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Effect of TiO₂ and Al₂O₃-ethylene glycol-based nanofluids on cutting temperature and surface roughness during turning process of AISI 1018

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Abstract. This paper presents the effect of TiO₂ and Al₂O₃-ethylene glycol based nanofluids on cutting temperature and surface roughness during turning process of AISI 1018. Minimum quantity lubrication (MQL) method has been recognized in minimizing the usage of cutting fluid, as a step to achieve cleaner environment and sustainable machining. However, the low thermal conductivity of base fluid in minimum quantity lubrication system caused the insufficient removal of heat generated in cutting zone. Addition of nanoparticles to the base fluid was then introduced to enhance the performance of cutting fluids. In this study, the machinability of AISI 1018 (mild steel) was investigated under dry machining and nanofluid minimum quantity lubrication method. Two types of nanofluids (TiO₂ and Al₂O₃ nanofluid) with concentration 0.05, 0.15 and 0.3 wt.% were used in this study. The experiments were conducted on lathe machine, using tungsten carbide as cutting tool. Three cutting speed (350, 550 and 750 m/min), three depth of cut (0.5, 1.0 and 1.5 mm) and fixed minimum quantity lubrication system nozzle pressure (5 bar) were applied throughout turning operation. To determine the relationship between machining parameters and cutting temperature and surface roughness values were measured. Based on results obtained, the cutting temperature of workpieces with usage of nanofluids in MQL system gave lower value compared to dry machining. The surface roughness of machined parts was also improved under NFMQL methods. In conclusion, when the nanofluid-MQL method was employed, the amount of cutting fluid was reduced and machining performance improved.

1. Introduction

In industrial manufacturing, machining is widely used in removing materials to convert it into the desired shape. Machining operation widely employed in methods such as turning, milling and drilling. Turning operation is specifically used to shaped cylindrical part using single-point cutting tools. However, the relative motion during machining can cause extensive plastic deformation, and almost



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99% of energy utilized from it were converted into heat [1]. As the temperature rises during machining, tool strength decrease, and leading to faster wear and tool failure [2]. Thus, the cutting fluids were used to cool down the heat around the cutting zone so that the workpiece and cutting tool can be kept under controlled temperature. However, since mid-1990s, there has been trend worldwide to minimize or eliminate the use of cutting fluids due to economic, environmental and human health issue during its use as well as during the disposal [3]. This has led to near dry machining and dry machining practices with significant benefits such as improving air and health quality, also reducing the cost of machining operations. Near dry machining (NDM) is basically the application of fine mist of an air-fluid mixture, containing very little amount of cutting fluids, to the cutting zone [4-6]. This process was also known as minimum quantity lubrication (MQL). The flow rates of MQL typically amount to 1-100 mL/h, estimated to be 1/10000 of that used in conventional flooding methods.

Depending on the type of machining operation, cutting fluid needed as coolant, lubricant or both. The effectiveness of cutting fluid depends on several factors such as type of machining operation, tool and workpiece materials, cutting speed and method of application [7]. Since MQL involves only a small amount of lubricant, it is essential to make sure that lubrication provided is sufficient [8]. However, common base fluids such as oil, water, ethylene glycol and etc. have poor thermal conductivity. Thus, a new generation of fluid with addition of nanoparticles need to be developed in order to enhance performance of cutting fluid in machining performance [9-13]. Therefore, various studies have conducted to investigate the effect and performance of adding nanoparticle in cutting fluids [4, 6, 14-16]. The performance of nanofluid containing various nanoparticles such as Al_2O_3 , TiO_2 , SiO_2 and MoS_2 has been widely researched. References [17-21] in their study have observed significant improvement in thermal behaviour of nanofluid as it enhanced the thermal conductivity as concentration of nanoparticles increased. However, the linearity of relationships still needs further research. Besides cooling functionality, nanoparticles in nanofluid also act as lubrication mechanism. Nanofluids have higher lubricity as nanoparticle provides formation of surface protective film, rolling effect, polishing effect and mending effect. The nano-sized particle can be deposited on damage surface in order to compensate the loss of mass [22-24].

Surface roughness is an indicator of quality for machined materials, therefore measuring surface roughness is important [25]. In measuring surface roughness, average surface roughness presented with R_a symbol; which is the arithmetic average value of departure of the profile from mean line to sampling length [26]. Surface roughness usually influenced by various factors such as tool geometry and feed, cutting conditions, tool wear and deflections, cutting fluids and workpiece properties [27, 28]. During turning process, heat generated by friction between cutting tool and workpiece would cause the cutting tool to wear. Thus, the cutting fluid penetrating between cutting tool and workpiece (cutting zone) plays an important role to control the heat generated at the contact surface and reduces friction. Therefore, it is important to measure the temperature at the cutting zone to ensure the effectiveness of using nanofluids as cutting fluid during machining process. Significant improvement made by various single-phase and hybrid nanofluids has been recorded in term of energy consumption, tool life and surface quality of workpiece. By realizing the multiple benefits offered by nanofluids, this research aims to better understand the effectiveness of TiO_2 and Al_2O_3 nanoparticle as an additive to the base fluid. This study demonstrates the effectiveness of nanofluid-MQL (NFMQL) method using TiO_2 and Al_2O_3 nanofluids in order to enhance the cooling capacity, as well as thermal conductivity and improving surface quality during turning of AISI 1018.

2. Experimental Procedure

2.1. Material, cutting parameters and cutting tool

The material used in the experiment is mild steel, with the specification of AISI 1018. As shown in its alloy composition in table 1, this alloy contains 0.212% of carbon and majority content of ferum (98.4%), with other composition including silicon, manganese and chromium. Tungsten carbide

T9125 were used during turning operation as cutting tool and were replaced for every different concentration of nanofluids used. Turning process in this study was conducted using Lathe Machine ERL 1330, with UNIST Coolubricator MQL system fixed to the lathe machine as can be seen in figure 1. Experiment conditions details of turning process were shown in table 2.

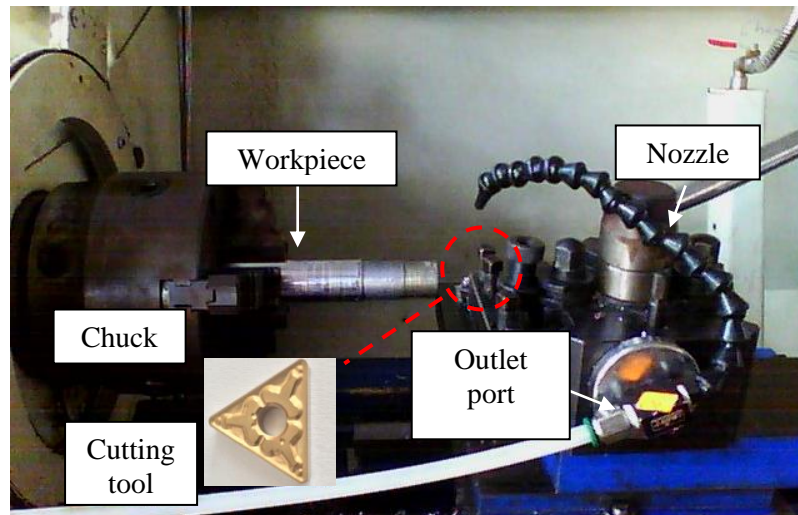


Figure 1. Experimental setup for turning operation with Nanofluid-MQL method.

Table 1. The alloy composition of AISI 1018 (mild steel).

Elements	Fe	C	Si	Mn	Cr	P
Weight (%)	98.4	0.212	0.222	0.561	0.162	<0.003

2.2. Nanofluids Preparation

In this study, the nanofluids were prepared by using TiO_2 (diameter 30-50nm) and Al_2O_3 (diameter 50nm) nanoparticles, purchased from US Nanomaterial Inc. Ethylene glycol (brand Sigma Aldrich) with purity $\geq 99.75\%$ was chosen as the base fluid. Each type of nanofluids was produced in three concentrations, 0.05, 0.15 and 0.3wt.%. The amounts of nanoparticles to disperse in the base fluid were calculated and weighted using weight balance. All concentrations were prepared by mixing the base fluid with nanoparticle using magnetic stirrer for 2 hours and ultra-sonicated in sonicator for another 3 hours. The long hours of sonication process were needed in order to ensure that nanoparticles well dispersed in base fluid. In this study, the stability and thermal properties for nanofluids were measured at each concentration. Zeta potential values were measured using Litesizer Particle Analyzer in order to analyse the stability of nanofluids. Meanwhile, thermal conductivity of nanofluids were measured using KD2 Pro Thermal Analysis under temperature 30°C , 50°C and 70°C . Table 3 shows the properties of ethylene glycol, TiO_2 and Al_2O_3 nanoparticles.

2.3. Cutting Temperature and Surface Roughness Measurements

The present work measures the effect of TiO_2 and Al_2O_3 nanofluids towards cutting temperature and surface roughness of machined workpiece throughout the turning process. Thus, the temperatures of workpiece were recorded in three different time frames; before, in the middle and at the end of the machining process using Forward-looking Infrared (FLIR) thermal camera. Meanwhile, the surface roughness of machined workpieces was measured using surface roughness tester.

Table 2. Experimental conditions.

Item	Description
Machine tool	Lathe Machine ERL 1330
MQL system	UNIST Coolubricator MQL
Workpiece material	AISI 1018 (mild steel)
Workpiece size	32mm diameter, 150mm length
Cutting tool	Tungsten Carbide T9125
Cutting speed (m/min)	350, 550, 750
Feed rate (mm/rev)	0.3, 0.4, 0.5
Depth of cut (mm)	0.5, 1.0, 1.5
Environment	Dry, Nanofluid MQL

Table 3. Properties of base fluid and nanoparticles.

Properties	Ethylene Glycol	TiO ₂	Al ₂ O ₃
Colour	Colourless	White	White
Density (g/cm ³)	1.113	4.23	3.95
Molar mass (g/mol)	62.07	79.86	101.96
Purity (%)	≥ 99.75	≥ 99	≥ 99

3. Results and Discussion

3.1. Properties of Nanofluids

The variations of thermal conductivity value in function of nanofluid concentration and temperature can be seen in table 4. It is clearly shown from data obtained that thermal conductivity increase when concentrations increase. This trend reveals that adding nanoparticles enhanced the thermal conductivity of fluids compared to the base fluid (ethylene glycol). However, thermal conductivity of nanofluids in this study was found not dependant to the temperature rise. Some results from certain concentration pointed out the decrement trend over increasing temperature. This finding contradicts to conclusions by some researchers that thermal conductivity increase with temperature rise due to more collisions between particle and increasing Brownian motions [29]. Nevertheless, thermal conductivity value for TiO₂ nanofluid with concentration 0.15% shows increment as temperature increased from 30°C to 70°C. This may related to stability of nanofluid, since dispersion of nanoparticle in base fluid did affect the measurement of thermal conductivity.

References [30-32] have also observed the enhancement of thermal conductivity of conventional fluids when added with nanoparticles. There are few factors that affected the enhancement of thermal conductivity of nanofluid such as temperature condition, the shape of nanoparticles, size of nanoparticles, type of nanoparticles and type of base fluids [33-35]. By adding the nanoparticles in base fluid, the thermal conductivity was expected to improve since nanoparticles have higher thermal properties compared to base fluid [36, 37]. In experimental investigation conducted by references [38, 39], the maximum enhancement of TiO₂ nanofluid was recorded at smaller particle size and higher concentration (0.2vol.% to 2.0 vol.%). Results obtained in this study coincide with this finding, where thermal conductivity value increase as nanofluid concentration increase at temperature 30°C. Other researchers [29, 33, 40] also agreed with this discovery, where addition of Al₂O₃ nanoparticle with various size to different base fluid increased the thermal conductivity.

Table 4. Thermal Conductivity of nanofluids vs temperature.

Concentration (%)	Thermal Conductivity (W/m°C)					
	TiO ₂ nanofluid			Al ₂ O ₃ nanofluid		
	30°C	50°C	70°C	30°C	50°C	70°C
0.05	0.283	0.315	0.288	0.295	0.292	0.290
0.15	0.298	0.303	0.323	0.296	0.294	0.285
0.30	0.298	0.294	0.294	0.298	0.298	0.291

The stability of nanofluids was measured using zeta potential analysis, which considered as qualitative observation of nanofluids colloidal stability in static conditions. The stability of nanofluids was determined by the zeta potential value, typically range from 0 to 60 mV, categorized to the different level of stability and settling. Table 5 shows the measured zeta potential value for both nanofluids for all concentrations. For TiO₂ nanofluids with concentration 0.05 and 0.30wt.%, the value indicates that the suspension has moderate stability and little settling. Meanwhile, concentration 0.15% gave value of 41.02 mV, indicates that the nanofluid has good stability with possible settling. The stability of TiO₂ nanofluid with concentration of 0.15% explained the enhanced thermal conductivity with increasing temperature discussed before. On the other hand, Al₂O₃ nanofluid with all three concentration gave lower zeta potential value, signifying that the nanofluid has some stability with lightly settling.

Table 5: Zeta potential value for nanofluids.

Concentration (%)	Zeta potential value (mV)	
	TiO ₂	Al ₂ O ₃
0.05	22.14	11.51
0.15	41.02	11.37
0.30	28.12	16.73

3.2. Effect of Nanofluids on Reducing Cutting Temperature

The heat generated at the cutting zone resulted from the friction of cutting tools and workpiece can be controlled or lowered by the penetration of cutting fluids into the zone. The cutting temperatures in this study were measured average nine times for every nanofluid concentration, according to different cutting speed and depth of cut. Figure 2 shows comparison of cutting temperature of workpiece during dry machining and NFMQL method. For NFMQL method, the temperature value of nanofluids with concentration 0.05wt.% and depth of cut 0.5mm were taken as comparison. Generally, the cutting zone temperature for all machining conditions shows increment trend as the cutting speed increased from 350m/min to 750m/min. However, dry machining record the highest value of temperature between 77.4°C to 81.2°C. In machining process, when the cutting speed rise, it generally increase the friction and subsequently increase the temperature of the chip-tool interface [41]. The high cutting temperature during dry machining happened because of no cooling agent was applied throughout machining operation. Meanwhile, the cutting temperature of workpiece when applied TiO₂ nanofluid range from 69.2°C to 73.5°C, reducing 10.6% of heat generated compared to dry machining. The usage of Al₂O₃ nanofluid reduces more temperature (18.5%) compared to dry machining. Figure 3 shows comparison between cutting temperature for both nanofluids under three concentrations. It shows that Al₂O₃ outperform TiO₂ nanofluids in reducing temperature for all concentrations, under different cutting speed.

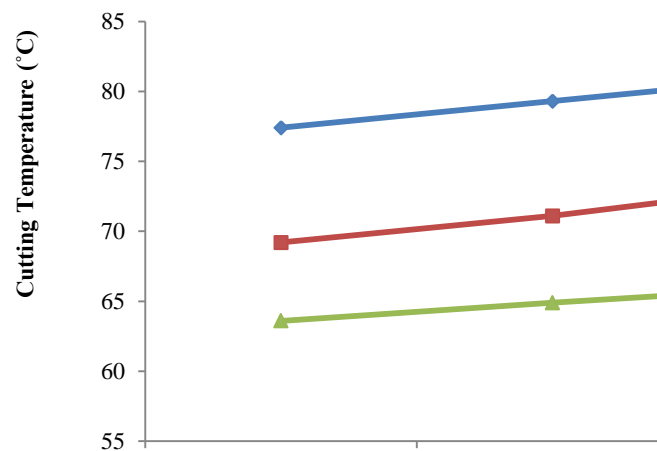


Figure 2. Cutting temperature of workpieces using dry machining and NFMQL method.

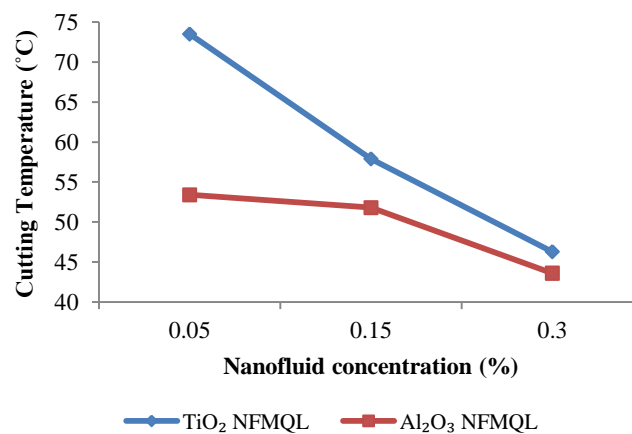


Figure 3. Cutting temperature of the workpiece using TiO₂ and Al₂O₃ nanofluids during NFMQL method.

Through the data obtained, the nanofluid application in MQL system has been proven successful in reducing the heat generated at the cutting zone. Efficient penetration of nanofluids into the cutting zone leads to the formation of nanoparticles layer with lower shearing strength. These layering around the particle may give a path for rapid conduction, thus lowering the heat generated at cutting zone. This finding was agreed by reference [42] where they conducted study on two different class of nanofluids, coolant and lubrication type. TiO₂ and Al₂O₃ nanoparticles which fall under lubricant type reduce grinding temperature (19.6%, 28.9%) and gave better performance compared to coolant type nanoparticles such as NiO and CuO (14.5%, 15.9%). Although both nanofluids gave better performance compared to dry machining conditions, significance difference of cutting temperature measured can be seen in both figure 2 and figure 3. The good performance of Al₂O₃ nanofluids in reducing cutting temperature can be explained by its structure and characteristics. The spherical shape of Al₂O₃ nanoparticle reduces the sliding friction to the workpiece surface, and instead change the friction to combination of rolling and sliding friction (bearing effect). Thus, alongside effective penetration into the cutting zone, less friction consequently decreases cutting force and cutting temperature of the workpieces. Thus, it can be concluded that mechanism of TiO₂ and Al₂O₃

nanoparticles in reducing cutting temperature were by decreasing the friction and cutting force, and not by increasing the heat removal through cooling actions.

3.3. Effect of Nanofluids on Surface Roughness Value

The surface quality of machined products is generally associated with the surface roughness of workpiece. In this study, surface roughness of machined workpiece for dry machining condition and NFMQL condition measured using surface roughness tester. Surface roughness presented with R_a symbol is expressed as irregularities of material resulted from various machining operations. Surface roughness usually affected by few factors such as cutting parameters, cutting fluids and workpiece properties. Figure 4 shows the surface roughness (measured in μm) for three machining condition with depth of cut 0.5mm and three different cutting speeds. The surface roughness of workpiece under dry machining condition obviously was higher compared to the NFMQL method's workpiece. Moreover, the roughness of the workpiece constantly reduces as the cutting speed increase. The same trend was also recorded for both nanofluids used in NFMQL method.

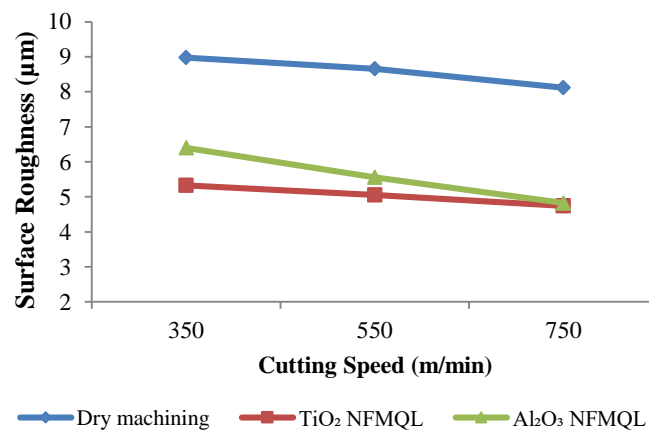


Figure 4. The surface roughness of machined workpiece during dry machining and NFMQL method.

Table 6 and 7 show the surface roughness value of machined workpiece using TiO₂ and Al₂O₃ nanofluid with various concentrations respectively. Based on the data obtained, when comparing the R_a value for workpiece under dry machining condition, TiO₂ nanofluid shows larger decrement compared to Al₂O₃ nanofluid. At cutting speed 350m/min and depth of cut 0.5mm, addition of TiO₂ nanoparticles enhanced the surface roughness by 39%, 65% and 83% for concentration 0.05, 0.15 and 0.3wt.% respectively. Moreover, the R_a values continue to decrease over the increasing cutting speed and nanofluid concentration.

For Al₂O₃ nanofluid, the overall roughness value decrease compared to dry machining condition. At cutting speed 350m/min and depth of cut 0.5mm, enhancement of R_a values recorded by 19.7%, 24.8% and 29.3% for concentration 0.05, 0.15 and 0.3wt.% respectively. The R_a value for these set of workpiece also follow the decrement trend as cutting speed and nanofluid concentration increased. Less improvement in R_a value by Al₂O₃ nanoparticles may be caused by two things. First, the properties of the nanoparticles that have high hardness compared to the workpiece and led to micro-abrasive on the workpiece surface. This finding also supported by Wang Y, Li C, Zhang Y, Yang M, Zhang X, Zhang N and Dai J [43], where higher concentration of nanofluid resulted in poorer surface quality of machined parts. The second opinion involved the stability of nanofluid, where the 'not so

well' dispersed nanoparticles in base fluid tend to agglomerate with each other to form microparticle. This microparticle increases the R_a value of machined workpiece, thus decrease the surface quality.

Table 6. Surface roughness value measured for workpiece using TiO_2 nanofluid.

Cutting speed (m/min)	Depth of cut (mm)	Surface roughness, R_a (μm)		
		TiO_2		
		0.05%	0.15%	0.30%
350	0.5	5.33	3.04	1.47
	1.0	5.88	3.55	1.85
	1.5	6.49	4.18	2.37
550	0.5	5.05	2.98	1.29
	1.0	5.45	3.42	1.62
	1.5	6.21	3.84	2.29
750	0.5	4.74	2.62	0.72
	1.0	5.05	3.37	1.53
	1.5	6.05	3.68	2.11

Table 7. Surface roughness value measured for workpiece using Al_2O_3 nanofluid.

Cutting speed (m/min)	Depth of cut (mm)	Surface roughness, R_a (μm)		
		Al_2O_3		
		0.05%	0.15%	0.30%
350	0.5	7.02	6.58	6.18
	1.0	7.89	7.04	6.50
	1.5	8.35	7.81	6.99
550	0.5	6.42	5.98	5.74
	1.0	7.17	6.49	6.04
	1.5	7.70	7.24	6.45
750	0.5	5.41	5.18	4.54
	1.0	6.16	6.08	5.02
	1.5	7.05	6.5	5.87

According to reference [44] there are three levels on how nanoparticles assist in cutting operation and affecting surface roughness during the machining process. For the first level, nanoparticles partially embedded a machined surface, sheared and change shape due to compression. The sheared off debris then continue to assist cutting, as well as nanoparticle that rolls on surface. When the nanofluid become more concentrated, partially embedded nanoparticles were ploughed off by new nanoparticle and continue to polish the surface. However, the ploughed off nanoparticle would develop thin films as a result of high loading damage, in accordance to result found by reference [45]. At the third level, when concentration of nanofluid further increase, nanoparticles impregnated the surface pores and later shoved off by incoming particles. These motions soon produce more lubricating film, thus the surface gets polished and improved quality surface.

Based on the result obtained through this study, it is clear that by adding nanoparticles in cutting fluid, surface quality of the machined workpiece can be enhanced. This statement was supported by reference [46] in their study where the addition of TiO_2 nanoparticles in vegetable oil reduce the average surface roughness by 34.7%, 11.64% and 7.22% compared to dry, conventional and wet machining respectively. Besides that, references [47] and [48] also evaluated the performance of nano graphite-based cutting fluid and found that the nanofluid reduce the cutting force by 54% and surface roughness by 30% compared to conventional flood cooling. However, for certain nanoparticles like Al_2O_3 , the selection of concentration value was important in order to ensure the improvement of

surface quality. References [43] and [49] agreed that by adding Al₂O₃ nanoparticles with concentration less than 2.0 vol.% can help produced more refined surface finish. Besides that, use of larger diameter (80nm) would also deteriorate the surface finish, compared to smaller diameter (40nm) of nanoparticles. This conclusion was also supported by [50-53].

4. Conclusions

The following conclusions may be drawn based on results obtained from the experimental investigation conducted:

- i) In term of stability of nanofluid, TiO₂ have moderate stability with possible settling, compared to Al₂O₃ nanofluid that has little stability and likely has settling. The more stable nanofluid would affect the enhancement of thermal conductivity; therefore exert influence on machining performance.
- ii) TiO₂ and Al₂O₃ nanofluid enhance the thermal conductivity in the function of increasing concentration, but not dependent in function of rising temperature. These occurred due to little stability of nanofluids produced.
- iii) Cutting temperature for workpiece machined under NFMQL method reduced compared to dry machining condition. The decrement in temperature resulted from proper cooling action by a nanofluid, which led to lower friction and increased heat removal.
- iv) When comparing both nanofluids in NFMQL method to dry machining, surface roughness, R_a value for workpiece using TiO₂ nanofluid gave better result than Al₂O₃ nanofluid. However, roughness of machined workpiece using both nanofluids shows decrement trend as the concentration increased.
- v) Based on results obtained through this study, it can be concluded that addition of nanoparticles to the cutting fluid does enhance the thermal conductivity, lower the cutting temperature at the cutting zone and improve surface roughness of the machined workpiece.

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