilling conditions. It was found that conventional cooling improved drilling characteristics relative to dry drilling, but the NFMQL conditions considerably reduced the torque and thrust force comparing the conventional cooling environments. Wang et al. [8] found that the use of MQL with CO_2 resulted in minimizing the tool wear while turning tantalum-tungsten alloy. The authors also noticed that a significant reduction in thickness of the chip obtained with MQL CO_2 relatively with liquid N_2. Liu et al. [9] confirmed that the cold air electrostatic assisted MQL results in better surface finish, less heat generation, reduced tool wear, and improved chip morphology compared to MQL, electrostatic MQL and cold air MQL in milling titanium alloys. The cold air electrostatic assisted MQL contributed for the minimization of cutting temperature in the tool-workpiece zone. Dash et al. [10] observed that the nose radius and feed have a significant effect on surface quality, with surface roughness decreasing as nose radius increases and surface finish deteriorating as feed increases. The use of a NFMQL improved tool life by 30.8% and 22.6% respectively and reduced the energy consumption by 50.64% and further improved surface quality, power consumption and tool wear comparing MQL in turning D3 steel. Sateesh et al. [11] suggested that vegetable oil-based nanofluids with boric acid nanoparticles as lubrication in machining EN19 steel to improve the performance such as cutting temperature, surface roughness and cutting forces. The results confirmed that the optimal parameters was achieved with a 0.5% incorporation of boric acid nanoparticles in canola oil, which led to decrease in cutting forces, temperature, and surface roughness to 22%, 14% and 20% respectively comparing pure canola oil. The impact of lubrication reduces the friction in the tool zone and thus helps to extend tool life and improve surface quality. Gupta et al. [12] studied the impact of dry, MQL and variation in nozzle position on the turning process of duplex stainless steel. Their analysis concluded that, lowest roughness values were observed in MQL with a reduction in 30%, consumption of power by 23 % and tool wear by 52% in comparison with dry environment. Maruda et al. [13] studied the LQL technique along with LQL+ extreme pressure (LQLEP) in turning AISI 1045. The authors observe that good lubrication and better cooling were attained with LQLEP pressure method. The reason for reduction in roughness is due to LQLEP paved way in obtaining uniform sharing of crest and valleys. In addition, they confirmed that LQLEP is a suitable method when compared with other machining condition such as dry and LQL. Emami and Karimipour [14] investigated the impact of cooling conditions in the turning process. A mechanistic force model integrating GEP optimization method was proposed to predict the specific machining force, which is then utilised to create a chatter stability design and develop a SLD curve. It further recommends the use of lubrication techniques in the "stable cutting design" to prevent cracks in the tool life and the work piece. The results showed that the lubrication modes can significantly affect the chatter stability limit and that the formation of chatter in the turning process creates destructive effect in terms of on tool portion rather than the lubrication. Sarikaya et al. [15] used nanofluids containing hBN, MoS_2, and graphene to study the

properties such as thermal conductivity, surface roughness, tool wear, viscosity, cutting temperature and microhardness in the machining of Haynes 25 superalloy. The study also includes different techniques such as ANN, ANFIS, and GP for modeling and optimization of the machining process. It was observed that graphene nanofluid was most effective in improving the machining performance, followed by hBN and MoS_2. Garcia-Martinez et al. [16] studied the impact of Cu-Ni 70/30 in the turning of ASTM B122 alloy under different cooling conditions using FEM simulation methodology and Hollomon function as the material behaviour model to determine the cutting force. According to results, the low initial lubrication (LIL) is a viable alternative to traditional lubrication approaches, as it leads to lower tangential force compared to dry cutting and flood lubrication. The LIL serves as an excellent lubrication in terms of economical and reduced environmental pollution. Moreover, the feed and depth of cut are the influential parameters affecting the cutting force. Hegab et al. [17] used MQL nanofluids and compared the cutting process performance under MQL and MQL nanofluid and found that the addition of 4 wt.% of MWCNTs (multi-walled carbon nanotubes) decreased flank wear to 45.6% while comparing MQL, and that the inclusion of 4 wt.% of Al_2O_3 (aluminum oxide) improves tool wear to 37.2% while machining Inconel 718. The study was proposed using ANN, ANFIS and GP methodology to design, analyse and optimize the performance of hard alloys. Elsheikh et al. [18] investigated the impact of nano-MQL using rice bran vegetable oil and nanoparticles Al_2O_3 and CuO on the turning of AISI 4340 alloy under an integrated AI model using vector functional link. The results confirmed that the use of CuO/oil nanofluid reduced tool wear and improved thermal conductivity while comparing Al_2O_3/oil NF based on its physical characteristics. The surface roughness and tool wear increased with excess feed and cutting speed, and decreased with excess cutting depth and a high R^2 value of 0.961-0.998 was obtained for all predicted responses using the developed model. Saleem et al. [19] compared lubrication performance of LQL under sunflower oil (SO), castor oil (CO) with dry mode during turning Inconel 718. The results disclosed that a significant decrease in tool wear of 26% and surface roughness of 52% was observed with LQLSO among other conditions. Also, SEM analysis clearly demonstrates that less adherence of material were noticed with SO conditions.

From the prior work, it was noticed that MQL minimizes the environmental impact significantly by reducing the usage of cutting fluid and eliminating the need of treatment and disposal. These benefits of near-dry machining are multiplied further while using of 100% biodegradable lubricants. Generally fluids like ethylene glycol, water, air etc are chosen as medium to eradicate heat in areas such as chemical, power generation and automobile sectors. But, their ability to transmit heat is restricted due to their poor heat transfer rate. Further, previous research articles indicate that thermal conductivity of ethylene glycol can be enhanced by dispersing copper as nano suspensions. Considering these facts along

with the benefits of MQL, it becomes obvious that this is the future of metal cutting fluid. Still, only limited research works were described in turning with copper nanoparticles. Hence, the innovation in the work lies in turning M2 steel with MQL using copper as nanofluid. Hence, a copper nano-particles based nanofluid was developed and the effectiveness in producing surface quality and minimizing the flank wear were analyzed. The main objectives of the present work is to (i) analyze the performance of copper as nanofluids with MQL on enhance the surface quality (ii) Also, the front and back surface of the chips are discussed in detail (iii) Lastly, the performance of nanofluids along with conditions like dry and oil to and improve the life of the tool and mechanisms of tool failure were examined.

2. Experimental Work

2.1 Experimentation

The layout the MQL System is shown in Figure 1. The MQL system comprises a tank, pump, control valve, pressure regulator, mixing chamber, compressor, and nozzle. The coolant conveyed to the blending chamber from tank. The measure of liquid conveyed to the slicing territory is confined through the control valve. The volume of the air is exactly measured through control valve. The packed air is coordinated into blending chamber and the coolant from the pipe blended with air in the blending chamber. At last, the mixture from the blending chamber is directed in the machining zone through a nozzle.

2.2 Nanofluid Preparation

Usually copper has got good thermal conductivity which enables them to put into use in automobile areas to eliminate heat. However, from the literature it was noticed that copper as nanofluids were rarely preferred as coolant in machining areas. Hence, the authors were inspired to use copper nanoplatelets as lubricant. The copper nanoparticle of size 60nm is chosen for arrangement of nanofluid and ethylene glycol as base liquid of 250ml is included with 1gram of copper as nanoparticles. The copper nanoparticles with ethylene glycol are kept in sonicator (Figure 2) for 45 min and subjected to magnetic stirrer for 60 min and the nanofluid was prepared. The steadiness of the nanofluids was elaborated under section 3.3.

2.3 Equipment Preferred

The performance of turning process is characterized by surface roughness, tool wear and chip morphology. The surface roughness (Ra) was resolved at 3 better spot on the work samples using Surfcorder SE3500 with cut off length 0.8mm, and the average values were recorded. The tool wear was

examined utilizing a Nikon estimating magnifying tool. The chip morphology was assessed with scanning electron microscopy of make Hitachi S-3400N to view the chips created under different environment.

2.4 Machine Details and Work piece used

The experiments were performed on a super jobber CNC machine as shown in Figure 3. The work material considered was M2 steel with diameter 20mm and length 100mm. The chemical composition were C = 0.87%, Si = 0.31%, Mn = 0.31%, P = 0.02%, Cr = 4.25%, Mo = 4.85%, V = 1.9% and W = 6.2%. The M2 steel has excellent toughness generally preferred in the manufacturing tool holders, forging dies and shear blades. The machining parameters are shown in Table 1.

3 Properties of fluids

3.1. Analysis of wetting angle

The time necessary for vaporization in the cooling system were analysed by the thickness and wetting angle of the fluids with the interaction of the surface. The wetting angle (θ) of the oil and the nanofluid was calculated through Kruss GMBH (Model: DSA25B) as shown in Figure 4. Generally, for a fluid to be competent, low wetting angle is necessary. The average wetting angle observed for the oil was 38.4° and for nanofluid was 27.3°. Since, nanofluid wetting angle < oil, it helps in reducing the temperature at the machining zone.

3.2 Thermal Conductivity Measurement

The thermal conductivity of the ethylene glycol based copper nanofluids prepared is examined using KD2 Pro thermal analyser (Make: Decagon Devices, USA) as shown in Figure 5a. The measurements were taken in the room temperature of 25°C in low mode power with time period of 120 seconds. Figure 5b shows that increase in temperature pave way to decline in the heat transfer rate. The reason behind this with high temperature the gap among the intermolecular rise up due to which the transfer of momentum reduces, hence a decrease in conductivity is observed.

3.3 Stability Test

The stability of the nanofluid prepared was physically observed through sedimentation technique. The images of the samples prepared at various stages were illustrated in Figure 6. If the fluid concentration remains steady with time, thus it is found to be a firm nanofluid. It was noticed that after a span of 14 days there were no settlement of the nano particle at the bottom of the beaker which is a clear indication that the prepared samples was found to be steady.

Also, the steadiness of the nanofluid is based on the ultra-sonication. Rise in the time of sonication improve the firmness of the fluid due to gathering of nanoparticles developed were minimized through increase in sonication time and the deposit of nanoparticles at the end of the container were also minimized. More nanoparticles were observed for period of 600 seconds. For a period of 3000 seconds after 14 days it was found that the prepared nanofluid was stable as shown in Figure 7.

3.4 pH examination

Analyzing the pH play an important role because more amount of nanoparticle to base fluids pave way to rise or decrease the value of pH. EQ-614 pH meter of Equiptronics- INDIA were used. Practically for the nanofluid to be stable the pH value should be in the range 8-12.5. The measured value for the sample was within the range (Figure 8), suggesting the nanoparticles were uniformly dispersed with the base fluid.

3.5 Analysis of Uncertainty

Uncertainty examination is carried out to authorize the correctness of the experimental trials performed. Errors due to uncertainties observed in the basic physical values into derived value were measured [20]. Each value was measured thrice for the responses and the average readings were noted. Also, the device preferred for measurements are selected in such a way that the uncertainties lie within a minimum range. The % of uncertainty was determined by the equation 1 and the uncertainty of the roughness and flank wear are depicted in Table 2 and 3 respectively.

$$S^2(q_k) = \frac{1}{(n-1)} \sum_{j=1}^{n} \left(\left(q_j - q \right)^2 \right) \quad (1)$$

n – Number of observation

q_k – Single observation

q– Arithmetic Average of observation

s – Standard deviation

q_i – Independent repeated observation

4. Results and Discussions

4.1 Assessment on surface roughness under varying environmental conditions

Figure 9 demonstrates surface roughness values were reduced with raise in cutting speed on varying environmental conditions such as dry, oil and nanofluids. In dry environment, there is excessive tension between tool and work material due to lack of lubrication [21]. These factors increase the

unevenness of the work surface, hence an increase in surface roughness is observed when compared with oil environment and nanofluid as environment. Figure 10a shows the surface roughness profile obtained through dry environment for cutting speed of 70m/min which has uneven profile, hence paves way in increasing the roughness values to 3.75 µm. Also, the minimum surface roughness (Figure 10b) profile obtained for cutting speed of 190 m/min shows that a decrease in roughness values (2.13 µm) obtained with increase in cutting speed. From Figure 9 it shows that surface roughness was decreased by 43% when cutting speed raised from 70 m/min to 190 m/min under dry environment.

Compared to the dry environment, machining with oil under MQL environment was found to reduce the surface roughness as shown in Figure 9. This can be due to the oil penetrating the work-tool interface providing excellent lubrication. Further, oil also continuously carries away heat from the machining zone [22]. The maximum surface roughness values obtained for cutting speed of 70 m/min were 1.70 µm as shown in Figure 11a. The minimum roughness value obtained with cutting speed of 190 m/min = 0.94 µm as shown in Figure 11b. It was noticed that maximum surface roughness value were decreased by 55% with oil environment when compared with dry environment. The nanoparticles in a base fluid establish a continuous film [23]. Owing to their enhanced thermal conductivity, nanofluids remove a large portion of heat from the machining zone [24]. Copper nanofluid with its surpassing heat transfer capabilities helps in maintaining the machining zone at a uniform low temperature. Thus, a reduction in surface roughness value is attained compared to oil environment and with dry environment. The surface roughness profile for cutting speed of 70 m/min (Figure 12a) attained were 0.81µm and surface roughness profile with cutting speed of 190 m/min were 0.45 µm as shown in Figure 12b. Hence, it was noticed that copper as nanofluids decreased the maximum surface roughness value by 78% with dry environment and 52% with oil environment.

4.2 Assessment on tool wear under varying environmental conditions

The important wear that governs the useful life of the tool is the collapse of the cutting edge known as flank wear. Additionally, it boosts the surface roughness, cutting forces and additional problems. Owing to the continuous cutting nature of the turning process, there is a continuous erosion of the cutting edge leading to accelerated flank wear. The flank wear for varying environment on cutting speed is shown in Figure 13. From the graph, increase in cutting speed result in raising the temperature, hence an increase in flank face was observed. The flank wear is increased by 64% when cutting speed is rise from 70 - 190 m/min as shown in Figure 13. In dry environment, due to absence of the lubrication, continuous friction between turned samples and tool helps in flank wear as shown in Figure 14a.

With oil environment, flank wear (Figure 13) were reduced by 67% in assessment to dry environment. With oil environment, a protective layer is created between tool- work interface [25]. Further, oil penetrates deeper in to the machining zone. These conditions favour in minimizing the temperature. Hence, by maintaining a low cutting temperature a reduction in flank wear (Figure 14b) attained compared to dry environment.

Machining with nanofluid reduced the wear on the flank face by 76% compared with dry environment and 28% with oil as environment as shown in Figure 13. Nano fluid enhances the heat transfer capability. Also copper with its better thermal conductivity and mobility, improves the conduction as well as the convection attributes of the cutting fluid. Thus, the tool wear (Figure 14c) were minimized when compared with other environments.

4.3 Assessment on chip morphology under varying environmental conditions

SEM images of chip profile under dry environment are shown in Figure 15a. The lack of lubrication leads to the development of heavy teeth, resulting in friction and massive cutting operations at the machining zone. This leads to formation of large serrated tooth. High temperature obtained in shear area which ends in thick lamella shape as depicted in Figure 15b. In case of oil environment, the images (Figure 15c) shows a smaller tooth compared to dry condition. The oil penetrates partially into the machining zone thereby reducing the friction. Henceforth, an even movement of chips is created causing a reduction in formation of serrated tooth. Further, thin lamella profile attained when compared with dry condition (Figure 15d) due to defensive layer provided through oil with MQL. With nanofluids, a low surface tension and contact angle is attained resulting in cushioning effect, hence a reduction in friction is noticed at the shear zone. Finally, a low serrated tooth (Figure 15e) with very thin lamella contour (Figure 15f) is generated compared to oil and dry environment.

5 Conclusions

In this work, experimental trials have been made in turning M2 steel to analyse the effect under dry, oil MQL and nanofluid MQL (NFMQL) on surface roughness and flank wear. The following conclusions were obtained:

1. In comparison to dry and oil environment, NFMQL shows good machining performance in terms of surface roughness, wear on flank face and reducing the saw-tooth developed.
2. In terms of surface roughness (Ra), the lowest value of 0.45 µm were noticed for NFMQL, 0.94 µm for oil MQL and 2.13 µm for dry environment. Hence, NFMQL outstandingly 78% and 52% lower than that attained with dry and oil MQL environment at cutting speed (Vc) of 190 m/min.

3. Further, it was noticed that average reduction in roughness value of 79 % and 58% with NFMQL among dry and oil MQL modes.

4. Copper nanoparticles have the ability to penetrate into the machining areas leading to excellent lubrication, hence a decrease in roughness is observed.

5. Also, with Vc as 190 m/min under NFMQL mode the lowest flank wear recorded (0.04 mm) and the highest wear attained was 0.168 mm with dry mode at Vc =190 m/min. Thus it is a clear indication NFMQL has surpassing heat transfer capability and also provides excellent lubrication.

6. It was observed that average decrease in flank wear with the use of copper nanofluid is 68% and 25% in comparison with dry and oil MQL modes.

7. With the use of nanofluid, it is observed from the SEM images that the chips with minimal teeth have been generated. Also, the nano fluids under MQL conditions ensured continuous and smooth flow of chips during machining.

Therefore, the use copper nanofluid under MQL conditions for turning of M2 steel greatly reduced surface roughness, flank wear and improved flow of smooth and continuous chips; which are most suited for better manufacturing with minimal production cost.

Nomenclature

NFMQL	Nanofluid minimum quantity lubrication
f	Feed (mm/rev)
V_c	Cutting speed (m/min) (OA)
OA	orthogonal array
RBO	Rice Bran oil
SEM	Scanning Electron Microscope
Ra	Average surface roughness
µm	Microns
CNC	Computer numerical control
Al_2O_3	Aluminium oxide
MoS_2	Molybdenum disulfide
MRR	Material removal rate
Zno	Zinc oxide
AISI	American Iron steel Institute
CuO	Copper oxide

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References

1. Naresh Babu, M., Anandan, V., Parthasarathi, N.L., et al. "Performance analysis in turning of D3 tool steel using silver nanoplatelets as additives under MQL", *J Braz. Soc. Mech. Sci. Eng*., **44**, p. 591 (2022).

2. Wang, X., Li, C., Zhang, Y., et al. "Influence of texture shape and arrangement on nanofluid minimum quantity lubrication turning", *Int. J. Adv. Manuf. Technol*.,**119**, pp. 631–646 (2022).

3. Chen, M., Peng, R., Zhao, L., et al. "Effects of minimum quantity lubrication strategy with internal cooling tool on machining performance in turning of nickel‐based superalloy GH4169", *Int. J. Adv. Manuf. Technol*., **118**, pp. 3673–3689 (2022).

4. Zhang, G., Chen, B., Wu, G., et al. "Experimental assessment of textured tools with nano-lubricants in orthogonal cutting of titanium alloy", *J. Mech. Sci. Technol.*, **36** (5), pp. 2489-2497 (2022).

5. Makhesana, M.A., Patel, K.M., Krolczyk, G.M., et al. "Influence of MoS_2 and graphite-reinforced nanofluid-MQL on surface roughness, tool wear, cutting temperature and microhardness in machining of Inconel 625", *CIRP. J. Manuf. Sci. Technol.*, **41**, pp. 225-238 (2023).

6. Ibrahim, A.M.M., Omer, M.A.E., Das, S.R., et al. "Evaluating the effect of minimum quantity lubrication during hard turning of AISI D3 steel using vegetable oil enriched with nano-additives", *Alexandria. Eng. J*., **61**(12), pp. 10925-10938 (2022).

7. Pal, A., Chatha, S.S., and Sidhu, H.S. "Assessing the lubrication performance of various vegetable oil-based nano-cutting fluids via eco-friendly MQL technique in drilling of AISI 321 stainless steel", *J. Braz. Soc. Mech. Sci. Eng*., **44**, p.148 (2022).

8. Wang, R., Wang, X., Yan, P., et al. "The effects of cryogenic cooling on tool wear and chip morphology in turning of tantalum-tungsten alloys Ta-2.5W", *J. Manuf. Process.*, **86**, pp. 152-162 (2023).

9. Liu, F., Wu, X., Xia, Y. et al. "A novel cold air electrostatic minimum quantity lubrication (CAEMQL) technique for the machining of titanium alloys Ti–6Al–4 V", *Int. J. Adv. Manuf. Technol.*, (2023).

10. Dash, L., Padhan, S., Das, A., et al. "Machinability investigation and sustainability assessment in hard turning of AISI D3 steel with coated carbide tool under nanofluid minimum quantity lubrication-cooling condition", *Proc I Mech E Part C: J Mechanical Engineering Science*., **235** (22), pp. 6496-6528 (2021).

M.Santhanakumar, Department of Industrial Engineering, Anna University, Chennai-25, INDIA

11. Sateesh, N., Ram Subbiah., Nookaraju, BCh., et al. “Analysis on effect of nanofluid on process parameters in machining of EN19 steel”, *Advances in Materials and Processing Technologies*., **8**, pp. 1757-1767 (2022).

12. Gupta, M.K., Boy, M., Korkmaz, M.E., et al. “Measurement and analysis of machining induced tribological characteristics in dual jet minimum quantity lubrication assisted turning of duplex stainless steel”, *Measurement*., **187**, p.110353 (2022).

13. Maruda, R.W., Wojciechowski, S., Szczotkarz, N., et al. “Metrological analysis of surface quality aspects in minimum quantity cooling lubrication”, *Measurement*., **171**, p.108847 (2021).

14. Emami, M., and Karimipour, A. “Theoretical and experimental study of the chatter vibration in wet and MQL machining conditions in turning process”. *Prec. Eng*., **72**, pp. 41–58 (2021).

15. Sarikaya, M., Sirin, S., Yildirim, C.V., et al. “Performance evaluation of whisker-reinforced ceramic tools under nano-sized solid lubricants assisted MQL turning of Co-based Haynes 25 superalloy”, *Cer. Int*., **47**, pp. 15542–15560 (2021).

16. Garcia-Martinez, E., Miguel, V., Manjabacas, M.C., et al. “Low initial lubrication procedure in the machining of copper-nickel 70/30 ASTM B122 alloy”, *J. Manuf. Proc*., **62**, pp. 623–631 (2021).

17. Hegab, H., Salem, A., Rahnamayan, S., et al. “Analysis, modeling, and multi-objective optimization of machining Inconel 718 with nano-additives based minimum quantity coolant”, *App. Soft. Comp. J*., **108,** p.107416 (2021).

18. Elsheikh, A.H., Elaziz, M.A., Das, S.R., et al. “A new optimized predictive model based on political optimizer for eco-friendly MQL-turning of AISI 4340 alloy with nano-lubricants”, *J. Manuf Proc*., **67**, pp. 562–578 (2021).

19. Saleem, M.Q., and Mehmood, A. “Eco-friendly precision turning of superalloy Inconel 718 using MQL based vegetable oils: Tool wear and surface integrity evaluation”, *J. Manuf. Proc*., **73**, pp. 112–127 (2022).

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20. Ashok, B., Raj, R.T.K., Nanthagopal, K., et al. “Lemon peel oil–A novel renewable alternative energy source for diesel engine”, *Energy Conversion and Management*., **139**, pp. 110–121 (2017).

21. Khandekar, S., Ravi Sankar, M., Agnihotri, V., et al. “Nano-cutting fluid for enhancement of metal cutting performance”, *Mat and Manuf Proc*., **27**, pp. 963–967 (2012).

22. Ganesan, K., NareshBabu, M., Santhanakumar, M., et al. “Experimental investigation of copper nanofluid based minimum quantity lubrication in turning of H 11 steel”, *J Braz. Soc. Mech. Sci. Eng*., **40**, p.160 (2018).

23. Naresh Babu, M., and Muthukrishnan, N. “Experimental analysis in drilling of AA 5052 using copper nanofluids under minimum quantity lubrication”, *Aust. J. Mech. Eng*., **18** (1), pp. 515-524 (2018).

24. Manimaran, R., Palaniradja, K., Alagumurthi, N., et al. “Preparation and Characterization of Copper Oxide Nanofluid for Heat Transfer Applications”, *App Nanosci*., **4**, pp. 163–167 (2014).

25. Padmini, R., VamsiKrishna, P., and Krishna Mohana Rao, G. “Effectiveness of Vegetable Oil Based Nanofluids as Potential Cutting Fluids in Turning AISI 1040 Steel”, *Trib Int*., **94**, pp. 490–501 (2016).

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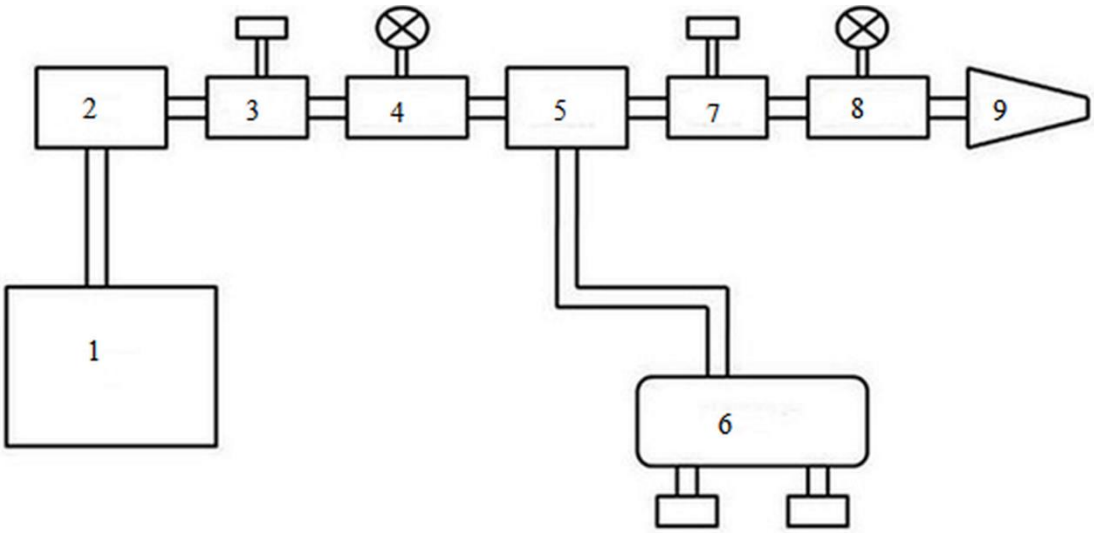

Figure 1. Plan of MQL system (1) Tank, (2) Pump, (3) Control valve (4) Pressure regulator (5) Blending chamber (6) Compressor (7) Control valve (8) Pressure regulator (9) Nozzle.

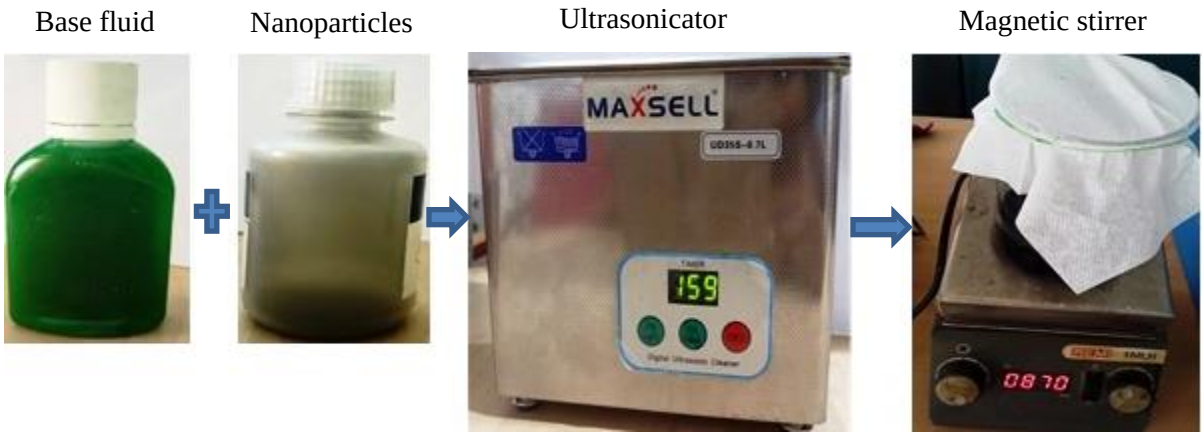

Figure 2. Nanofluid preparation

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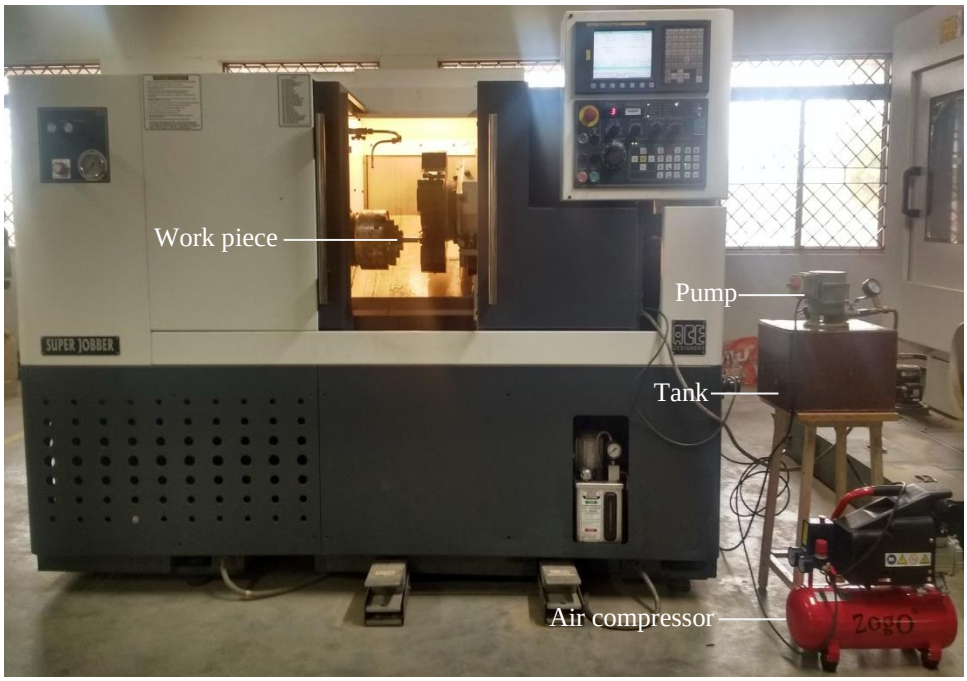


Figure 3. Super Jobber CNC Lathe Machine

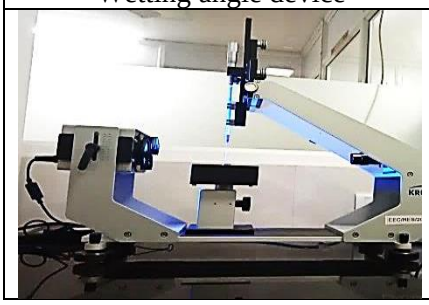
Wetting angle device	Oil	Nanofluid
		

Figure 4. Wetting angle measurement

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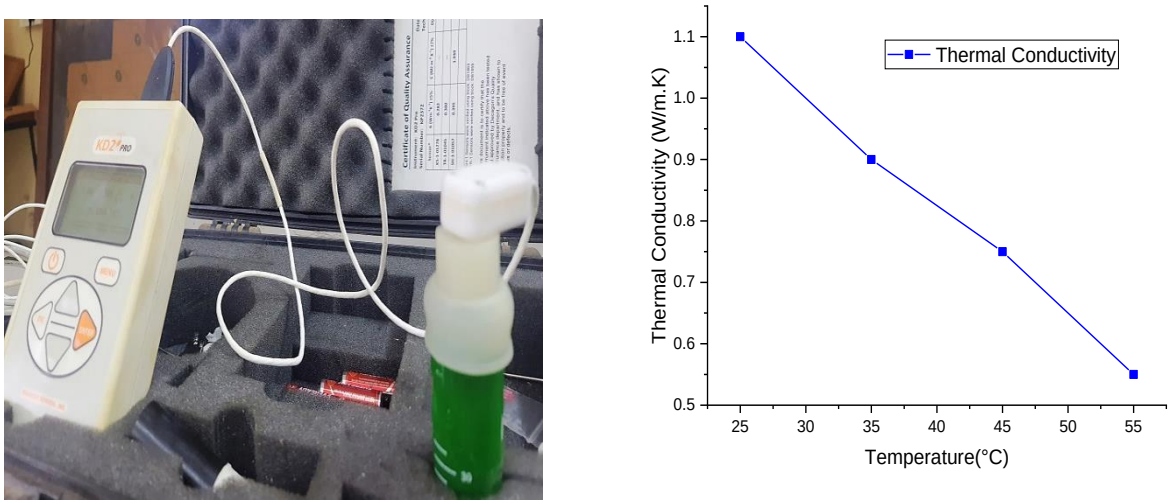


Figure 5. (a) KD2 Pro thermal analyser **(b)** Thermal conductivity of nanofluids

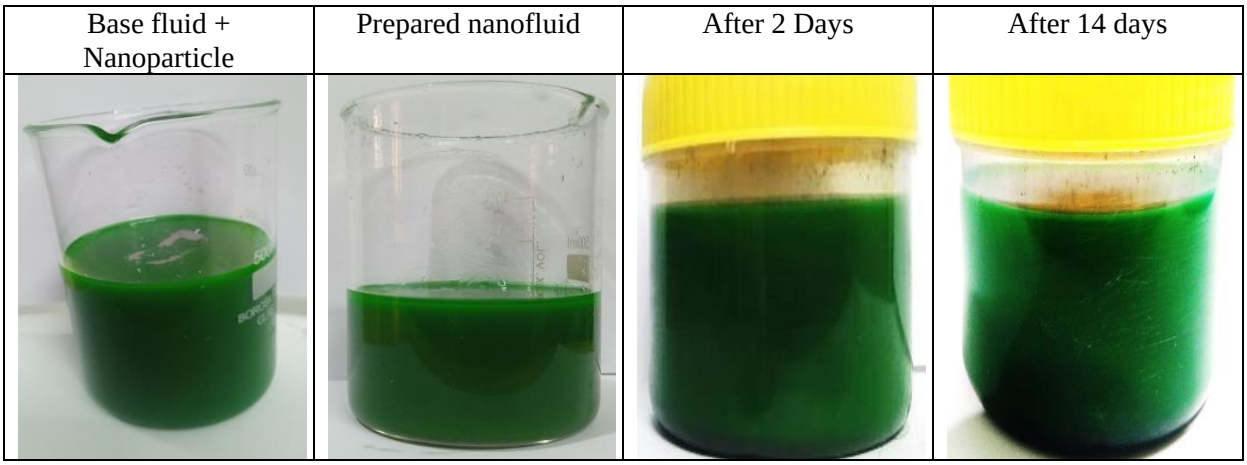
Base fluid + Nanoparticle	Prepared nanofluid	After 2 Days	After 14 days
			

Figure 6. Nanofluid stability pictures

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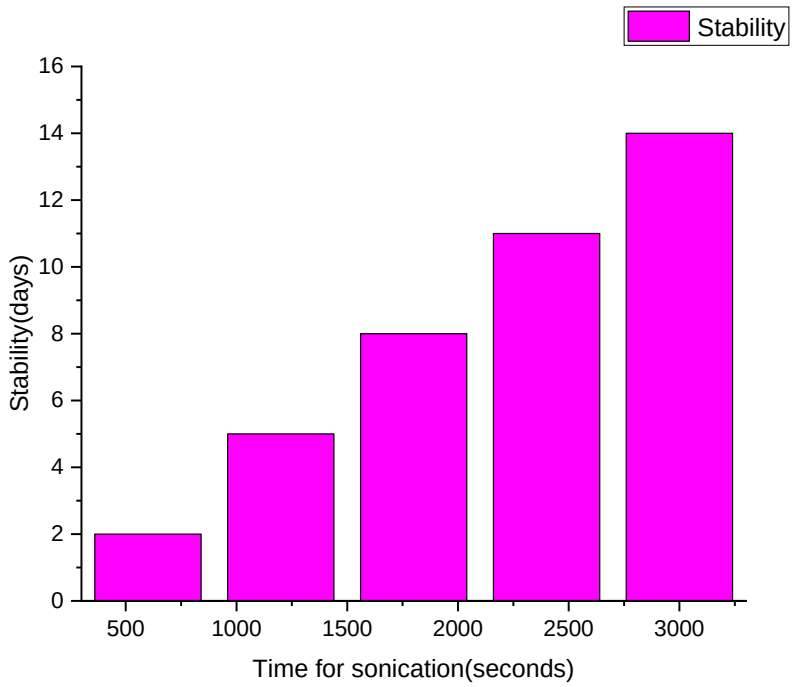


Figure 7. Stability Vs time for sonication

Figure 8. Digital pH meter

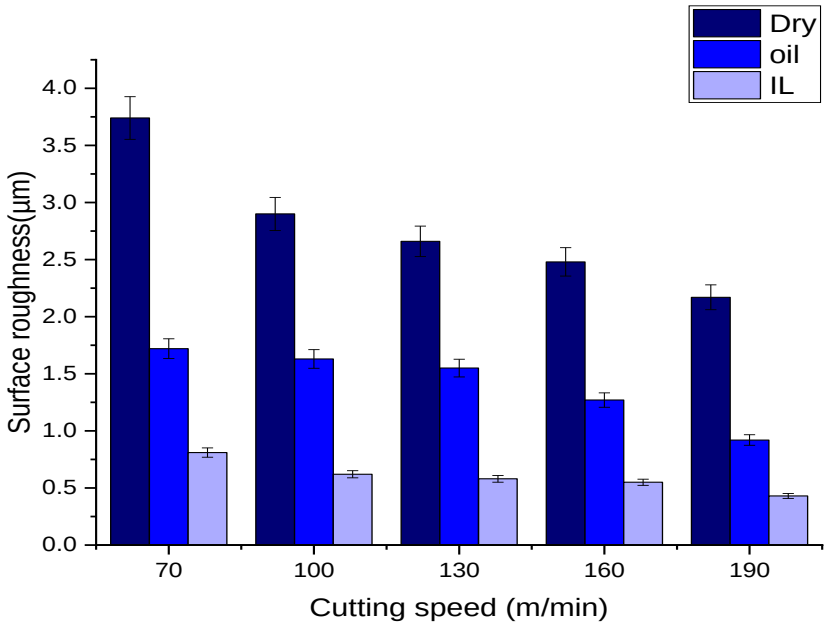


Figure 9. Variation of Ra with cutting speed on varying environments (error bars show the measurement uncertainty)

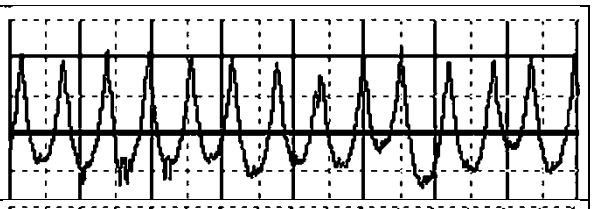
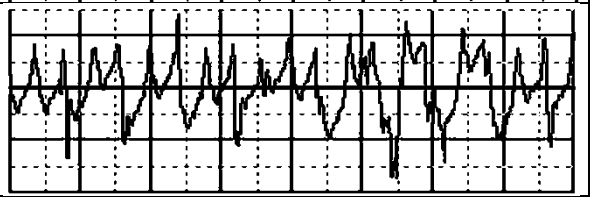
(a) Cutting Speed (Vc) = 70m/min	
(b) Cutting Speed (Vc) = 190m/min	

Figure 10. Surface roughness profile for dry environment

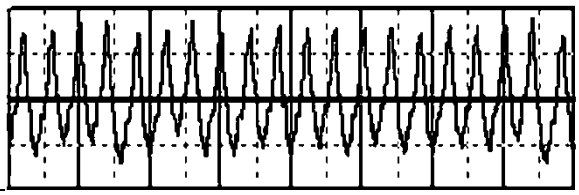
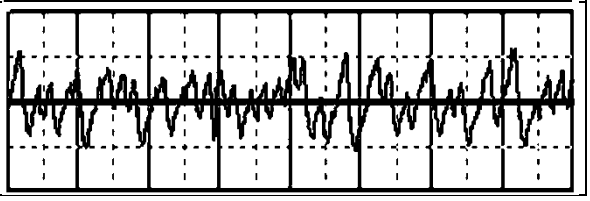
(a) Cutting Speed (Vc) = 70m/min	
(b) Cutting Speed (Vc) = 190m/min	

Figure 11. Surface roughness profile for oil environment

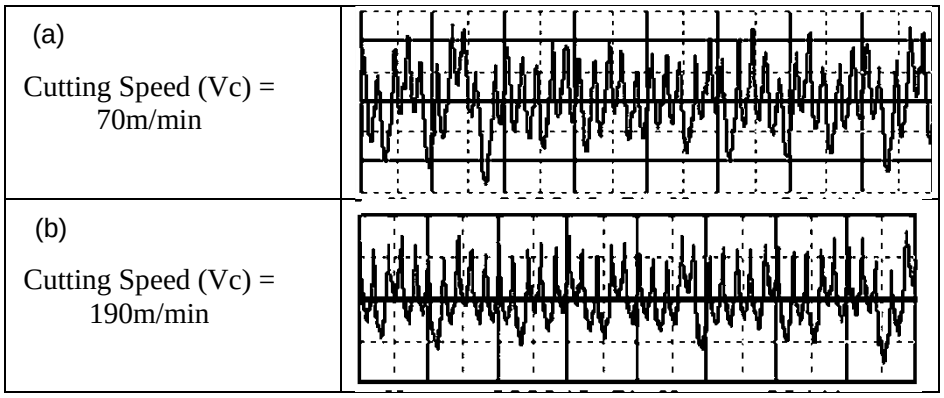


Figure 12. Surface roughness profile for Nanofluid environment

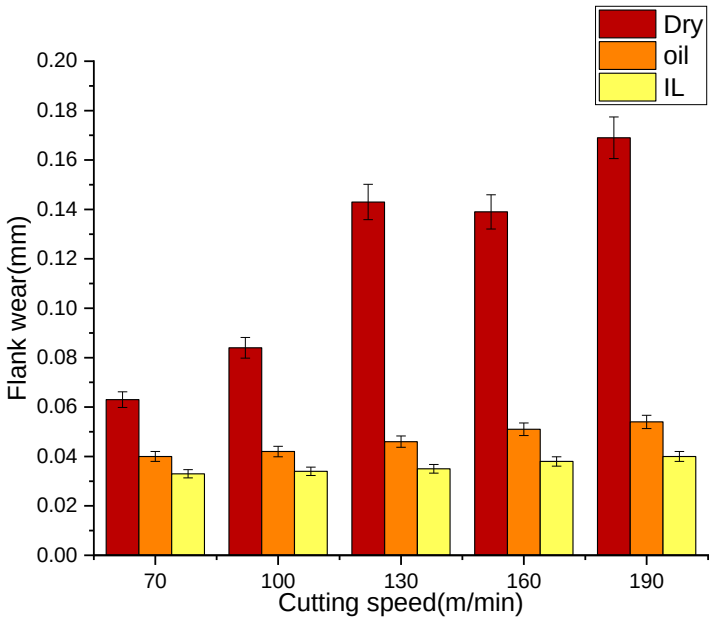


Figure 13. Variations of flank wear with Vc on different environments (error bars show the measurement uncertainty)

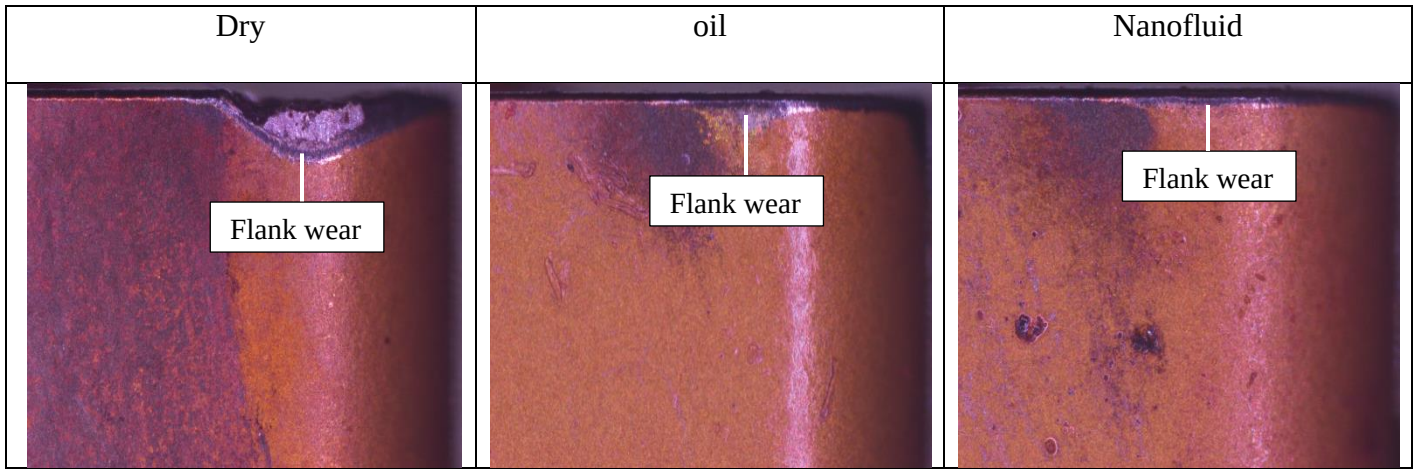


Figure 14. Images of Tool wear under (a) Dry environment, (b) oil Environment (c) Nanofluid Environment

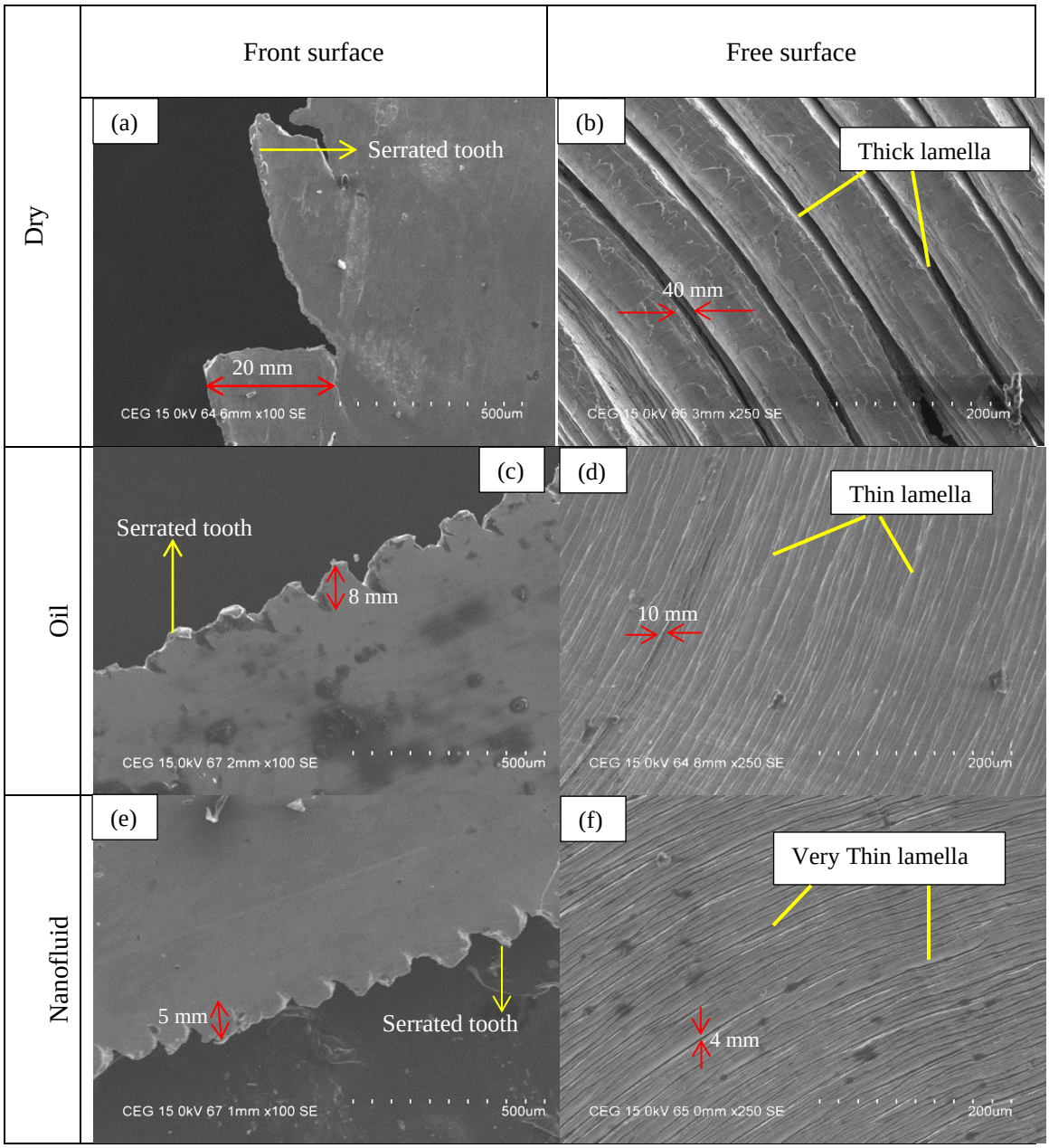


Figure 15. SEM image of chips

Table 1. Machining values

Tool holder	PCLNL 2525M 12
Cutting tool (insert)	Carbide
MQL Flow rate	9 ml/min
Air pressure	2 bar
Cutting tool (insert) shape	C
Oil used	gingerly oil
Cutting speed	70,100,130,160,190 m/min
Feed	0.1 mm/rev
Environment	Dry, oil and Nano fluid
Depth of cut	0.2 mm

Table 2. Uncertainty values for Ra

Trial Number	**Condition**	**Surface Roughness (Ra) µm**			**Average values (Ra) µm**	**Uncertainty**
		R1	R2	R3		
1	Dry	3.73	3.74	3.72	3.74	3.74±0.008
2		3	2.8	2.9	2.9	2.9±0.005
3		2.8	2.6	2.6	2.66	2.66±0.004
4		2.54	2.4	2.51	2.48	2.48±0.007
5		2.13	2.18	2.2	2.17	2.17±0.003
6	oil	1.7	1.65	1.81	1.72	1.72±0.002
7		1.62	1.56	1.71	1.63	1.63±0.004
8		1.57	1.4	1.68	1.55	1.55±0.005
9		1.32	1.27	1.24	1.27	1.27±0.001
10		0.94	0.85	0.97	0.92	0.92±0.002
11	Nanofluid	0.81	0.75	0.88	0.81	0.81±0.004
12		0.62	0.54	0.71	0.62	0.62±0.001
13		0.58	0.55	0.62	0.58	0.58±0.003
14		0.51	0.6	0.54	0.55	0.55±0.003
15		0.45	0.47	0.38	0.43	0.43±0.002

Table 3. Uncertainty values for Flank wear

Trial Number	Condition	Flank wear (mm)			Average values (mm)	Uncertainty
		R1	R2	R3		
1	Dry	0.06	0.062	0.068	0.063	0.063±0.07
2		0.081	0.087	0.084	0.084	0.084±0.01
3		0.12	0.15	0.16	0.143	0.143±0.04
4		0.139	0.141	0.138	0.139	0.139±0.09
5		0.168	0.169	0.171	0.169	0.169±0.02
6	oil	0.041	0.039	0.042	0.04	0.04±0.01
7		0.044	0.041	0.043	0.042	0.042±0.03
8		0.047	0.045	0.046	0.046	0.046±0.02
9		0.052	0.050	0.051	0.051	0.051±0.05
10		0.055	0.053	0.056	0.054	0.054±0.04
11	Nanofluid	0.031	0.033	0.035	0.033	0.033±0.01
12		0.035	0.037	0.032	0.034	0.034±0.05
13		0.036	0.035	0.036	0.035	0.035±0.06
14		0.038	0.037	0.039	0.038	0.038±0.09
15		0.04	0.038	0.042	0.04	0.04±0.08

Biographies

Ganesan received his BE degree from Anna University- Chennai, India in 2009, ME degree from Anna University- Chennai, India in 2012. He is currently pursuing PhD from Anna University- Chennai, India. He is also an Assistant Professor in the department of Mechanical Engineering at Jaya Engineering College-Chennai, India and has 12 years of teaching experience. His current research interests include nanofluids, machining and Optimization techniques.

Naresh Babu obtained B.E. in Mechanical Engineering from Bangalore University, India and received his MTech in Production Engineering from MS University, Tirunelveli in 2002. He received his PhD in Mechanical Engineering from the Anna University Chennai, India in 2015. He has 20 years of experience in teaching. He had led various research projects and published 25 research articles in peer reviewed journals. His research interests include unconventional machining process, optimisation and minimum quantity lubrication using nanofluids.

Gurusamy obtained B.E. in Mechanical Engineering in the year 1996, ME in Production Engineering in 1999. He received his PhD in Mechanical Engineering from the Anna University Chennai, India in 2014. He has 23 years of experience in teaching. He had published 53 research articles in peer reviewed journals. His research interests include composites, nanomaterials, squeeze casting and additive manufacturing.

Santhanakumar has completed his BE in Mechanical Engineering at Dr.Sivanthi Aditanar College of Engineering, Tiruchendur, Anna University,India in the year 2005 and ME in Industrial Engineering, College of Engineering Guindy, Anna University, Chennai, Tamilnadu, India in 2008. He has completed his PhD in the Department of Industrial Engineering, College of Engineering Guindy, Anna University, Chennai, Tamilnadu, India in 2018. He has 15 years of teaching/research experience in handling core Mechanical and Industrial Engineering subjects, and published more than 48 research articles in reputed international journals; 28 article in various conferences. He is expertise the areas such as Abrasive Machining Processes, Multi Response Optimisation and Operations Research.

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