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Regular Article

Performance comparison of vegetable oil based nanofluids towards machinability improvement in hard turning of HSLA steel using minimum quantity lubrication

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Abstract. The search of finding best vegetable oil based nanofluid from a set of three nanoparticle enriched cutting fluids for machining is core objective of the work. Extensive research has been done to replace conventional cutting fluids by nanofluids, but abundant analysis for vegetable oil based nanofluids is accomplished in this work which was not seen earlier. Also, the study investigated the cutting performance and comparative assessment towards machinability improvement during hard turning of high-strength-low-alloy (HSLA) AISI 4340 steel using four different compositions of nanofluids by minimum quantity lubrication (MQL) technique. Cutting are investigated and analyzed through this article during hard turning using minimum quantity lubrication (MQL). Cutting force, tool wear (flank and crater), surface integrity (surface roughness, residual stress, microhardness, and surface morphology), and chip morphology are considered as technological performance characteristics to evaluate the machinability of hardened AISI 4340 steel. Additionally, the effect of various fluid properties like thermal conductivity, viscosity, surface tension and contact angle were examined for all nanofluids. Three set of nanofluid samples were prepared using Al_2O_3, CuO and Fe_2O_3 with rice bran oil and their various properties are analysed at 0.1% concentration. On comparison among these three nanofluids used, CuO nanofluid exhibited superior behavior followed by Fe_2O_3 nanofluids while Al_2O_3 nanofluid was last in the row.

Keywords: Nanofluids / machinability / hard turning / HSLA steel / MQL

1 Introduction

Necessity is the mother of invention and sense of incompleteness urges us to carry out the research work chasing perfection. The backbone of industrial world, manufacturing industry is becoming advanced with newer technologies. The aim to produce higher industrial grade finished products with economic price and without disturbing any ecological equilibrium. To remain competitive and grow in the domain of production industry, implicative researches are prominent need of the hour to be executed. This research presents machinability aspects examined during hard turning operation of AISI 4340 steel; popular for its strength and toughness. The focus of research work is cutting fluid, which is newer and makes the experimental investigation more authentic and protuberant. Nanofluid enriched with nanoparticles of Al_2O_3, Fe_2O_3 and CuO and rice bran oil (an eco-friendly vegetable oil) as base oil is used as cutting fluid with MQL technique to perform the machining operation. Various cutting fluid properties such as thermal conductivity, viscosity, surface tension and contact angle is analysed where from the result, some significant improvements are made that proves the nanofluid a finer and economic replacement of conventional cutting fluid. Machinability responses like cutting force, tool-chip contact length and surface integrity aspects as microhardness, chip morphology, machined surface morphology are scrutinized with utmost care to see the advancements in these parameters. The results furthermore are a mere proof of the fact that vegetable oil based nanofluid can outperform conventional cutting in every required aspect by abundant magnitude without harming the surrounding environment.

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2 Literature review

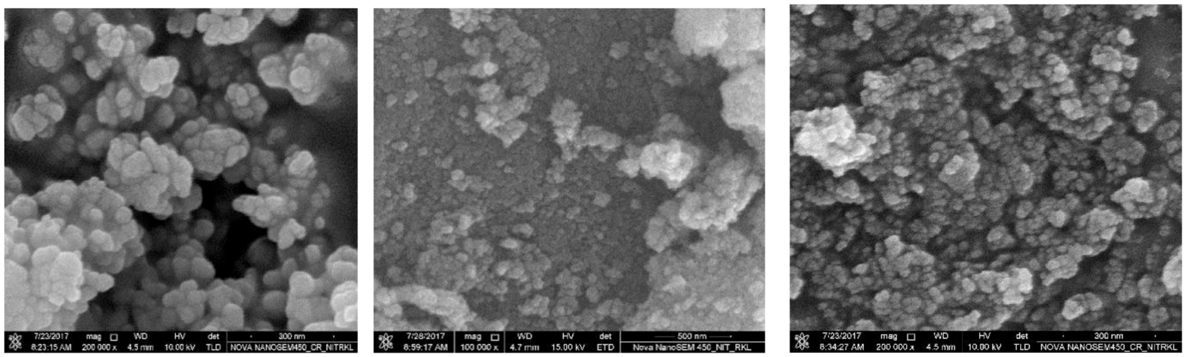
Roy and Ghosh [1] performed high speed turning operation on AISI 4140 steel with coated carbide inserts under different cutting environments to examine the tool tip temperature. From the experimental results, it was concluded that better cooling and heat absorbing capacity was observed in MQL with nanofluid compared to dry and flood cooling condition. Also tool tip temperature reduced by 10–30% in MQL machining with nanofluid compared to dry and flood cooling. Gajrani et al. [2] conducted the hard machining experiments with different cutting fluids and compared the results in terms of machining forces, tool life, friction and surface roughness. From the experimental outcomes, it was deduced that nanoparticles enriched green cutting fluid performed better than other fluids in terms of all machinability aspects.

Rajmohan et al. [3] proposed two types of cutting fluids for turning stainless steel. The experimental results revealed that cooling and lubricating property of cutting fluid were enhanced due to addition of nano-particle and feed was observed to be the most contributing parameter for cutting force. Sharma et al. [4] conducted hard turning experiments on AISI D2 steel specimen with carbide inserts under two types of cutting environments. Cutting temperature and surface roughness were observed in two cutting environments. From the experimental results it was divulged that minimum temperature and superior surface quality were attained with nanofluid compared to that with normal coolant. Turning operation was carried out on Ti-6Al-4T by Ali et al. [5] under various cutting environments. Surface roughness and tool wear were analysed. The results exhibited that nano lubricant with surfactant produced better results in terms of tool life and surface roughness compared to three other cutting environments. Gupta et al. [6] compared the performances of three nanofluids during turning Titanium alloy with CBN inserts. The experimental results revealed that speed, feed and cooling conditions were three significant factors for the responses. Approach angle was found less important for the responses. Surface quality was improved with graphite based nanofluid compared to other two nanofluids. Raja et al. [7] proposed a new coolant i.e. zinc oxide based nanofluid for turning of mild steel specimen. Cutting temperature and surface finish were measured as machining characteristics and compared under two different cutting environments. Better results were obtained with nanofluid than conventional cutting fluid. Paturi et al. [8] analysed the surface roughness of Inconel 718 during turning using MQL with WS_2 solid lubricant and with normal MQL mode. The result exhibited that better surface finish was observed with WS_2 solid lubricant assisted MQL than normal MQL. Sharma et al. [9] performed turning operation on AISI 1040 steel with dry, wet and MQL with conventional cutting fluid and Al_2O_3 based nanofluid. Four responses were chosen for the comparative assessment: cutting forces, tool wear, roughness and chip morphology. Better results were found for MQL with nanofluid. Machining performance of nickel based alloy under different cutting environments was performed by Chetan et al. [10]. Better results in terms of tool life, surface finish, chip characteristics and cutting forces were obtained with nanofluid machining. Excellent performance was observed for alumina based nanofluid between alumina and silver oxide nanofluids. Maruda et al. [11] investigated the effects of three cutting environments on chip formation zone during machining of AISI 316 stainless steel. From their investigation, it was found that coefficient of friction on the tool rake face and chip thickening coefficient were reduced but the sliding angle of chip was increased when machining with MQCL + EP/AW compared to other two cutting conditions. Moreover, effective shape of chips were produced with MQCL + EP/AW based cutting.

Various wettability characteristics of cutting fluid on tool surface were studied by Behera et al. [12] during turning of Inconel 718 with MQCL mode using coated and uncoated carbide inserts. From the results, it was observed that the spreading characteristics of nanofluid was directly proportional to the surface tension and was found to be very crucial. Out of five nanofluids, best wettability behaviour was observed for non-ionic surfactant based cutting fluid. Moreover, the chip curl radius, tool wear and coefficient of friction were reduced by using these nanofluids. Liew et al. [13] optimized the cutting condition during the turning of AISI D2 steel using nanofluid. The results showed that cutting speed was the significant parameter for tool wear and feed was the dominant parameter for surface roughness. Singh et al. [14] evaluated the performance of a hybrid nanofluid in hard turning. It was found that better results in terms of machining forces and surface roughness were observed for hybrid nanofluid in comparison to individual nanoparticle based fluids.

Patole and Kulkarni [15] optimized the cutting parameters during MQL turning 4340 steel with nanofluid. They observed that feed was the most important parameter for roughness and MQL with nanofluid produced better result in comparison to other three cutting conditions. Singh et al. [16] experimentally investigated the machinability characteristics of AISI 304 stainless steel under nano-lubrication using MQL technique. Various machining characteristics such as flank wear, cutting zone temperature and surface roughness were studied. From the experimental results, it was concluded that the flank wear was drastically reduced even at high speed and feed with the high concentration of nano particles. Also, both cutting temperature and surface roughness were declined with high concentration of nano particles. High speed, low feed and depth of cut were responsible for good surface finish whereas low speed, feed and depth of cut were responsible for low cutting zone temperature. Gupta and Sood [17] analyzed surface roughness in NFMQL assisted turning of titanium alloy. Two types of nanofluid were utilized: Al_2O_3 and MoS_2. The experimental results delineated that feed was the most effective parameters for Ra and Rq surface roughness parameters whereas speed was the most influential parameter for Rz.

Kumar et al. [18] studied various machinability aspects of hardened AISI D2 steel under environmentally conscious



(a) Copper oxide (b) Iron oxide (c) Aluminium oxide

Fig. 1. Molecular structures of three different nanoparticles.

spray impingement cooling. The results showed that good surface quality, better tool life and less cutting temperature were observed in spray impingement cooling environment. Hegab et al. [19] studied the effects of nano cutting fluids on cutting tool performance and chip morphology during turning of Inconel 718. Two types of nano additives were considered i.e. Al_2O_3 and MWCNT. The results showed that both the nano fluids performed better to the machining condition where no nano particles used. Out of two nano particles enriched cutting fluid, MWCNT enriched fluid performed better.

The influence of machining parameters on cutting force and tool wear was studied by Khalil et al. [20] during machining nickel based super alloy under MQL condition with nano lubricants and the results were compared with dry cutting conditions. Abrasion wear was the main wear mechanism for the tool wear. Out of two cutting conditions, MQL with nano lubricant performed better than dry cutting condition regarding both tool life and cutting force. Park et al. [21] analyzed the tool wear on both coated and uncoated tools during Inconel machining. Various cutting environments were selected i.e. dry, wet, MQL with nano lubricant and MQL without nano lubricant. Moreover, cryotreated inserts were also utilized in this study. From the experimental outcomes, it was deduced that tool wear was stable for cryotreated inserts. MQL and nano lubricant were found to be ineffective compared to dry and wet cutting condition. Gutnichenko et al. [22] studied the influence of graphite nanoparticles in vegetable oil during machining of alloy 718 with a cemented carbide tool. Tool wear, surface roughness, cutting force and vibration were analyzed and the results were compared with dry and plain MQL. Better results were obtained with nanofluid MQL compared to other two cutting environments.

From the literature review, it has been concluded that hard turning operation was accomplished with vegetable oil but not especially with rice bran oil, which has a comparatively higher thermal conductivity as base fluid for nanofluid preparation. Uncoated cermet is never found earlier as cutting tool in the available experimental investigations. Furthermore the use of Fe_2O_3 nanofluid was not found for turning operation as a cutting fluid with MQL. So the experimental work is highly recommended to be done to study the improvements in nanofluid properties like thermal conductivity, viscosity and enhancements in machinability responses such as force analysis, various surface integrity aspects, tool life, etc.

The present work focuses on finding a better alternative to replace conventional cutting fluid that is used for machining operation. Earlier investigations have revealed that vegetable oil based nanofluids have outperformed other conventional cutting fluids in terms of better heat dissipation, better tool life, less flank wear finer surface texture, etc. This experiment has rice bran oil enriched nanofluid with three nanoparticles Al_2O_3, Fe_2O_3 and CuO are compared using MQL with hard turning of AISI 4340 steel. Thus this present work is a sincere attempt to find out the best nanofluid and discuss its impact on various machining responses while hard turning operation using nanofluid.

3 Materials and methods

3.1 Nanofluids

Nanofluids have shown the emerging trend of being used for high performance applications and researches are searching newer areas of application because of its remarkable potential. Nanofluids are continuously proven as finer alternatives for cutting fluids in experimental investigations because of its superior heat transfer capability.

3.2 Nanoparticles

The nanoparticles are foremost ingredients to prepare nanofluid. They seems like powder but their FESEM analysis gives a better insight of them. Molecular structures of nanoparticles are pictured shown below in Figure 1.

Iron oxide (Fe_2O_3) nanoparticle is synthesised by using precipitation method, by blending ferrous chloride tetrahydrate and ferric chloride hexahydrate according to the previous REF paper. In order to get a homogeneous solution, 0.1 M of ferrous chloride tetrahydrate and 0.2 M of ferric chloride hexahydrate were added to 100 ml of deionized water and steered by using magnetic stirrer. The reaction mixture of the obtained solution was heated at 60 °C for 15 min using a water bath and 14 ml of 25%

Table 1. Chemical composition and physical properties of vegetable oil.

Chemical composition of vegetable oil		Physical property of vegetable oil	
Fatty acid	Percentage (%)	Character	Value
Myristic acid	0.6	Moisture	0.1–0.15%
Palmitic acid	21.5	Density (15°C)	0.913–0.920
Stearic acid	2.9	Refractive index	1.4672
Oleic acid (an Omega 9 fatty acid)	38.4	Saponification value	187
Linoleic acid (LA, an Omega 6 fatty acid)	34.4	Unsaponifiable matter	1.8–2.5
α-Linolenic acid (ALA, an Omega 3 fatty acid)	2.2	Oryzanol	1.5–1.8

sodium hydroxide was added to this solution. To get a pellet, the black precipitate which was formed upon completion of the reaction was centrifuged at 7000 rpm for 15 min. The pellet was dried at 60 °C after washing three times using deionized water, to get the desired iron oxide nanoparticle powder. The average size of the three nano particles were found less than 50 nm.

3.3 Vegetable oil

Vegetable oil is selected among all available conventional cutting oils because of several reasons. The foremost one is they are eco-friendly. Secondly vegetable oils are nearly perfect Newtonian fluids. After a lot of analysis and research, rice bran oil is found as most suitable base oil among a set of vegetable oils. Thermal conductivity of rice bran oil is highest among those vegetable oils such as avocado, canola, grape seed, olive, peanut, macadamia nut, rice bran, safflower, sesame, soybean, sunflower and walnut. From the literature review, it has been observed that mostly nanoparticles were intermixed with water, paraffin, alcohol but not vegetable oil with MQL especially for hard turning of an alloy steel. The chemical composition and physical properties of rice bran oil are shown in Table 1.

3.4 Nanofluids preparation

The two key ingredients required for formulation of nanofluid is a base oil and nanoparticles. For readiness of nano liquids, the nanoparticles (0.1% of aluminium oxide, copper oxide and iron oxides) were scattered in rice bran oil. In order to get the homogeneous dispersion of nanoparticles, the mixture was stirred using magnetic stirrer for about 45 min, where the high-frequency vibrations strike nanoparticles. The obtained solution was then sonicated for 2 h each utilizing an ultrasonic sonicator to get the desired nanofluids. After ultra-sonication, nanofluids are considered ready for using as cutting fluid for machining operation. Figure 2 shows the preparation of nanofluid to its application in hard turning of AISI 4340 steel. This flow diagram shows the various stages of nanofluid preparation. Figure 2a shows the mixture of base fluid (rice bran oil) and nanoparticle kept on magnetic stirrer. Figure 2b shows after mixing of nanoparticles in the base fluid they are kept in ultra sonicator where uniform colloidal solution is formed. Figure 2c is MQL setup that has a high pressure valve to convert cutting fluid to moistures. Figure 2d shows the hard turning operation that was carried out with prepared nanofluid in the place of conventional cutting fluid.

The iron oxide nanoparticles are characterized using field emission scanning electron microscope (FE-SEM). It is observed that nanoparticles are well dispersed and the size of nanoparticles range from 10 to 30 nm for iron oxide nanoparticles, as shown in Figure 3a. The size of both the copper oxide and aluminium oxide nanoparticles were less than 50 nm. To conform their size distribution and dispersion, both the nanoparticles are also characterized with FE-SEM, shown in Figure 3b and c. It was found that, both the nanoparticles are well dispersed and their size range from 35 to 45 nm for copper oxide nanoparticles and 21–34 nm for aluminium oxide nanoparticles. After the mixing of different nanoparticles in the base fluid, the solution was both stirred and sonicated to get the desired mixture. After sonication, the solution was kept under observation about 24 h and it was found there was no sedimentation of nanoparticles and nanoparticles are dispersed uniformly.

3.5 Work and tool material

Hard turning is chosen as it is one of the most primitive cutting operation in fabrication industry, AISI 4340 is considered as workpiece as they are extensively used for aircraft landing gears, automotive heavy shafts and popular for its strength and toughness. The chemical composition of AISI 4340 steel is presented in Table 2. Uncoated cermet inserts of square shape are used as cutting tool for this experimental analysis.

3.6 Design of experiment

Taguchi's orthogonal array is a scientifically proven mechanism that evaluates improvements in products, processes and services. Best parameters can be found for optimum result keeping numbers of analytical investigations minimal. The Taguchi method possesses enormous potential for low budget experimental analysis. Since nanofluid procurement, preparation and machining is costly, Taguchi L_{16} orthogonal array was selected for the machining activity to get the optimum results from a reduced set of experiments. For each cutting parameter four levels were considered shown in Table 3. Rough layers

Fig. 2. Flow diagram of nanofluid preparation to its application stage as cutting fluid in hard turning operation.

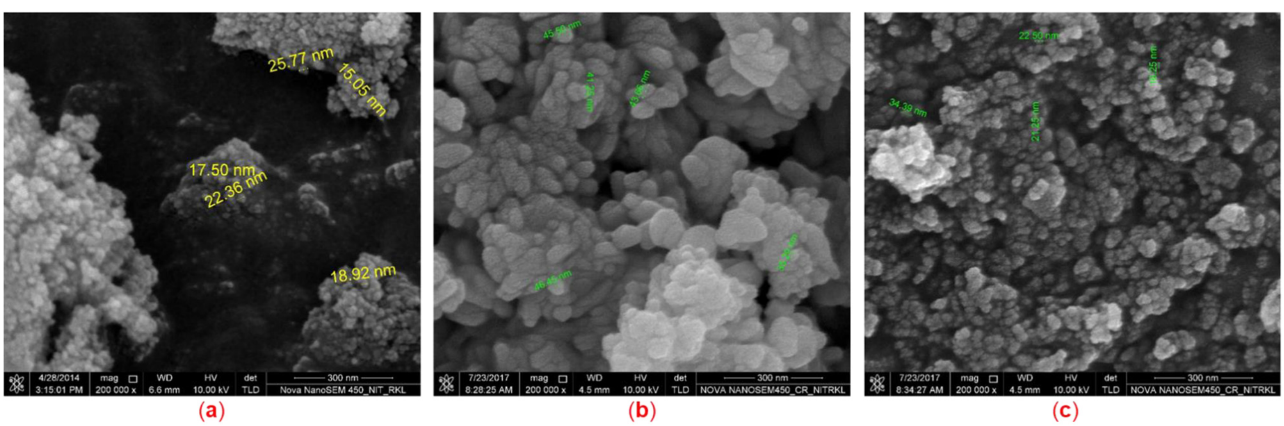


Fig. 3. SEM analysis of nanoparticles.

were removed from the outer surface of the cylindrical workpiece to avoid any kind of non-consistency on the output performance of machining responses. Three experiments were performed for each combination of speed, feed and depth of cut to keep the experimental error minimum.

3.7 Measurement setup

Several machines are used to measure the nanofluid properties which are shown in Figure 3. Various nanofluid properties were analysed once vegetable oil based nanofluids are prepared. Thermal conductivity was measured with the help of hot disk thermal constant analyser shown in Figure 4a. Viscosity was measured by the help of Rheometer that is pictured in Figure 4b. Surface tension was measured by Tensiometer at Figure 4c. Goniometer helped in measurement of contact angle shown in Figure 4d.

Taylor Hobson roughness tester used to measure the surface quality of machined workpiece after performing the hard turning experiments. Scanning electron microscope (SEM) analysed the all morphological aspects of chip, machined surface and flank and rake surface of inserts. Dynamometer attached to charge amplifier used to analyse the cutting force. Advanced optical micro-

Table 2. Chemical composition of work material.

Elements	Fe	Ni	Cr	Mn	C	Mo	Si
Weight %	95.61	1.55	0.90	0.77	0.397	0.275	0.339

scope is used to measure tool chip contact length, flank wear, etc. Vikers hardness tester found the microhardness of the machined surface. Bruker D8 surface texture measurement used for residual stress measurement. Three readings were taken for each response and mean was calculated thereafter and considered as final result for the specific response.

The whole machining operation, especially hard turning of AISI 4340 has been carried out with prepared nanofluids which can be explained in a pictorial form shown in Figure 5. This is the whole setup of hard turning of AISI 4340 alloy steel using three different nanofluid using MQL technique. Dynamometer attached to a charge amplifier and then to data acquisition system which is further connected to a computer that act as a signal analyser. Different numerical and statistical analysis can be done via the signal analyser. MQL (Minimum Quantity Lubrication) is used by integrated lubricated system in which highly pressurised nanofluids are sprinkled to heat affected zone by the nozzle. Nanofluids are pressurized by the compressor. Higher the pressure, better the fluid atomisation and so is the cooling. The machining conditions for the present experimental research is shown in Table 3.

4 Results and discussion

4.1 Nanofluid properties

There are some basic properties of any fluid that held responsible for its characteristic behaviour. Four fundamental fluid properties such as thermal conductivity, viscosity, surface tension and contact angle are considered in the present work. These properties are those on the basis of which every aspects of machinability can be explained.

Thermal conductivity is the measure of heat dissipation rate from a heat affected zone especially the work-tool

Table 3. Cutting conditions.

Machining tool	HMT Lathe
Machining operation	Hard turning
Workpiece material	AISI 4340 steel (Ø 45 mm, 600 mm, 47 ± 1 HRC, heat treated)
Tool holder	PSBNR 2020 K12
Tool material	Uncoated cermet (SNMG 120408)
Cutting speed (m/min)	80,100, 120, 140
Feed (mm/rev)	0.05, 0.1, 0.15, 0.2
Depth of cut (mm)	0.1, 0.2, 0.3, 0.4
Lubricating environment	MQL with CuO + RB oil, Al_2O_3 + RB oil and Fe_2O_3 + RB oil
Supply mode	MQL
Flow rate	150 ml/h
Machining length	120 mm
% of nanoparticle	0.1%

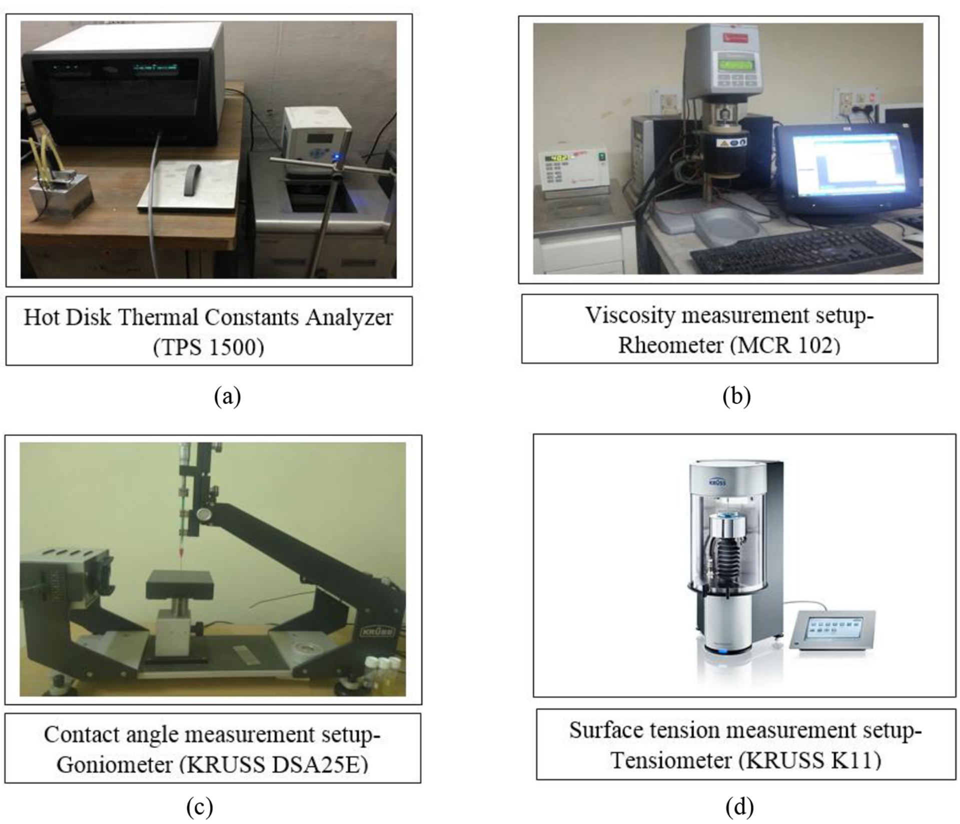


Fig. 4. Nanofluid properties measurement using various equipment.

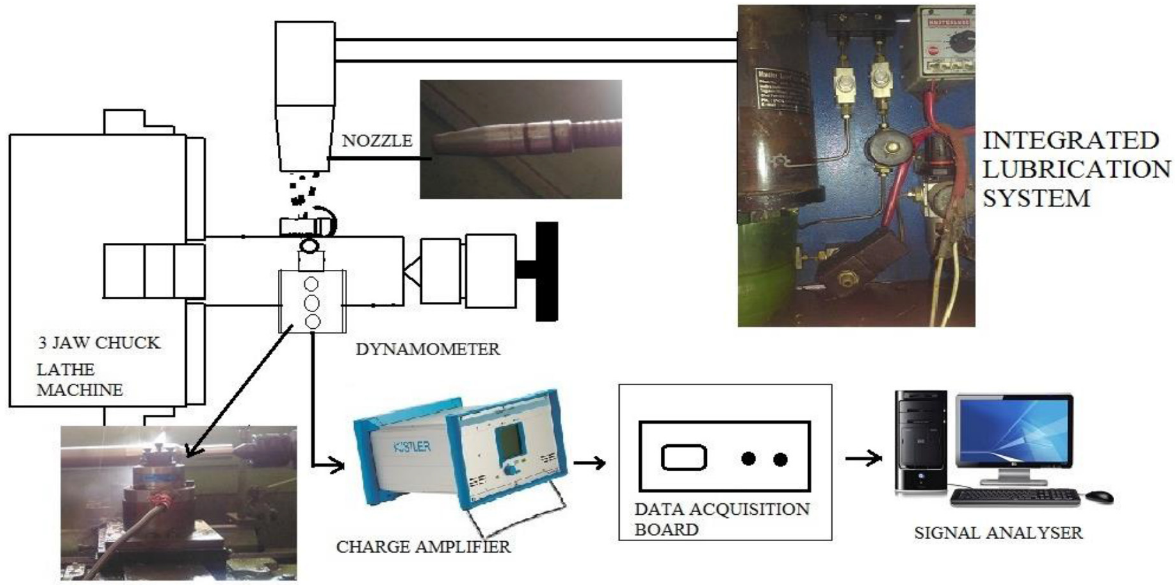


Fig. 5. Experimental setup.

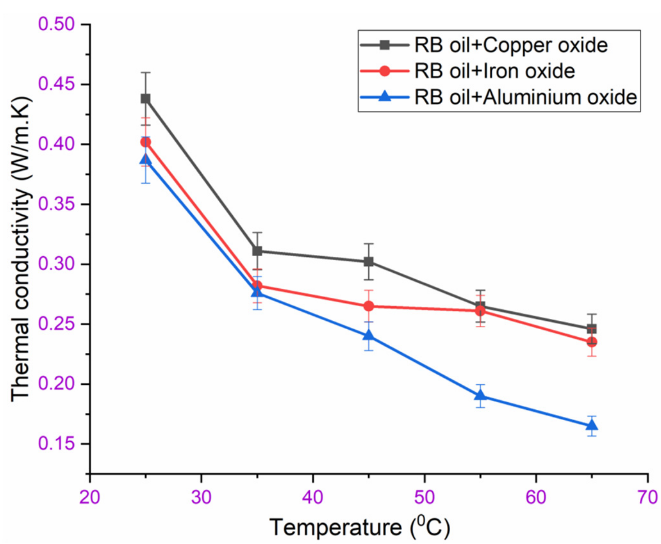


Fig. 6. Variation of thermal conductivity with temperature.

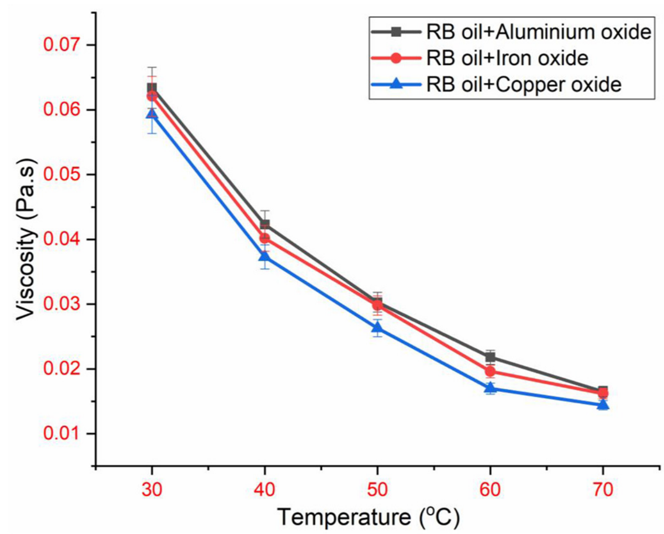


Fig. 7. Variation of viscosity with temperature.

interface to the outer environment having lower temperature. Figure 6 shows that copper nanofluid shown better thermal conductivity as compared to other twos. As temperature increased, thermal conductivity of nanofluid decreased as all the samples contained 0.1% of nanoparticles which was kept constant. Viscosity is the measure of shear stresses applied by one layer to its adjacent layer to resist it from flow. Figure 7 shows that aluminium oxide shows higher viscosity among three and copper performed lowest. With increase in temperature, all nanofluids shown a decreasing slope. Surface tension is the fluid property that enables the fluid to act like a stretched membrane. Figure 8 concluded that aluminium achieved highest surface tension as compared to other two nanofluids. Copper was at bottom level for surface tension comparison. Contact angle is a property of fluid that measures the wettability of solid surface at liquid-vapour interface. From Figure 9, it can be deduced that aluminium nanofluid shown higher magnitude of contact angle. Copper nanofluid shown the minimum and iron is intermediary.

4.2 Machining attributes analysis

4.2.1 Cutting force

Cutting force is an important response in machining activity. Many factors such as cutting variables, tribological characteristic of fluid, properties of tool and workpiece and tool geometry affects the cutting force. In nanofluid machining, fluid film generated due to the presence of nano particles in the fluid. Fluid film reduces the friction. And

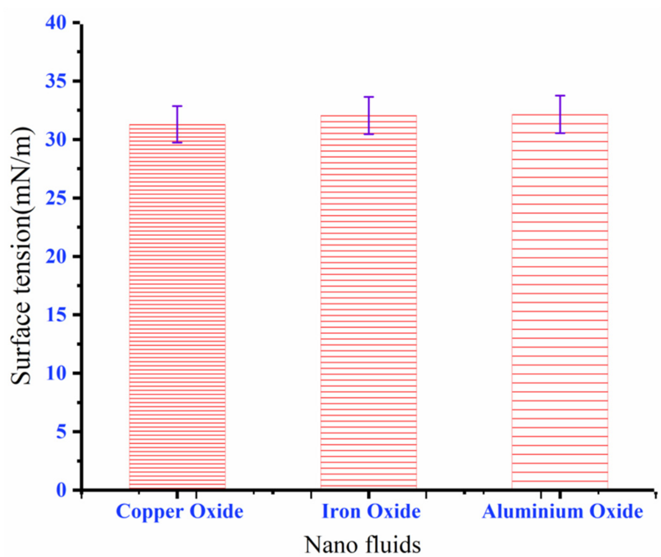


Fig. 8. Surface tensions for three nanofluids.

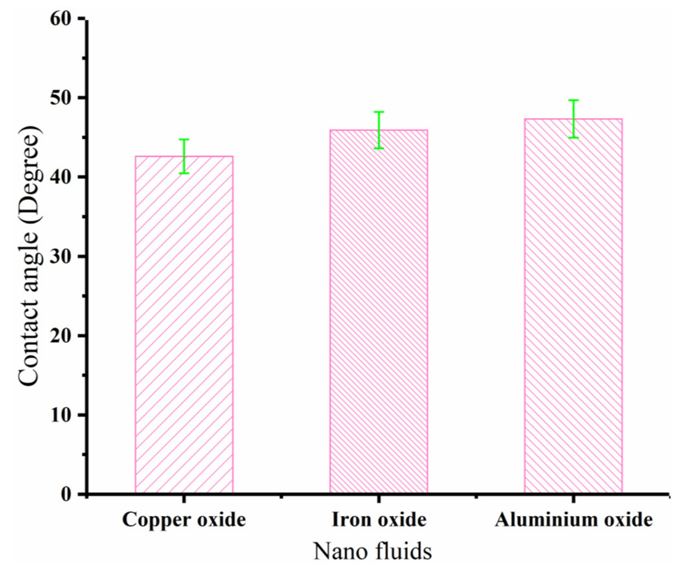


Fig. 9. Contact angles for three nanofluids.

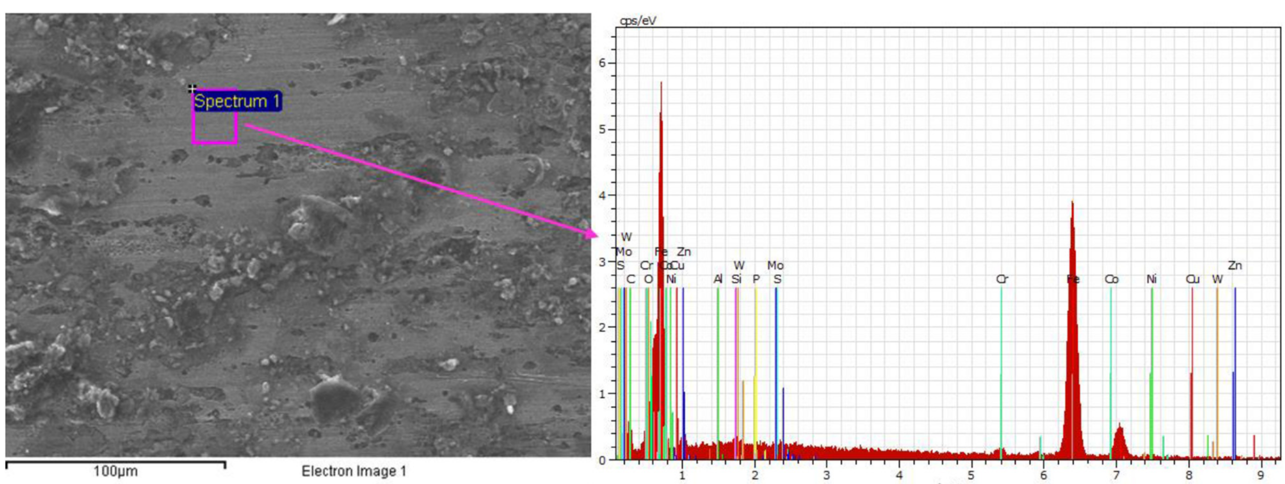


Fig. 10. SEM image with EDS spectrum for machined surface.

this fluid film also produces lubrication that led to declining of cutting force. From the SEM with EDS analysis graph shown in Figure 10, high percentage of copper and low percentage of aluminium was achieved. Their weight percentage distribution on machined surface is shown in Table 4. The low percentage of aluminium found due to poor spreadability and high viscosity. Hence fluid film could not be formed effectively. That's why more force was observed for aluminium oxide based nanofluid. The formation of fluid film led copper oxide based nanofluid to experience less force. Cutting force comparison for three nanofluids is shown in Figure 11. As discussed earlier, with formation of fluid or lubricating film, friction decreases. When friction decreases, material adhesion will be less. Because adhesion of material highly depends upon the sharpness of cutting edge and sharpness of the edge retained with the lubricating film. So more material adhesion was observed for aluminium oxide based coolant

Table 4. Weight percentage distribution of nanoparticles with other elements on machined surface.

Element	Weight (%)
Fe	78.20
C	3.9
Cr	1.14
O	0.64
Si	0.38
Mo	0.05
Ni	0.02
W	0.85
Co	0.24
Cu	0.40
Al	0.11

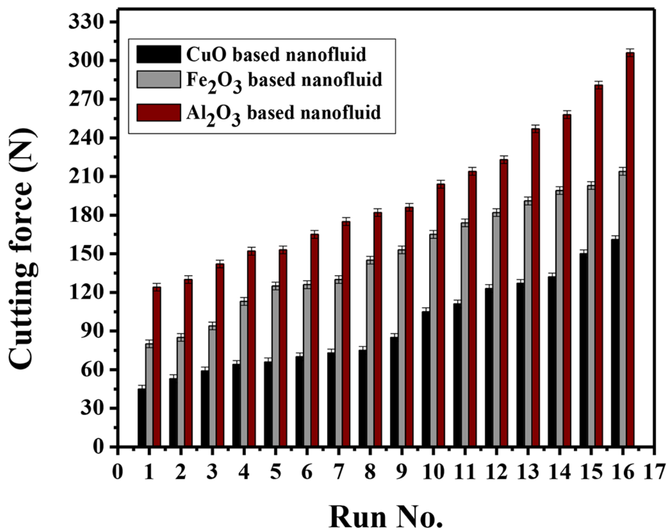


Fig. 11. Cutting force comparison for three nanofluids.

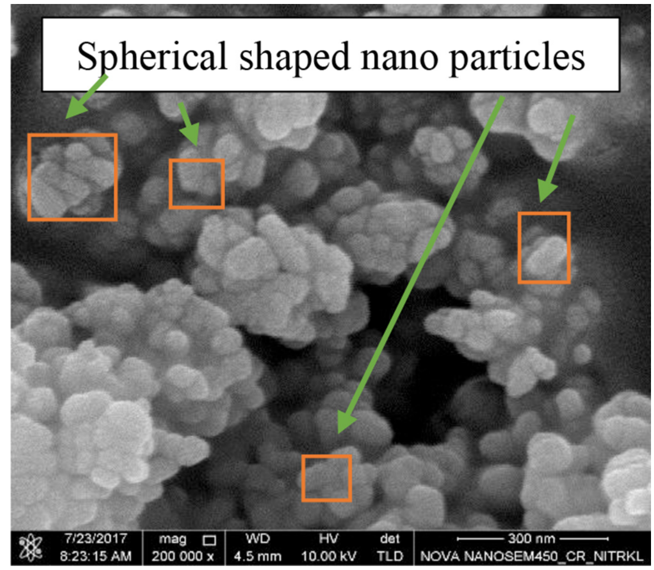


Fig. 13. Spherical shaped of copper oxide nanoparticles.

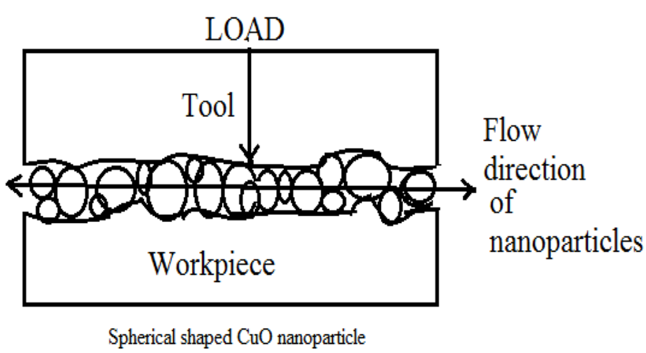


Fig. 12. Cushioning effect of CuO nanoparticles.

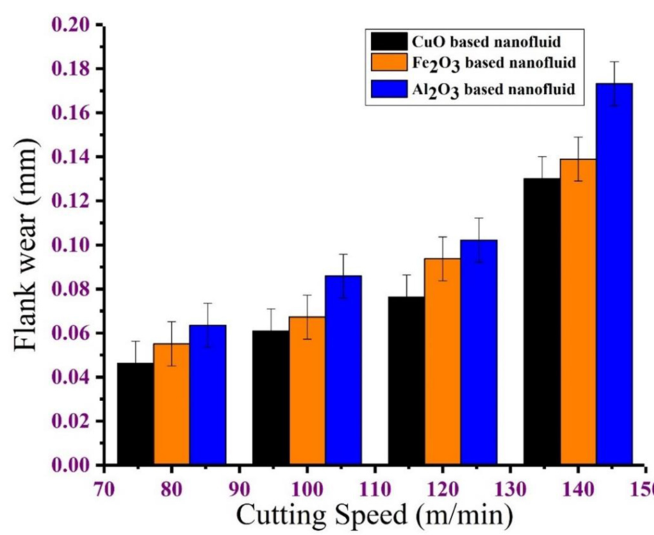


Fig. 14. Flank wear variation with cutting speed for three nanofluids.

compared to cooper oxide based coolant. So more material adhesion promotes more cutting force. Also, the heat dissipation rate increases with copper based nanofluid due to high thermal conductivity and hence protects the cutting edge from being deformed by heat, hence magnitude of force declined. As discussed earlier, fluid film produced by the nanofluid influences the cutting force. The fluid film produced by the nanofluid possesses a property of micro damping, which is also dependent on the shape of the nanoparticles. Spherical shape nanoparticles provide better cushioning effect. The fluid film absorbs the shocks caused due to dynamic fluctuation. Nanoparticles present in the nanofluid produced cushion-effect shown in Figure 12 absorbing any kind of sudden load or impact that lowers the cutting force fluctuations. Though both CuO and Al_2O_3 have spherical shaped nanoparticles but CuO based nanofluid shown better cushioning effect because higher volume of spherical nanoparticles containment which is shown in Figure 13 and produced good fluid film. Flank wear acutely affects cutting forces and less flank wear was observed for copper nanofluid thus lesser force was experienced. In between copper and aluminium, iron has shown nearly average result.

4.2.2 Flank wear

Failures of tool always gone through a process having three stages i.e. primary wear, gradual growth of wear and total tool failure. This 4340 alloy steel is difficult to be machined. Moreover, it suffered from friction at work-tool-chip interface. More temperature generated at both rake and flank faces due to friction. Less wear was found at low speed, but as speed progresses more wear was found on the flank face of the insert for all types of nanofluids as shown in Figure 14, here feed and depth of cut were kept constant as 0.2 mm/rev and 0.4 mm respectively. However, thick abrasion marks and chipping were observed in case of aluminium oxide nanofluid due to insufficient cooling and

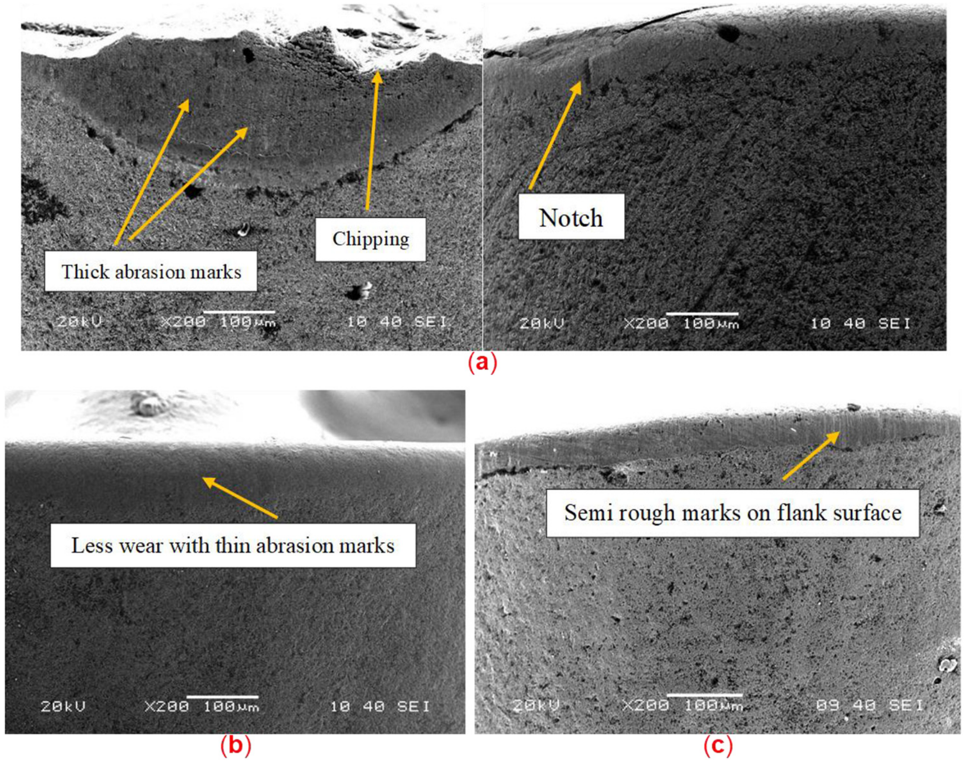


Fig. 15. Flank surface of the insert using (a) aluminium oxide, (b) copper oxide, and (c) iron oxide based nanofluids.

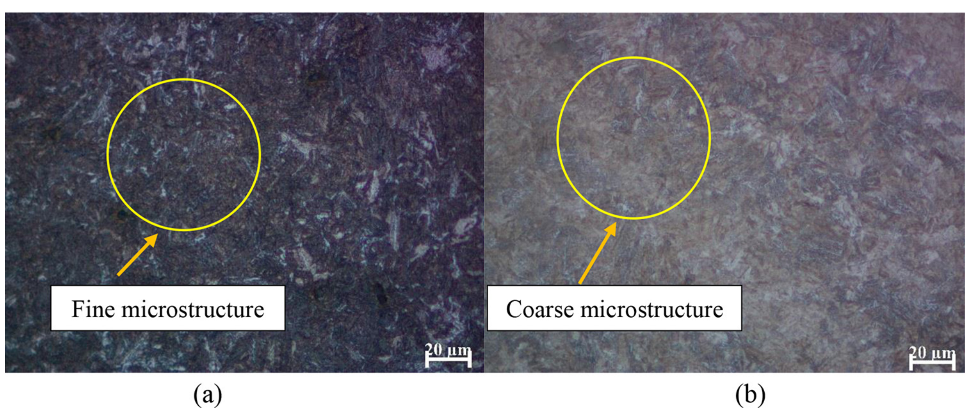


Fig. 16. Microstructure of the machined surface using (a) copper oxide, and (b) aluminium oxide based nanofluids.

lubrication as shown in Figure 15a, for which high temperature might be generated because aluminium oxide nanofluids possessed low thermal conductivity and high viscosity. Also it has high contact angle and surface tension that promotes less spreadability and wettability properties. Friction also increased at tool-work and tool-chip interfaces at high speed and feed due to the enlargement of chip area. Therefore, temperature increases at both the interfaces for which tool life decreases. Microstructure of the specimen plays a crucial role for tool life. With fine microstructure, machinability of the material increased as a result, tool life increased. However, tool life was severely affected with coarse microstructure. This primarily happened in hardened steel due to less thermal conductivity property. Adding to that heat cannot be dissipated outside the primary deformation zone owing to that property. Retention of temperature made microstructural alterations. In the present investigation, fine microstructure was observed for copper oxide based nanofluid and coarse microstructure was observed for aluminium oxide based nanofluid as shown in Figure 16a and b. As discussed earlier, retention of temperature is the main reason for microstructural alteration. So, because of high thermal conductivity, low viscosity, better wettability and spreadability characteristics of copper oxide nanofluid, better heat dissipation and better microstructure attained resulting less tool wear for copper oxide based nanofluid shown in Figure 15b, whereas this was not happened with

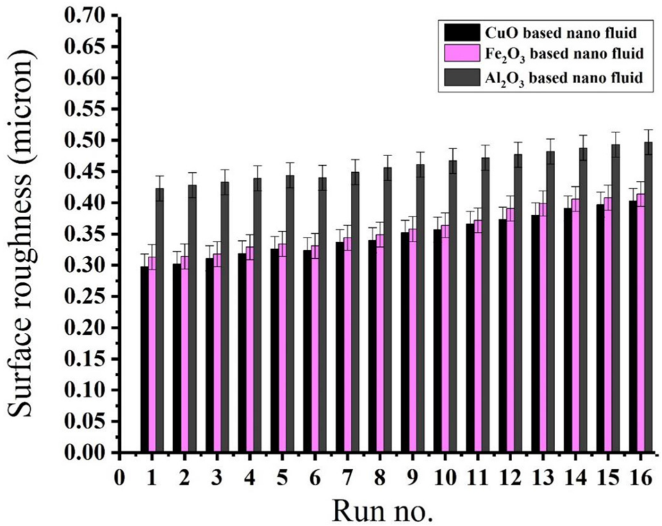


Fig. 17. Surface roughness comparison of three nanofluids.

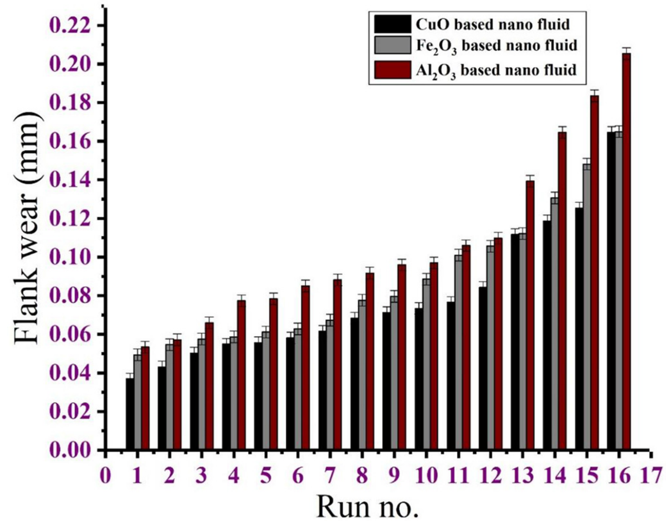


Fig. 18. Flank wear comparison of three nanofluids.

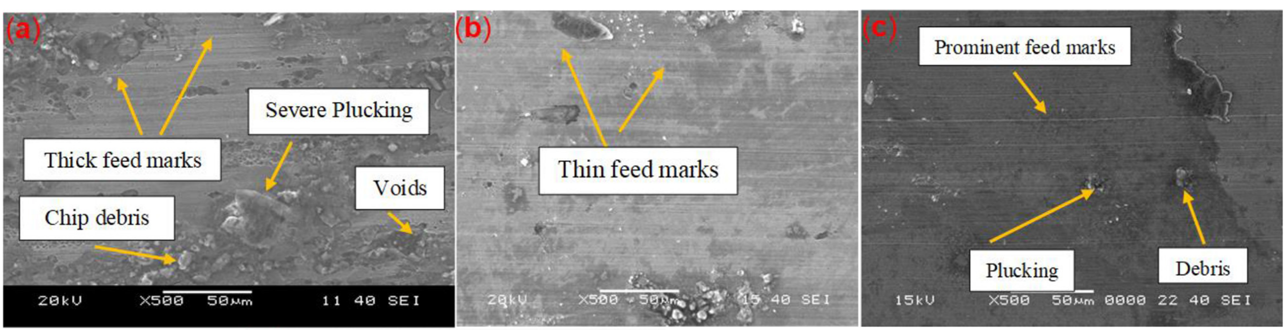


Fig. 19. Machined surface morphology using (a) aluminium oxide, (b) copper oxide, and (c) iron oxide based nanofluids.

aluminium oxide based nanofluid. Notch wear was also observed on flank face during machining with aluminium oxide based coolant as shown in Figure 15a. And this was mainly happened due to chip hammering. As uneven thicker chip flow was observed with this nanofluid. Because of this type of chip flow, chips were accumulated and the evacuation process became complicated. So more adhesion was observed at the tool surface, resulting more tool wear. Iron shown intermediary result as shown in Figure 15c, where aluminium shown the worst and copper shown the best.

4.2.3 Surface roughness

Roughness is an important surface integrity aspect in hard machining. The quality of a machined surface can be properly understood by surface roughness. In the present experimental investigation, Ra was taken as the roughness parameter and measured with Taylor Hobson roughness tester. Both the measurement and cut-off length were set as 4 mm and 0.8 mm, respectively. The instrument was calibrated before the experiment. Three locations were marked around the circumference of the workpiece and measurement was taken. For each location, measurement was repeated three times for error minimization and the mean value was taken as final. As shown in Figure 17 aluminium oxide based nanofluid produced high roughness as compared to other nanofluids. And good surface finish was obtained with copper oxide based nanofluid. Because with copper oxide based nanofluid, less force and high tool life was observed as shown in Figures 11 and 18. Less chatter was observed during machining and thin feed marks were found on the machined surface as shown in Figure 19b. With feed, volume of material increased and material in the form of chips accumulated at tool-work and tool-chip interface, for which friction increased that led to increment of surface roughness. At high speed, heat dissipation to surroundings is less due to insufficient time. Having more temperature deteriorated the surface quality. Copper oxide based nanofluid has more thermal conductivity and less viscosity, so better heat dissipation was there for which friction and temperature reduced and good surface quality obtained. As discussed earlier, more roughness was observed for aluminium oxide based nanofluid because of less conductivity and high viscosity. Heat was not properly dissipated from the machined surface to the surroundings with this fluid. As a result, various surface damages like severe surface plucking, chip debris voids and thick feed marks were observed as shown in Figure 19a for which roughness increased.

Surface tension is responsible for contraction of liquid surface. Thus liquids possess higher surface tension shows poor wettability and spreadability ultimately leads to improper cooling and lubrication. From Figures 8 and 9, it can be deduced that copper nanoparticle enriched cutting fluid has lesser surface tension and contact angle so it wets and spreads in the machined surface better than other nanofluid resulting finer surface texture. Aluminium oxide nanofluid performs very poor and Iron oxide nanofluid was intermediate in these tests with prominent feed marks, minor plucking and debris shown in Figure 19c. Even at lower speeds nearly 80 m/min, aluminium nanofluid gave the worst surface finish. Built-up edge (BUE) formed at cutting edge cause tool geometry distortion that led to improper surface finish as shown in Figure 20.

4.2.4 Tool-chip contact length

The length between the contact and leaving point of chip on the tool rake face is called contact region. High strain and nonlinear plastic deformation occurs in chip formation process during hard turning. High temperature and stress also generated during chip formation process at the contact interface. Therefore, tool-chip contact length is an important aspect in hard turning. The tool-chip contact length is highly influenced by variety of coolants used and coolant delivery system employed. It also depends upon factors like, tool life, cutting force, heat and power generation. In machining with all types of nanofluids, sliding marks were observed on tool rake face whereas very low sticking of chips were observed. Copper oxide based nanofluid having low viscosity and more thermal conductivity. Hence proper cooling was achieved with this nanofluid as compared to others. Moreover, proper atomization was found for copper oxide based nanofluid due to less surface tension. And during experiment larger wetted area was observed for this nanofluid. Due to larger wetted area and proper cooling for copper oxide based nanofluid, shorter tool-chip contact length with smooth sliding marks and few burnt marks (black spot) were observed as shown in Figure 21a. Whereas for aluminium oxide based nanofluid, large tool – chip contact length with thick sliding marks and prominent burnt marks were observed as shown in Figure 21b because of insufficient cooling and wettability characteristics due to low thermal conductivity, high viscosity, contact angle and surface tension. Furthermore, lengthy and thicker chips with higher curl radius produced with aluminium oxide based nanofluid because of long tool-chip contact length whereas, short and thinner chips are produced with copper oxide based nanofluid because of small tool-chip contact length. The tool-chip contact length was also affected by the expansion and contraction of chip. The portion of chip adhered to the rake face of the insert subjected to expansion due to high temperature. But the portion where the fluid particles will be adhered to the chip surface subjected to contraction due to the cooling effect. The latent heat of the chip surface is absorbed by fluid droplets through evaporative cooling. Due to this contraction and expansion, bending or curling of chips from the rake face observed. As the bending will be more, tool-chip contact length will be less. Fluid having high thermal conductivity, evaporates quickly due to higher rate of heat transfer compared to fluid with less thermal conductivity. Hence more bending of chip was observed with copper oxide based nanofluids compared to other fluids as shown in Figure 22 resulting less tool-chip contact length for copper oxide based nanofluids drawing conclusion of less force, roughness with high tool life. Tool wear is an important parameter affects extensively tool-chip contact length. From Figure 18, it can be concluded that less flank wear has

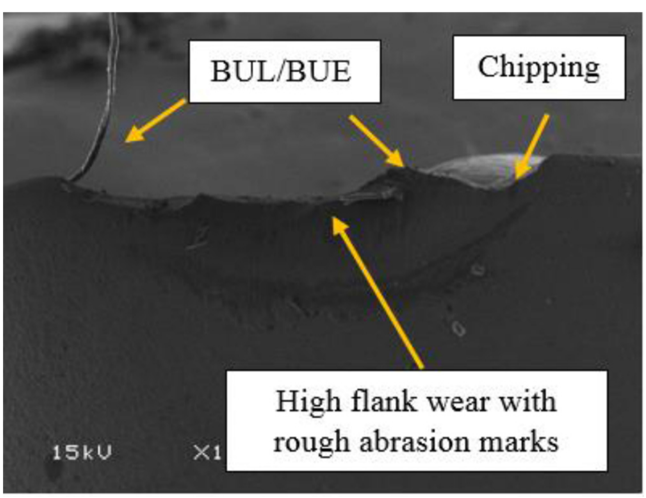


Fig. 20. Built-up edge formation with aluminium oxide nanofluid.

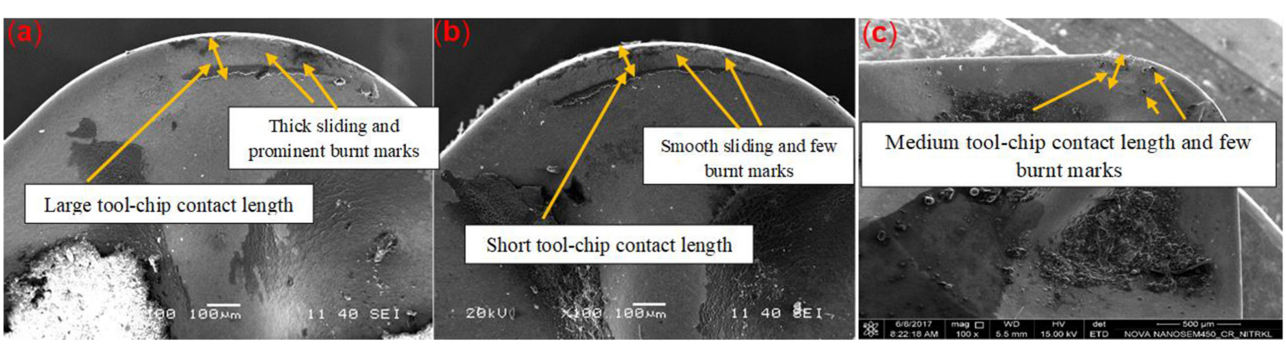


Fig. 21. Tool-chip contact length using (a) aluminium oxide, (b) copper oxide, and (c) iron oxide based nanofluids.

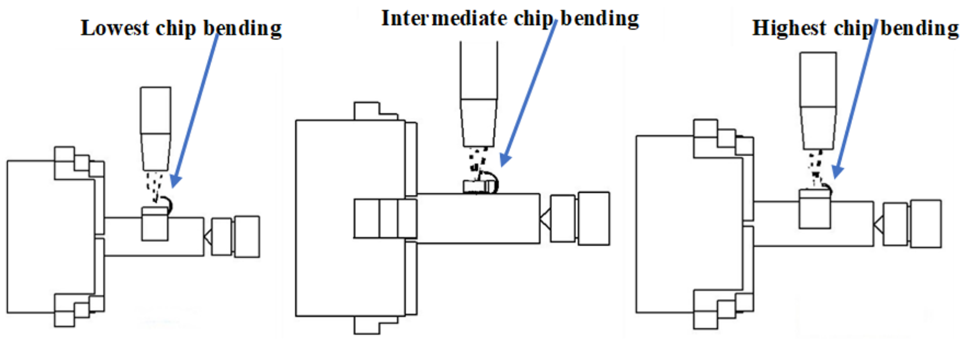


Fig. 22. Chip bending phenomenon using different nanofluids.

been achieved by copper nano particles enriched nanofluid, which is a possible reason of lesser magnitude of tool-chip contact length in case of copper nanofluid. Iron oxide enriched nanofluid shows intermediary results (medium tool-chip contact length, Fig. 21c) having two extremes possessed by copper and aluminium nanofluid.

4.2.5 Microhardness

Surface microhardness is a matter of primary concern in the machining activity. The machining parameters are found to be dominant on work hardening characteristics of the specimen, hence they must be analysed with utmost care. In the present experiment, the influence of cutting speed on the hardness at the surface and subsurface region of the machined specimen was investigated. The discrepancy of microhardness with the distance from the edge towards the centre of machined sample with different speed levels using three nanofluids were demonstrated by Figure 23. From the above mention graphs, it was observed that higher microhardness was obtained at higher speed for all three nanofluids. Because strain rate plays an important role at higher speed. With high strain hardening, microhardness of the specimen increased. Temperature increased at shear zone at higher cutting speeds that led to phase transformation occurred and hardness enhanced. Temperature made the top layer of the material subjected to severe work hardening. But sometimes, hardness is obtained the depth beneath the surface due to low thermal conductivity of material. As discussed earlier, phase transformation plays an important role. Hence after machining with each cutting fluid, samples were cut from the machined surface along the plane perpendicular to the axis of rotation as shown in Figure 24 by WEDM (Wire electro discharge machining). Then the samples were mounted and polished through various grade papers. After paper polishing, samples were polished using cloth and microhardness measurement was performed with Vickers microhardness tester. Each reading was repeated three times for error minimization. Finally the mean value was considered and to investigate the effect of phase alterations at the microstructural level, polished samples were etched with nital and analysed by advanced optical microscope. From the microstructural analysis, two phases were observed; black and white. Black phase shown hard pearlite and white was the ferrite phase. And the hardness in steel specimen mainly depends upon the hard pearlite phase. In copper oxide based nanofluid, more ferrite phase was observed compared to pearlite phase as shown in Figure 25b so less hardness was found. Because temperature affects the hardness, with fluid having high conductivity, both the strain hardening and phase transformation can be minimized. But in case of aluminium oxide based nanofluid, harder pearlite phases were observed than ferrite phase as shown in Figure 25a. Therefore, hardness of higher magnitude was obtained.

As discussed earlier, low thermal conductivity influenced the microhardness temperature was found to be retained sometimes owing to that. Hardened alloy steel has lower thermal conductivity. More hardness would have been experienced if surface cooled improperly. From Figures 8 and 9, it was observed that copper nanoparticle enriched cutting fluid have lower surface tension and contact angle. Hence it wetted and spreaded better on machined surface and made better cooling and lubrication resulting less microhardness. Aluminium shown the worst and Iron stood in between them having medium pearlite and ferrite phases.

4.2.6 Residual stress

In the turning operation, residual stress is generated in two mutual perpendicular directions. One is in feed direction and other is in the circumferential direction. And the stress generated in the circumferential direction is always higher than the stress generated in feed direction. Hence circumferential stress has been measured in this study. In the present work, with a set of three nanofluids, tensile residual stress was observed for all compressive stress converted to tensile stress due coolant effect. Residual stress was measured by cutting the samples through WEDM process as shown in Figure 24 after the experimental run for each nanofluid. Bruker D8 advanced XRD texture measurement machine was used to measure the residual stress. The second reason for the conversion of compressive stress to tensile stress might be the high mechanical property, severe work hardening and low thermal conductivity of 4340 hardened alloy steel. Stress was measured on the machined surface both force and stress reduces along the depth due to reduction of heat. The surface finish, cutting force and tool life these three responses highly influenced the residual stress. From the

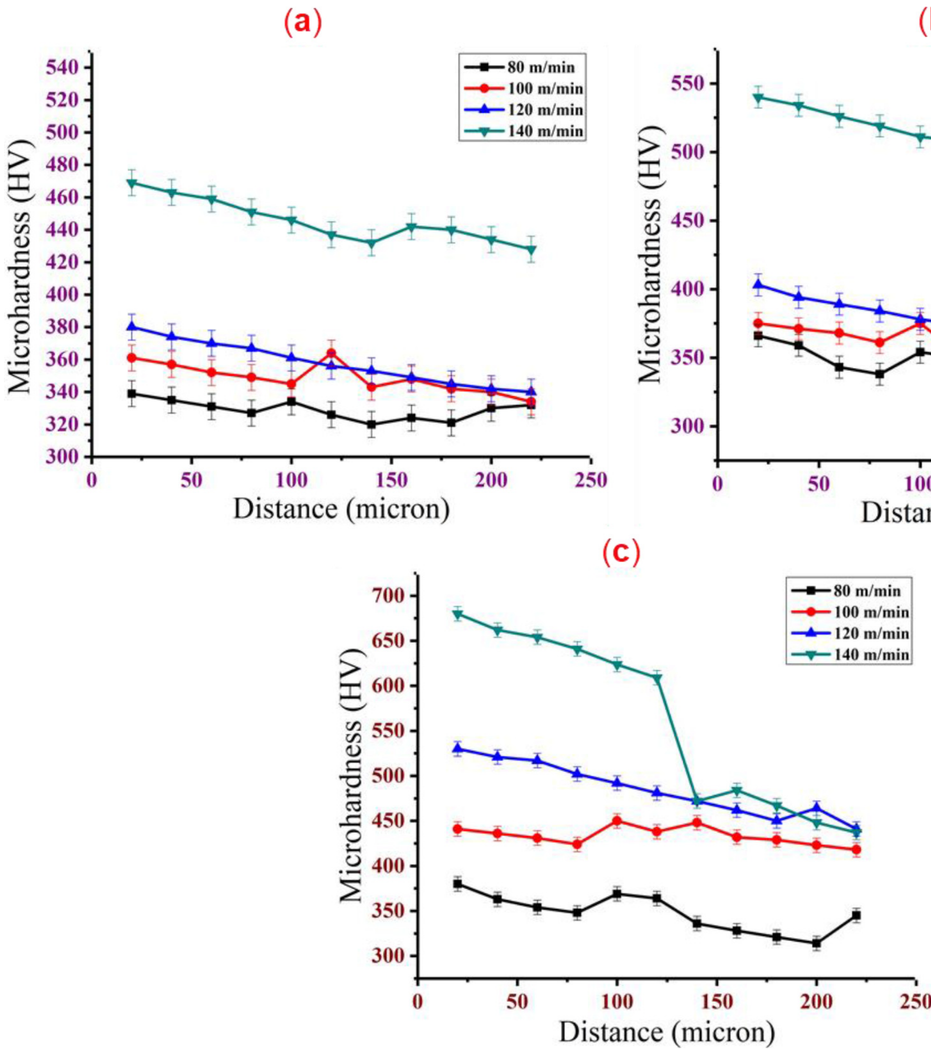


Fig. 23. Microhardness variation with different speed levels using (a) copper oxide, (b) iron oxide, and (c) aluminium oxide based nanofluids.

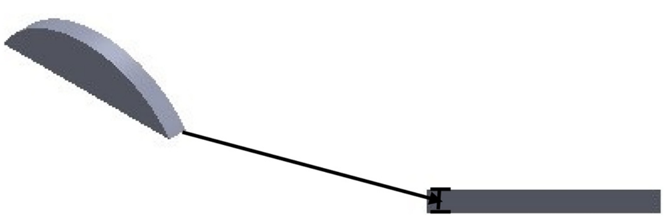


Fig. 24. Machined surface for microhardness experiment.

experimental results, that least residual stress was observed for copper oxide based nanofluid in comparison to other fluids. As seen from Figures 6 and 7, copper oxide based nanofluid is having high thermal conductivity and less viscosity. For which less force, roughness and high tool life was observed as shown in Figures 11, 17 and 18. Also, less temperature generated on the machined surface due to high conductivity, a major reason for the reduction of residual stress. As residual stress highly depends upon the surface heat generation. Moreover, the residual stress depends upon machining parameters, specifically on the speed because of its temperature sensitivity. Moreover, heat generation is more with cutting speed. From Figure 26 it can be concluded that with speed, stress is increasing for all nanofluids, where feed and depth of cut were kept constant at 0.2 mm/rev and 0.4 mm, respectively.

From earlier discussion, we found that generation of heat at machined surface potently influenced residual stress. With copper nanoparticle enriched cutting fluid, both cooling and lubrication of machined surface was achieved effectively. Due to its higher wettability and spreadability characteristics, lesser residual stress had been observed for copper nanofluids. Aluminium shown higher residual stress and iron nanofluid performed in between them.

4.2.7 Machined surface morphology

In the current research, both coarse scale and fine scale surface damages were noticed on the machined surface. Material side flow was observed for all types of nanofluids.

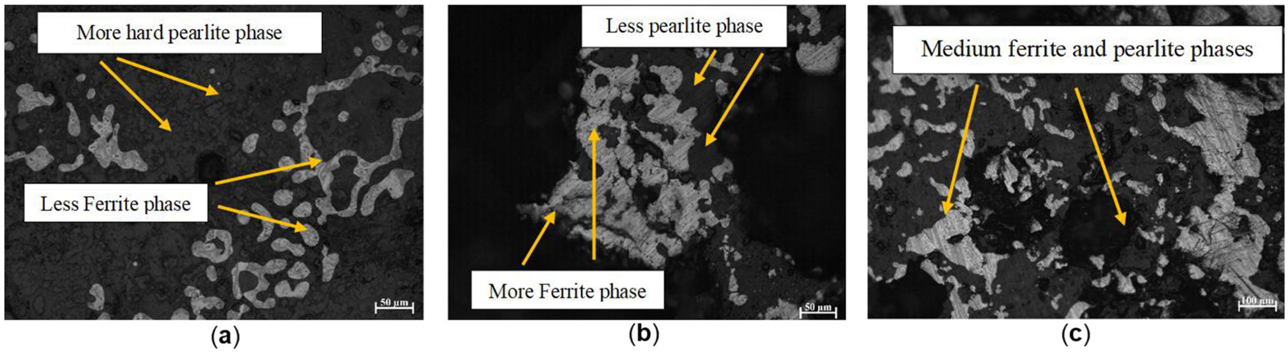


Fig. 25. Microstructure having pearlite and ferrite phases using (a) aluminium oxide, (b) copper oxide, and (c) iron oxide based nanofluids.

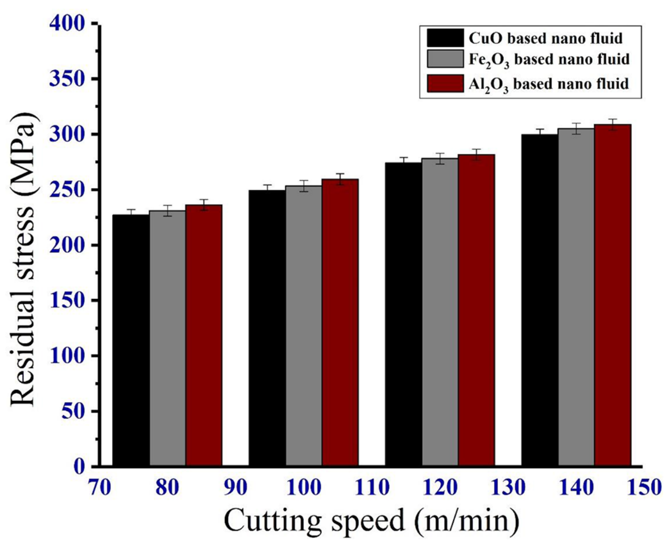


Fig. 26. Residual stress comparison among three nanofluids with respect to cutting speed.

But more material flow was observed for aluminium oxide based nanofluid and less side flow was observed for copper oxide based nanofluid owing to better heat dissipation, because of high thermal conductivity as shown in Figure 27. As material flow depends upon temperature. And at high temperature, material behaves like a high viscous material. The tool life also influences the surface quality of the machined specimen. With high tool life, smooth surface i.e. less side and plastic flow was observed. But with higher tool wear, high material side flow, surface cracks, plucking, chip debris were observed as more temperature is generated with worn out inserts. Also, the material adhesion is highly dependent on temperature. This might be another reason why good surface quality was observed with copper oxide based nanofluid compared and not with other nanofluids because Figures 14 and 18 inferred that high tool life (less flank wear) was produced with copper oxide based nanofluids compared to others. Moreover, massive cracked surfaces were observed with aluminium oxide based nanofluid compared to others. Whereas no surface damage in form of cracks was observed for copper oxide based nanofluid as shown in Figure 28a and b. Surface damage in the form of cracks mainly depends upon thermal and mechanical load. Due to high cutting force, stress generated at tool-work contact region cause to form cracks. As we can see from Figures 11 and 26 both cutting force and residual stress were found more for aluminium oxide based nanofluid. As cracks found on the machined surface for aluminium oxide based nanofluid, intensive oxidation might be the other reason. Moreover, generation of cracked surface depends upon roughness. Higher roughness was observed with aluminium oxide based nanofluid, so more cracks found.

Copper oxide enriched nanofluid have better spreadability and wettability characteristics of that led to finer grade of cooling and lubrication on the machined surface. Hence generation of heat on that surface deteriorated showing superior surface morphology. The performance of iron was in between two other nanofluids with medium material side flow and small crack regions shown in Figure 28c.

4.2.8 Chip and its morphology

Chips and its morphological aspects affect various machining attributes such as surface quality, tool life and machining temperature. Three types of chips are formed in hard machining; continuous type, segmented type and serrated type. In segmented type, prominent saw teeth are found without any shear band whereas in serrated chip, saw teeth with adiabatic shear band is observed. In the present experiment, both segmented chip and serrated chips were observed but for different nanofluids. Heat dissipation highly influenced the chip formation process in machining. Chips with better morphological characteristics formed with more heat dissipation. At higher cutting speeds temperature generation is more because of inadequate time for heat transfer. The principal mechanism for the segmented and serrated chip formation is that the crack initiation and propagation are attributed to the shear band extending from the edge of the tool to free surface during the machining process [23]. During hard turning process, high compressive stresses are experienced due to negative rake angles of the cutting tools [24] which lead to the formation of cracks and plasticization due to the brittleness

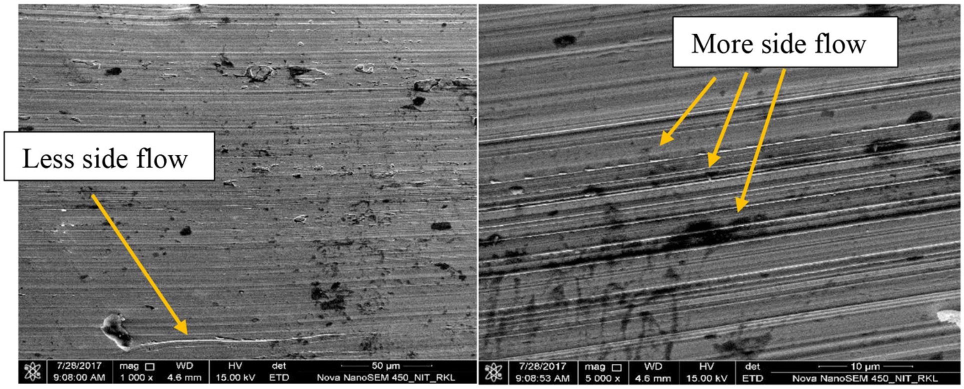


Fig. 27. Side flow of material on the machined surface using (a) copper oxide, and (b) aluminium oxide based nanofluids.

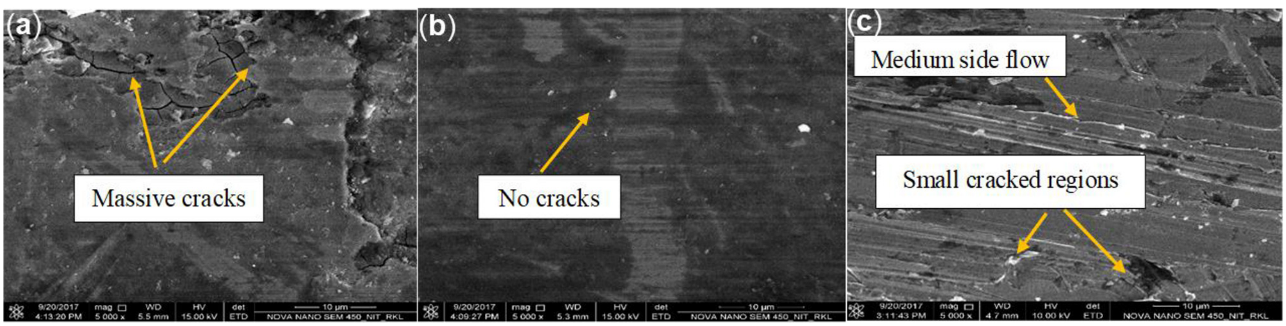
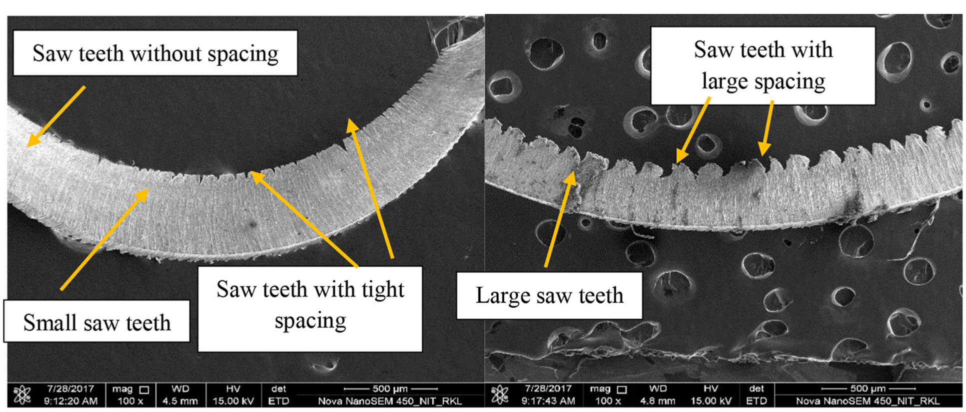


Fig. 28. Morphology of the machined surface using (a) aluminium oxide, (b) copper oxide, and (c) iron oxide based nanofluids.



(a) (b)

Fig. 29. Chip morphology using (a) copper oxide based, and (b) aluminium oxide based nanofluids.

of the hardened steel, occurs at the chip's primary shear plane, resulting serrated chips. These cracks start on the chip's free surface and go deeper towards the tool nose, relieving the energy stored and acting as a sliding surface for the material segment [25]. Simultaneously, heating and plastic deformation of the material occurs at the leading edge of the cutting tool. The process repeats itself in a cyclic manner after the chip segment has slipped with another new formation of crack and chip segment results in formation of saw-tooth chip [26]. During the machining with copper oxide based nanofluid, chips with tightly spaced saw teeth and saw teeth without any spacing was observed as compared to other nanofluids shown in Figure 29a. But for aluminium oxide based nanofluid, chips with widely spaced saw tooth produced as shown in Figure 29b due to insufficient cooling compared to copper

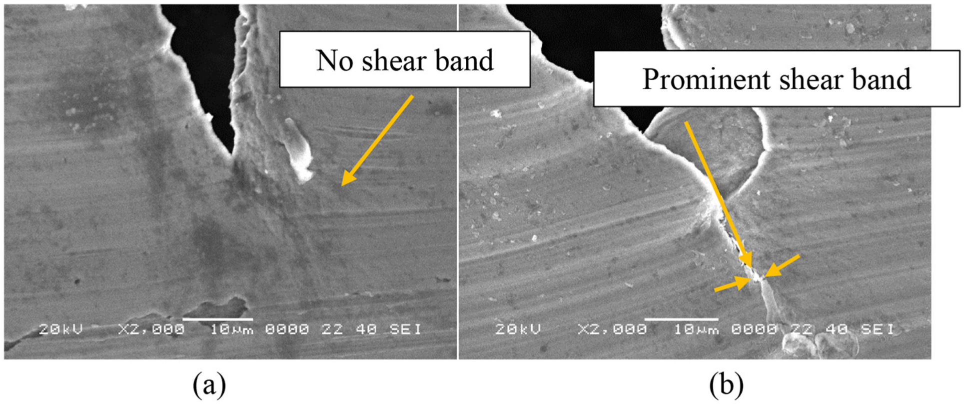


Fig. 30. Chip morphology with shear band using (a) copper oxide based, and (b) aluminium oxide based nanofluids.

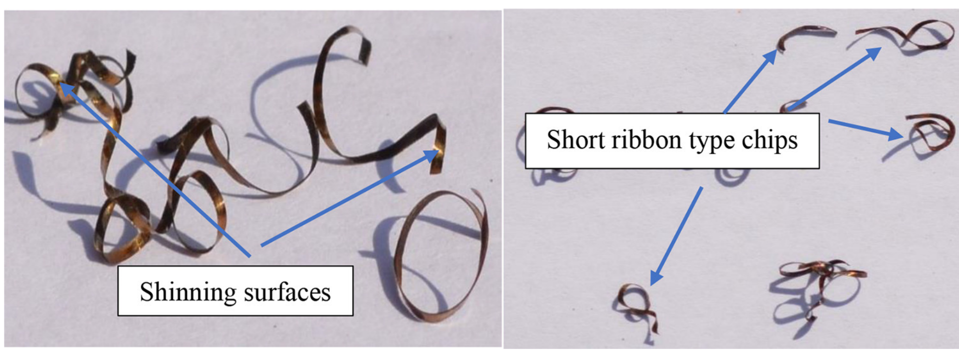


Fig. 31. Chips produced using copper oxide based nanofluid.

oxide based nanofluid. Moreover, small saw teeth were observed with copper oxide based nanofluid compared to aluminium oxide based nanofluid. Among three nanofluids, prominent shear band was observed for aluminium oxide based nanofluid shown in Figure 30b because of low thermal conductivity. But for copper oxide based nanofluid, chips without any shear band were observed as shown in Figure 30a. Moreover, for better thermal conductivity, for quality of easier wetting and spreading of copper oxide based nanofluid, chips with golden colour and shinning surface were observed among all nanofluids shown in Figure 31a. That implies more heat was liberated through the chips with copper oxide based nanofluid. Chip thickness, an important machining attribute, is highly influenced by tool life. More the tool wear, higher is chip thickness and less thickness is observed less tool wear. With copper oxide based nanofluid, thin chips are produced due to high tool life compared to other fluids. Short ribbon type chips were produced as shown in Figure 31b with copper oxide based nanofluid which indicates chip breakability. As we know fluid having, high thermal conductivity will evaporate more. So there will be a pressure difference at the machining zones. For which more fluid will be supplied to that area, cause chip to experience backward force, which ultimately cause breaking of chips. The majority of tests performed using copper oxide based nanofluid showed segmented chips as shown in Figure 31 because of the effective impingement of nanoparticles on the generated chips which increased the chip helix angle and forced the long chips for breaking. The above mechanism was found with copper oxide based nanofluid because of high thermal conductivity. However, with aluminium oxide based nanofluid, long deleterious, snarled chips formed as shown in Figure 32. Because with the fluid having low thermal conductivity, temperature at the cutting zone and friction between tool-chip interface increased. Another phenomenon, chips with lower curl radius was observed for copper oxide based nanofluid, whereas with aluminium oxide based nanofluid, chips having more curl radius was found as shown in Figure 33a and b.

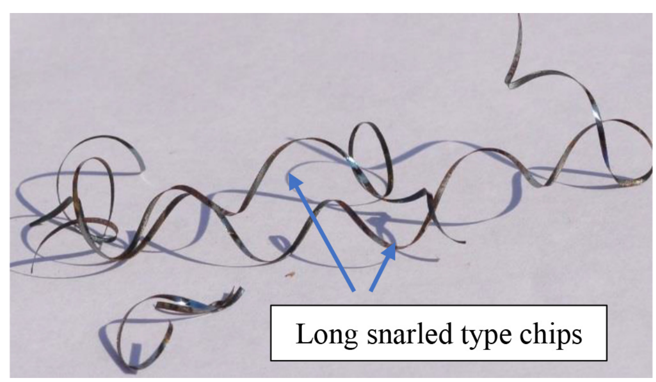


Fig. 32. Chips produced with aluminium oxide based nanofluids.

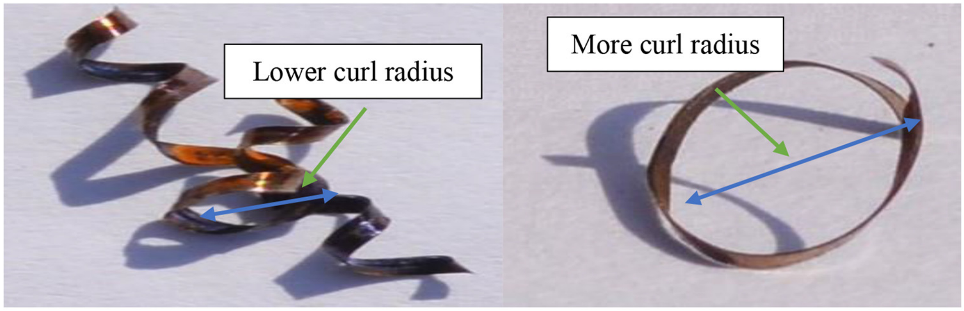


Fig. 33. (a) Lower curl radius chip with copper oxide and (b) chip with more curl radius with aluminium oxide based nanofluids.

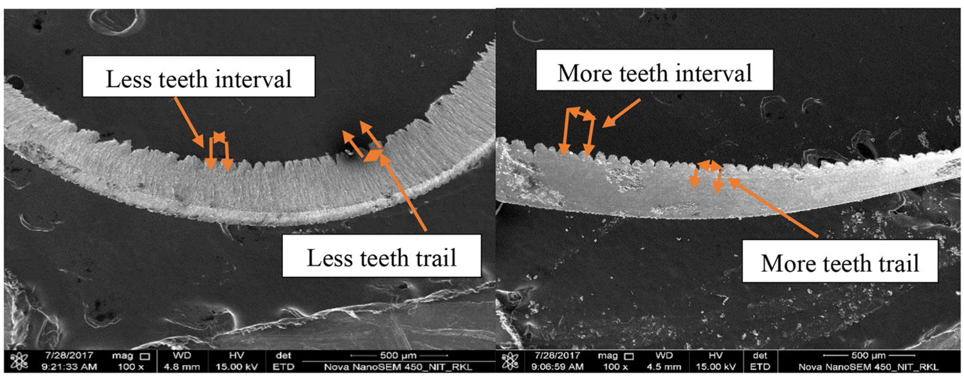


Fig. 34. (a) Saw teeth interval and trail of cutting chips with copper oxide and (b) aluminium oxide enriched nanofluids.

As more heat dissipated with copper nanofluid, chips with less teeth interval and trail was observed whereas with aluminium nanofluid chips with more teeth interval and trail was noticed as shown in Figure 34a and b. The constructional features of the chips produced by iron oxide based nanofluid were somehow similar with chips produced with copper oxide based nanofluid. Chips with medium size saw tooth were observed with iron oxide based nanofluids shown in Figure 35.

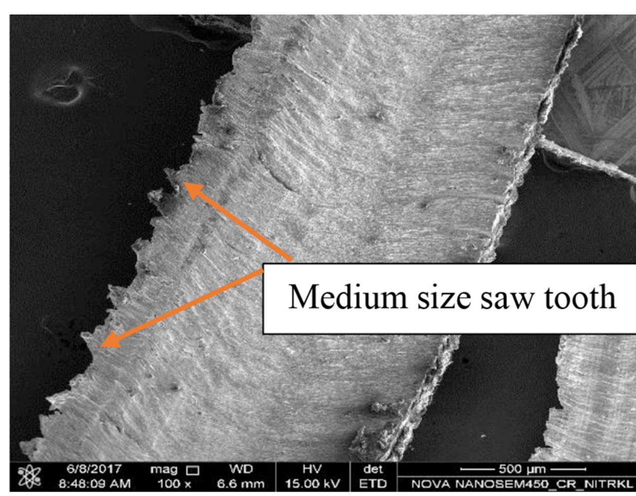


Fig. 35. Chip morphology using iron oxide based nanofluid.

5 Conclusions

The present work draws the following conclusions.

– In comparison of among three NFMQL cutting fluids (CuO, Al_2O_3, and Fe_2O_3) the study demonstrated: (i) superior machined surface morphology, (ii) short-thin chips with lower curl radius, (iii) improved surface quality, (iv) least flank wear, (v) shorter tool-chip contact length along with smoother sliding marks, and (vi) minimum microhardness and residual stress are obtained on machining with copper oxide nanofluid as coolant.

– The change of nanofluid also shows surprising results on the surface roughness values. It has been found that, the surface finish of machined part improves with the change in nanofluid form aluminium-oxide based nanofluid to copper-oxide based nano-fluid. Because the viscosity of copper oxide base nanofluid is lower compared to the other two fluids, this results in proper settlement of the nanofluid in work-tool interface, hence, which provides the cushioning effect which may induce low machine chattering and vibrations.

- Also, it is observed from the microstructural analysis that, while using the copper oxide based nanofluids fine structure are produced as compared to other two nanofluids. The main possible reason is that the heat carrying capacity of copper oxide is more as compared to other two, which may result in less microstructural changes. Thus, fine laminar structure seems to produce lower cutting temperature, which results in lesser cutting force while using copper oxide based nanofluid.
- The application of nanoparticles in minimum quantity lubrication technique have shown promising results in improving the performances of hard-turning process concerning cutting tool life due to the superior cooling and lubrication properties which enhance the interface bonding between the tool and work piece surfaces. Thus, it can be applied to machining of difficult-to-cut materials and different machining processes to improve the performance characteristics.

References

[1] S. Roy, A. Ghosh, High-speed turning of AISI 4140 steel by multi-layered TiN top-coated insert with minimum quantity lubrication technology and assessment of near tool-tip temperature using infrared thermography, Proc. Inst. Mech. Eng. B: J. Eng. Manuf. 228 (2014) 1058–1067

[2] K.K. Gajrani, D. Ram, M. Ravi Sankar, Biodegradation and hard machining performance comparison of eco-friendly cutting fluid and mineral oil using flood cooling and minimum quantity cutting fluid techniques, J. Clean. Prod. 165 (2017) 1420–1435

[3] T. Rajmohan, S.D. Sathishkumar, K. Palanikumar, S. Ranganathan, Modeling and analysis of cutting force in turning of AISI 316L stainless steel (ss) under nano cutting environment, Appl. Mech. Mater. 766–767 (2015) 949–955

[4] P. Sharma, B.S. Sidhu, J. Sharma, Investigation of effects of nanofluids on turning of AISI D2 steel using minimum quantity lubrication, J. Clean. Prod. 108 (2015) 72–79

[5] M.A.M. Ali, A.N.M. Khalil, A.I. Azmi, Effect of Al_2O_3 nano-lubrication with Sodium Dodecyl benzene Sulfonate (SDBS) on surface roughness and tool wear under MQL during turning of Ti-6AL-4T, IOP Conf. Ser. Mater. Sci. Eng. 114 (2015) 012110

[6] M.K. Gupta, P.K. Sood, V.S. Sharma, Optimization of machining parameters and cutting fluids during nano-fluid based minimum quantity lubrication turning of titanium alloy by using evolutionary techniques, J. Clean. Prod. 135 (2016) 1276–1288

[7] A.S.H. Raja, N. Surendar, V. Vignesh, S. Ravi, C. Narendhar, Temperature analysis when using metal oxide-based ZnO as a new coolant for turning process based on minimum quantity lubrication method (MQL), Int. Res. J. Eng. Technol. 3 (2016) 486–492

[8] U.M.R. Paturi, Y.R. Maddu, R.R. Maruri, S.K.R. Narala, Measurement and analysis of surface roughness in WS2 solid lubricant assisted minimum quantity lubrication (MQL) Turning of Inconel 718, Proc. CIRP 40 (2016) 138–143

[9] A.K. Sharma, A.K. Tiwari, A.R. Dixit, Effects of Minimum Quantity Lubrication (MQL) in machining processes using conventional and nanofluid based cutting fluids: a comprehensive review, J. Clean. Prod. 127 (2016) 1–18

[10] C. Jalandhar, B.C. Behera, S. Ghosh, P.V. Rao, Application of nanofluids during minimum quantity lubrication: a case study in turning process, Tribol. Int. 101 (2016) 234–246

[11] R.W. Maruda, G.M. Krolczyk, P. Niesłony, J.B. Krolczyk, S. Legutko, Chip formation zone analysis during the turning of austenitic stainless steel 316L under MQCL cooling condition, Proc. Eng. 149 (2016) 297–304

[12] B.C. Behera, Chetan, D. Setti, S. Ghosh, P.V. Rao, Spreadability studies of metal working fluids on tool surface and its impact on minimum amount cooling and lubrication turning, J. Mater. Process. Technol. 244 (2017) 1–16

[13] P.J. Liew, A. Shaaroni, N.A.C. Sidik, J.A. Razak, M.S. Kasim, M.A. Sulaiman, Optimization of cutting condition in the Turning of AISI D2 steel by using carbon nanofiber nanofluid, Int. J. Appl. Eng. Res. 12 (2017) 2243–2252

[14] R.K. Singh, A.K. Sharma, A.R. Dixit, A.K. Tiwari, A. Pramanik, A. Mandal, Performance evaluation of alumina-graphene hybrid nano-cutting fluid in hard turning, J. Clean. Prod. 162 (2017) 830–845

[15] P.B. Patole, V.V. Kulkarni, Experimental investigation and optimization of cutting parameters with multi response characteristics in MQL turning of AISI 4340 using nano fluid, Cogent Eng. 4 (2017)

[16] N. Singh, R.K. Singh, A.R. Dixit, Experimental investigation of machinability characteristics under minimum quantity lubrication using graphene based nano-cutting fluid, Int. J. Adv. Res. 5 (2017) 1065–1078

[17] M.K. Gupta, P.K. Sood, Surface roughness measurements in NFMQL assisted turning of titanium alloys: an optimization approach, Friction 5 (2017) 155–170

[18] R. Kumar, A.K. Sahoo, P.C. Mishra, R.K. Das, Measurement and machinability study under environmentally conscious spray impingement cooling assisted machining. Measurement (2018) DOI:10.1016/j.measurement.2018.12.037

[19] H. Hegab, U. Umer, M. Soliman, H.A. Kishawy, Effects of nano-cutting fluids on tool performance and chip morphology during machining Inconel 718, Int. J. Adv. Manuf. Technol. 96 (2018) 3449–3458

[20] A.N.M. Khalil, A.I. Azmi, M.N. Murad, M.A.M. Ali, The effects of cutting parameters on cutting force and tool wear in machining Nickel Titanium Shape Memory Alloy ASTM F2063 under Minimum Quantity Nanolubricant, Proc. CIRP 77 (2018) 227–230

[21] K.-H. Park, G.-D. Yang, D.Y. Lee, Tool wear analysis on coated and uncoated carbide tools in inconel machining, Int. J. Prec. Eng. Manuf. 16 (2015) 1639–1645

[22] O. Gutnichenko, V. Bushalya, S. Bihagen, J.E. Stahl, Influence of GnP additives to vegetable oil on machining performance when MQL assisted turning alloy 718, Proc. Manuf. 25 (2018) 330–337

[23] A. Panda, S.R. Das, D. Dhupal, Experimental investigation, modelling and optimization in hard turning of high strength low alloy steel (AISI 4340), Matér. Tech. 106 (2018) 1–17

[24] M. Dogra, V.S. Sharma, A. Sachdeva, N.M. Suri, J.S. Dureja, Tool wear, chip formation and workpiece surface issues in CBN hard turning: a review, Int. J. Precis. Eng. Manuf. 11 (2010) 341–358

[25] W. Konig, M. Klinger, R. Link, Machining hard materials with geometrically defined cutting edge − field of applications and limitations. CIRP Ann. Manuf. Technol. 39 (1990) 61–64

[26] K. Sobiyi, I. Sigalas, Chip formation characterization and TEM investigation of worn PCBN tool during hard turning, Mach. Sci. Technol. 19 (2015) 479–498

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