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Influence of nanolubricant particles' size on flank wear in hard turning

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ABSTRACT

This paper presents the effects of cutting speed, nanoparticles' size, and their concentration in water-based TiO_2 nanofluid on the magnitude of tool flank wear and tool wear rate. The types of nanoparticles and base fluid, nanoparticle size, and nanoparticle concentration can affect the tribological and heat transfer properties of nanofluids, and thereupon, these parameters can affect the cutting forces and temperatures during the metal cutting process, thereby affecting tool wear and nanolubricant consumption. According to the achieved results, with an increase in the size of nanoparticles from 10 to 50 nm, the average decrease in cutting tool flank wear reduces from 46.2% to 34.8%.

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Flank; Wear; Nano; Fluid; TiO_2; Particle; Size; Lubricant; Hard; Turning

Introduction

In general, machining hardened steels with hardness exceeding 45 HRC is referred to as *hard turning*.[1] Hard turning has always been associated with challenges such as achieving appropriate surface roughness, reducing cutting forces, decreasing tool wear, and lowering heat generation during the metal cutting process.[1] Among these, extensive tool wear due to high cutting forces and temperatures is of prime importance; this importance originates from tool wear effect on surface integrity, dimensional accuracy, machining cost, etc.

Lower cutting tool wear may be obtained by choosing proper cutting parameters, developing modern machining processes, choosing coated cutting tools (e.g. multi-layer coatings), and applying lubricants during the cutting process.

Growth and development of hard machining processes are largely owed to the appearance of new state-of-the-art tools such as Cubic Boron Nitride (CBN), Polycrystalline Cubic Boron Nitride (PCBN), and ceramics and newly developed techniques to deposit nanocomposite coatings such as AlTiN, TiAlN/TiSiN, and nanocrystalline AlTiCrN.[2] These types of cutting tools are able to combine high hardness and toughness together due to their nanoparticles. These properties will lead to better machining performance (such as lower cutting tool wear, lower machining cost, etc.). Therefore, these coated tools are good candidates for hard machining processes.

Despite the necessity to develop coated cutting tools, it should be stipulated that although dry-machining is possible in some cases, there are still many issues (e.g. thermal damages to workpiece, metallurgical changes, and tool life) which make it inevitable to use cutting fluids.[3–5] In addition, cutting fluids are also used to (1) reduce frictional force, (2) reduce heat dissipation from cutting zones, (3) reduce machining stresses, and (4) help to remove chips.

Lowering the friction force is the key to explain the mechanism by which cutting fluids can decrease cutting tool wear; smaller values of frictional force reduce both heat generation and forces in machining zones and smaller cutting force and temperature attenuate wear mechanisms. Therefore, there are benefits in applying cutting fluids from the standpoint of cutting tool wear. This is while the trend in machining science and technology is to omit or minimize cutting fluid application in machining processes. Therefore, in the recent years, advanced techniques such as dry cutting, high-pressure coolant, minimum quantity lubrication (MQL), electrostatic minimum quantity lubrication (EMQL), minimum quantity cooling lubrication (MQCL), and cooling with compressed air have been developed[3–5] or new lubricants have been introduced (e.g. nanofluids).[5,6]

In the MQL technique, the cutting fluid is a jet of compressed air containing little droplets of oil which is applied to the machining area[3]; the main objective is to lubricate; therefore, oil is used as the main active medium. On the other hand, the main task in the MQCL technique is to reject heat from the material removal area; therefore, the main medium will be an emulsion concentrate.[3] EMQL is another technique in which tiny amounts of the lubricant are charged electrostatically and then these negatively charged particles are directly applied to the cutting zone.[4]

Modern cutting fluid methods require a small amount of cutting fluid; therefore, the coolant needs to have excellent abilities to cool and lubricate, improving lubricative characteristics; Maruda et al. added phosphate ester-based anti-wear additives to the MQCL technique and observed smaller cutting tool wear in comparison with dry and MQCL condition due to creation of a tribological film on the contact area between the cutting tool and chip.[5] Nanofluids are a group of engineered fluids prepared by dispersion solid nanoparticles in a base fluid

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with the aim of enhancing its heat transfer characteristics. Therefore, nanofluids are well solution for MQL technique.[6]

In 2011, Vasu and Reddy investigated the application of Al_2O_3 nanofluid in machining Inconel 600. According to the obtained results, using this nanofluid will lead to significant reductions in tool wear, surface roughness, cutting forces, and temperatures.[7] However, the effect of nanoparticles' size and their concentration on process output was not studied.

In 2014, Sayuti et al. studied workpiece surface roughness and cutting insert wear in case of using SiO_2 nanofluid as a lubricant; according to the achieved results, increasing nanoparticles concentration will decrease cutting tool wear.[8] Nanoparticles behave like some nanobearings, and increasing their concentration increases their chance to be present at interfaces and the latter reduces friction force.

In 2016, Muthusamy et al. used ethylene glycol/TiO_2 nanofluid in machining AISI 304 and reported longer cutting tool life due to formation of an oxide layer during the oxidation wear mechanism which protects the cutting edge from dynamic loading during the machining process.[9]

In 2016, Najiha et al. used TiO_2 nanofluid in the MQL technique and reported a remarkable reduction in cutting edge fracture and chipping in comparison with MQL condition.[10] This observation is mainly due to the superior thermal properties of TiO_2nanofluid to reject heat from cutting regions.

In a most recent work, Sharma et al. (2016) used TiO_2 nanofluid as lubricant in the cutting process and reported lower tool wear and surface roughness.[11] This observation was also reported by Ukamanal et al. in machining AISI 316 and can be attributed to the advanced thermal specifications of TiO_2nanofluid.[12]

According to the abovementioned studies, adding nanoparticles such as MoS_2, TiO_2, CuO, and Al_2O_3 to a base fluid can enhance not only the heat transfer characteristics of the lubricant but also the anti-abrasion and anti-friction properties of the fluid. The enhancement in heat transfer characteristics reduces the temperature within the cutting zones; accordingly, it reduces cutting tool temperature and attenuates cutting tool wear mechanisms.

Research on thermal conductivity, convection coefficient, and tribological properties of nanofluids indicate that the mentioned properties are functions of nanoparticles type, base fluid, nanoparticles' size, and concentration. Based on the experimental studies by Chon et al. (2005), the improvement in $k_{nanofluid}$ (i.e. thermal conductivity of the nanofluid) decreased with increasing nanoparticles' size in the range of 11–150 nm.[13] Further investigations by Calvin et al. showed that in practice, a change in the size of the nanoparticles in the range of 36–47 nm does not have any effect on $k_{nanofluid}$.[14] Further studies by Yang et al. (2010) revealed that in a range of 30–90 nm, increasing aluminum oxide nanoparticles' concentrations and/or decreasing their size will improve $h_{nanofluid}$[15]; such an improvement in $h_{nanofluid}$ (i.e. convention coefficient) of TiO_2nanofluids was reported by Khajehzadeh et al. (2018).[16]

Table 1. Mechanical properties of AISI 4140 steel.[8]

Yield stress (MPa)	Ultimate tensile stress (MPa)	Density (kg/m^3)	Elastic modulus (GPa)	Elongation (%)	Poisson's ratio
417	655	7700–8030	190–210	27.5	0.27–0.3

The above literature review indicates that the type of nanoparticles and base fluid as well as the nanoparticle size and concentration in the base fluid contribute to the reductions achieved in cutting force and heat generation during the material removal process and therefore on the resultant tool wear. This subject has not been studied yet. Therefore, the present paper concentrates on the effects of TiO_2 nanoparticles' size and concentration on cutting tool flank wear and wear rate.

Materials and methods

Orthogonal cutting experiments

In the present research work, AISI 4140 steel-made solid bars Φ39 mm were used (Table 1). This is a chromium–molybdenum alloy steel. The presence of chromium provided the steel with appropriate hardness, while the molybdenum guaranteed high strength and uniform hardness across of the steel. This steel is one of the most popular materials in different industries, with applications in the manufacturing of shafts, cams, camshafts, crankshafts, gears, chain wheels, nuts, screws, etc. Surface hardness of the specimens was adjusted to 48 ± 1 HRC.

Cutting tool and machining parameters

A TN50D turning machine was utilized to hard-turn the specimens. Moreover, insert and tool holder were selected from SECO Co.: SNMG 090308-MF2 TP15 and PSBNR 2020K 09. Turning inserts with tungsten carbide substrate deposited with two coating layers (TiCN and Al_2O_3) were used. Used cutting tool specifications: rake angle $\gamma = -6°$, side and end cutting edge angles $\kappa_r = 75°$ and $\kappa'_r = 15°$, radius of tool nose $r_\varepsilon = 0.8$ mm. The experimental tests were carried out with a permanent depth of cut and feed ($a_p = 0.9$ mm and $a_f = 0.11$ mm/rev).

Nanofluid preparation

In order to prepare water-based TiO_2 nanofluid, firstly, sodium dodecyl benzene sulfonate (SDBS) was added to the base fluid (water) at a weight equal to one-tenth of the weight of the nanoparticles (Table 2). Then, the surfactant was dis-

Table 2. TiO_2 nanoparticles attributes.

	Particle size (nm)	Surface area (m^{2}g^{-1})	Purity (%)	Appearance	Bulk density (gm^{-3})	Real density (gm^{-3})
TiO_2 (Anatase)	10–25	200–240	99	White Powder	0.24	3.9
TiO_2 (Rutile)	50	25	99.9	White Powder	0.65	–

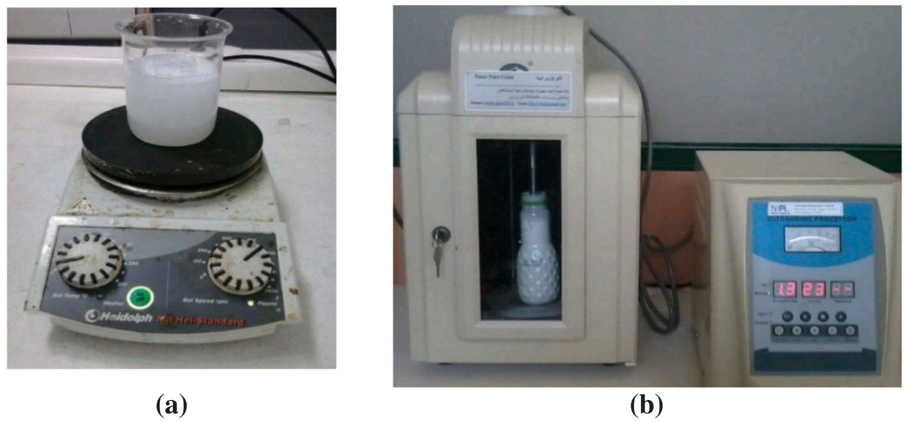


Figure 1. Equipment items used for preparing the nanofluid: (a) magnetic stirrer and (b) ultrasonic stirrer.

solved in water under magnetic stirring. The SDBS was used to enhance the nanofluid stability.[16]

Upon dissolving the SDS in water, nanoparticles of TiO_2 were added to the solution and the solution was once more subjected to magnetic stirring for 20 min (Fig. 1(a)). Continuing with the procedure, in order to better suspend the particles across the base fluid, the obtained nanofluid was transferred into a special vessel where it was ultrasonicated on an ultrasonic stirrer for 3 h (230 V, 55 kHz, 350 W, Fig. 1(b)).

Flank wear measurement

The wear on the tool flank occurs due to friction and hence abrasive contact of the machined part and tool flank. An increase in the tool flank region increases machining forces and required power for the cutting operation.

As illustrated in Figs. 2 (a–c), wear traces are relatively uniform along the middle segment of the cutting edge only, so that one may refer to maximum or average flank wear within this segment (VB_{max} and VB, respectively) to express the tool wear in terms of the tool flank. In general, tool flank measurement is easier than the crater wear measurement. As such, the tool wear was evaluated based on the tool flank measurement.

Measurement of flank wear was carried out every 6 min (Fig. 8). Primary cutting test shows that wear traces in zone B have irregular patterns; therefore, with respect to ISO 3685:1993, the measuring process was concentrated on central regions of the main cutting edge and the maximum value in this region (i.e. VB_{max}) was selected as a wear criterion. Experimental tests to measure VB_{max} were repeated three times for each cutting test and the average value was recorded. In order to omit the effect of previous machining cuts, a new cutting edge was used for each test. In the present research,

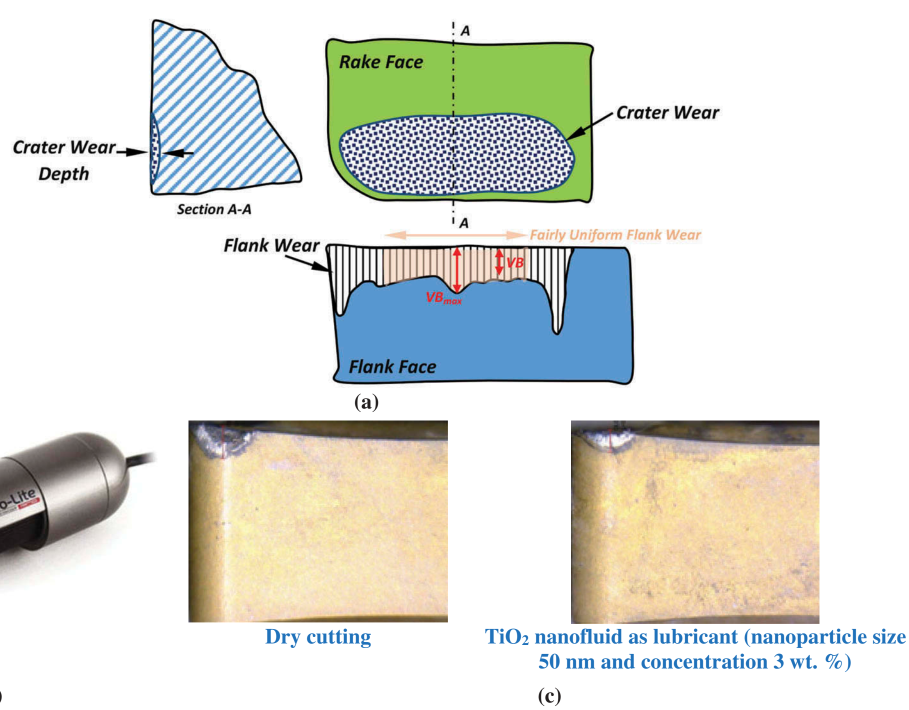


Figure 2. Wear on tool flank: (a) schematic representation, (b) utilized digital microscope, and (c) differences in tool flank wear in case of dry cutting and using TiO_2 nanofluid (a_f = 0.11 mm/rev,V_c = 60 m/min).

Table 3. Cutting parameters and their values.

	Cutting condition	Level 1	Level 2	Level 3
V_c	Cutting speed (m/min)	60	90	120
d_p	Particle size (nm)	10–25	50	–
	Concentration (% wt.)	0.5	1.5	3.0

a digital Dino-Lite AM-413ZT microscope (Fig. 2(b)) was used for VB_{max} measurement. The microscope provided for magnification at 20×–200×.

Experiment design and measurement

The experimental tests were executed under a full factorial scheme; input parameters include the cutting speed (V_c), nanoparticle size, and nanoparticle concentration (Table 3).

A simple system was designed and manufactured for nanofluid application to the cutting zone. The distance of the nozzle from the cutting area was 0.25 m and its diameter was 2 mm. The cutting tests were carried out with a volume flow of 500 mL/min. Moreover, a rotor coupled with a small electromotor ensured uniformity of the nanofluid concentration by rotating the rotor at low rpm (Fig. 3).

The principal component of machining force (F_c) was measured using a calibrated KISTLER dynamometer equipped with a KISTLER 5070 charge amplifier. In order to measure cutting tool temperature, a small blind hole was created in the cutting tool and near cutting edge using super drill machining; then a thermocouple cable (Testo 735-2) entered the created hole and measured cutting temperature with the help of Comfort software X35.

Results and discussion

Main cutting force

In the present research, F_c was observed to decrease by an average of 16% upon using TiO_2 nanofluid as cutting fluid (Fig. 4(a)). Nanoparticles penetrate into the tool–chip interface and act as nano bearings, thereby changing the friction regime from slipping to rolling.

Increasing the nanoparticle concentration from 0.5% to 3% will increase the reduction in F_c from 9.6% to 22.3% (Fig. 4(a)). In fact, an increase in the nanoparticle concentration improved their chances of being present at contact faces, where a layer of slipping particles is developed and decreases the resultant friction and cutting forces (Fig. 5).

Increasing the size of nanoparticles from 10 to 50 nm lowered average decrease in F_c from 14.6% to 4.8% (Fig. 4(b)). This reduction can be explained by the fact that, with smaller nanoparticles, not only it is easier for the particles to penetrate into the contact surfaces and change the friction regime from slipping to rolling,[7,8] but also the area-to-volume ratio of the particles will grow larger, thereby improving the heat transfer from the machining zone,[13–15] attenuating the tool wear, and finally reducing the cutting forces.

Cutting tool temperature

In the present research, the cutting tool temperature was observed to decrease by an average of 43% upon using nanofluid as cutting fluid (Fig. 6). The same trend was reported by Ukamanal et al.[12]

The amount of temperature reduction is highly affected by nanofluid's type, size, concentration, lubricant applying method[3,4] and machining condition. Due to the superior thermal properties of TiO_2 nanofluid,[13–16] further heat can be rejected from the cutting zone. Moreover, with its desired properties, the nanofluid can reduce the friction force[10–12] which in turn lowers the generated heat in secondary and third shear zones.

Smaller nanoparticles and increasing their concentration will increase $h_{nanofluid,}$[16] and the latter will intensify nanofluid cooling ability. Therefore, a larger deal of heat could be rejected from the material removal zone (Fig. 6).

By increasing nanoparticles' concentration from 0.5% to 3%, the reduction in steady-state temperature grew from 29.4% to 37.6% (Fig. 6(a)). This behavior can be explained by the fact that an increase in nanoparticles' concentration improves both $k_{nanofluid}$ and $h_{nanofluid,}$[13–16] which may end up lowering the temperature across the cutting zones.

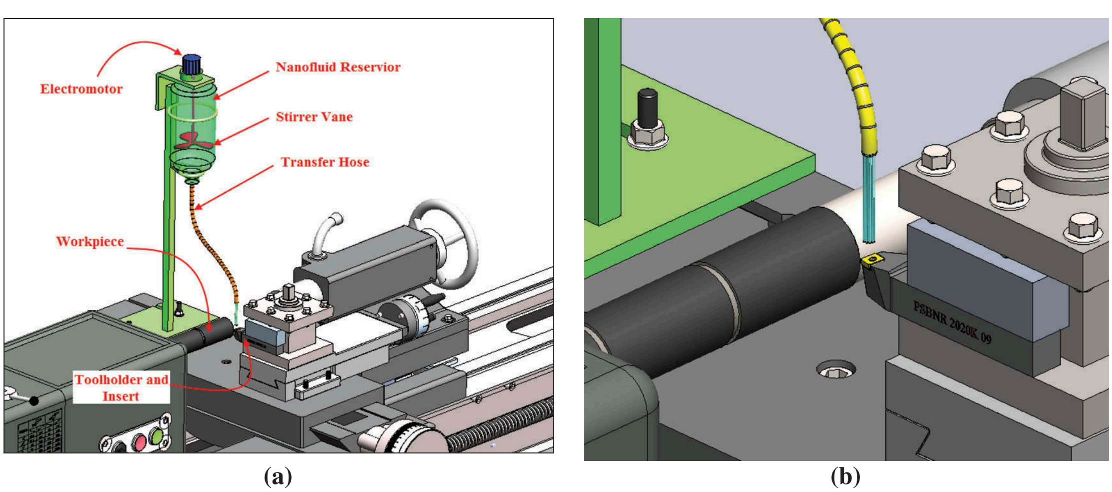
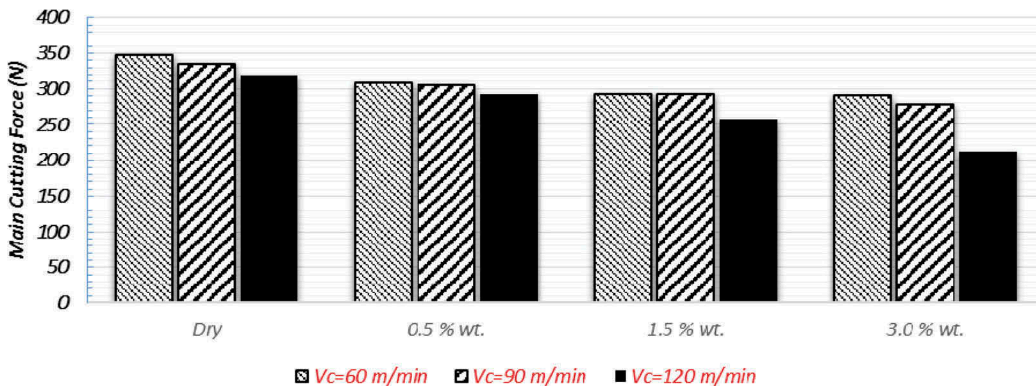
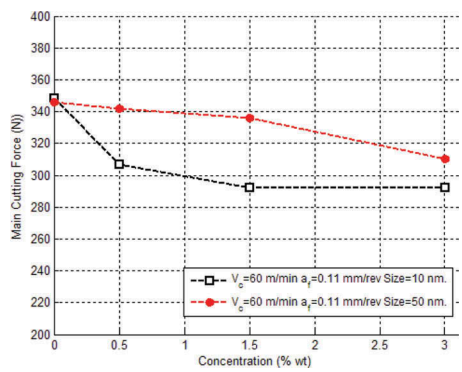


Figure 3. The system used to transfer the nanofluid to the machining tool.



(a) nanoparticle size 10 nm



(b) Cutting speed 60 m/min

Figure 4. Impacts of nanofluid concentration and nanoparticle size on F_c (feed: 0.11 mm/rev).

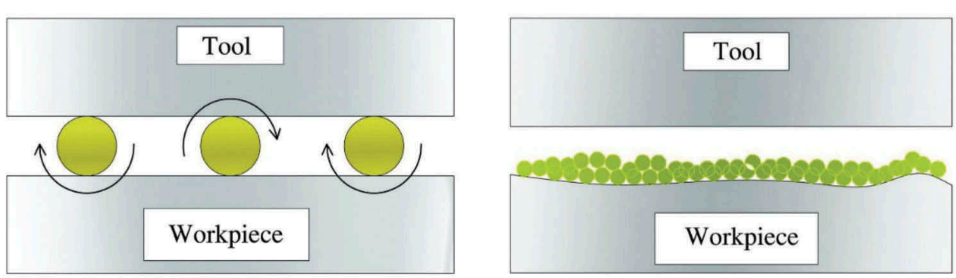


Figure 5. Nanoparticles exhibiting a rolling behavior, thereby reducing the slipping friction.

Upon increasing the nanoparticle size from 10 to 50 nm, the decrease in steady-state temperature dropped from 43% to 33% (Fig. 6(b)). The ratio of nanoparticle's area-to-volume is greater in case of smaller nanoparticles, thereby increasing $k_{nanofluid}$.[14] Therefore, a decrease in the size of nanoparticle increases $h_{nanofluid}$ and leads to further reduction in cutting tool temperature.

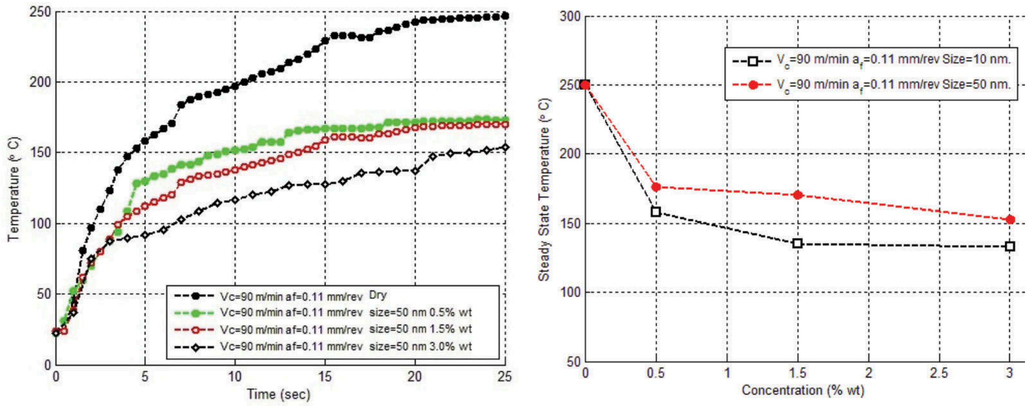
Cutting tool flank wear

One of the most important observations in the present research was the significant reduction (averagely 35.9%) in VB_{max} upon using water-based TiO_2 nanofluid as cutting fluid (Fig. 7).

Similar trends were reported by previous research studies.[7–9] However, the average amount of reduction in VB_{max} reported by various authors is different; this paper presents an average reduction of 35.9% in VB_{max} while the amount of reduction reported by Vasu et al. is about 55%. This is mainly due to differences in type, size, and concentration of applied nanofluids. As mentioned previously, thermal characteristics of nanofluids are functions of nanoparticles' type, size, and concentration.[13–15] In addition to nanofluid's characteristics, the lubricant applying method (dry, MQL, MQCL, flood, etc.) and cutting parameters can affect the amount of reduction in friction forces, $k_{nanofluid}$ and $h_{nanofluid}$, and cutting tool wear. However, the effect of nanoparticles' size and concentration on cutting tool wear was not studied in previous research studies.

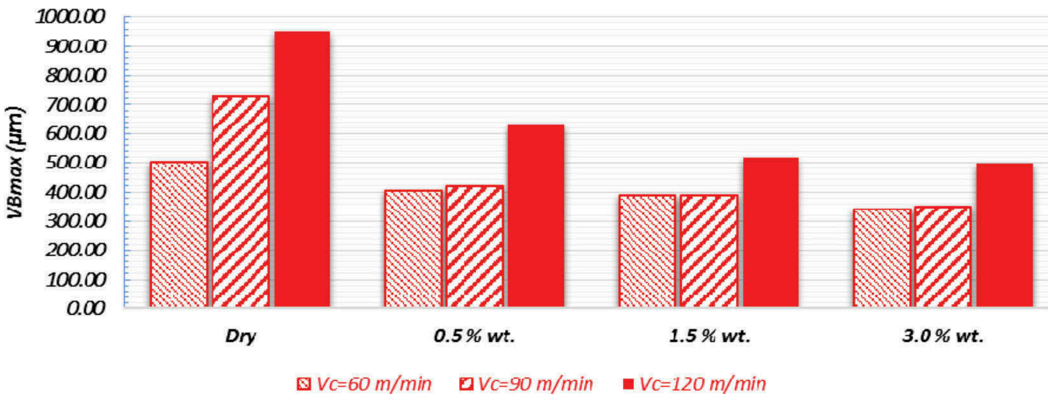
The following mechanisms can describe how nanofluids can reduce VB_{max} in the cutting process:

a. With its characteristics, the nanofluid can reduce the friction coefficient and cutting forces, and given that

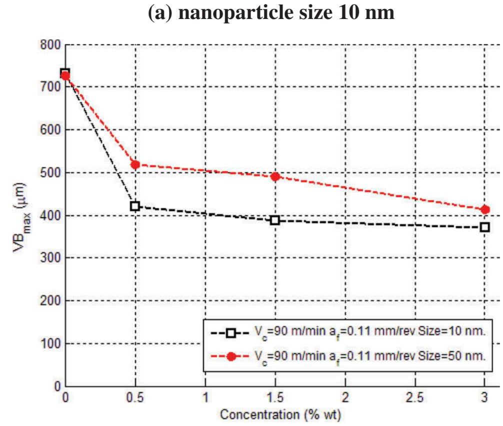


(a) (b)

Figure 6. The effect of nanofluid concentration and nanoparticle size on the cutting tool temperature.



(a) nanoparticle size 10 nm



(b) Cutting speed 90 m/min

Figure 7. Impacts of nanofluid concentration and nanoparticle size on the flank tool wear (feed: 0.11 mm/rev).

the force and temperature on the contact area are key drivers of adhesive wear, the reduction in the forces by the nanofluid can attenuate adhesive wear of cutting tool.

b. Thanks to its high $h_{nanofluid}$, nanofluid is able to lower cutting temperature over the cutting zone significantly. Therefore, with respect to the fact that cutting temperature is the key driver of diffusion and electrochemical wears, nanofluid is able to attenuate these wear mechanisms.

Increasing concentration from 0.5% to 3%, average decrease in VB_{max} increases from 30.1% to 41.32% (Fig. 7(a)). The following are the main causes supporting this behavior:

a. An increase in the nanofluid concentration can improve the thermal performance of the system,[13–15] so that further heat can be rejected from the cutting zone, thereby retarding wear due to diffusion which commonly occurs at elevated temperatures.

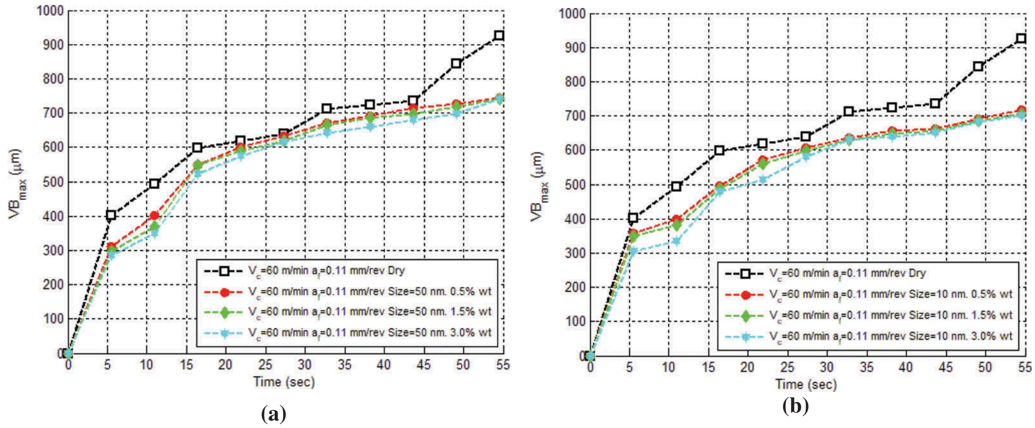


Figure 8. The impact of nanoparticles' size and their concentration on tool wear rate (V_c = 60 m/min and a_f = 0.11 mm/rev).

b. Higher nanofluid's concentration increases the likelihood of forming a rolling layer across the tool–chip interface. Such a layer can decrease the friction coefficient and thereby retard adhesive wear.

Increasing the size of nanoparticles from 10 to 50 nm will decrease reduction in VB_{max} from 46.2% to 34.8% (Fig. 7(b)). This phenomenon can be caused by either of the following:

a. The ratio of nanoparticle's area-to-volume is greater in case of smaller nanoparticles, thereby increasing $k_{nanofluid}$. Accordingly, a reduction in the size of nanoparticle leads to higher $h_{nanofluid}$, hence reducing cutting tool temperature and, in turn, abrasive wear of the tool.
b. Smaller nanoparticles can penetrate into the tool–chip interface and reduce the abrasive wear easier.

It is necessary to mention here that higher concentrations of nanoparticles were found to significantly increase toxicity. In addition, nanoparticles with the smallest size have the highest mortality rate. Therefore, there should be an optimum value for nanofluid concentration and nanoparticles' size in which both improvement in machining performance and lowest toxicity and mortality are achieved.

Considering the impacts of increasing the nanoparticle concentration and decreasing the nanoparticle size on the reduction of cutting force (16%) and temperature (42%), it is observed that the rate of tool flank wear decreases by reducing the nanoparticle size from 50 to 10 nm and/or increasing concentration from 0.5% to 3% (Fig. 8).

Conclusion

In the present research, the effects of size and concentration of TiO_2 nanoparticles in a water-based nanofluid on F_c, cutting temperature, and VB_{max} were experimentally studied in hard turning of hardened AISI 4140 steel. For this purpose, a series of experimental tests were performed to study the effects of nanoparticle size and concentration on the magnitude of VB_{max}. Within the selected ranges for machining parameters, the following conclusions are made:

(1) Using water-based TiO_2 nanofluid reduces VB_{max} averagely by 35.9%, in comparison with dry cutting.
(2) Increasing nanoparticles' concentration from 0.5% to 3%, will change average reduction in VB_{max} from 30.1% to 41.32%.
(3) Increasing nanoparticles' size from 10 to 50 nm, will change the average decrease in VB_{max} from 46.2% to 34.8%.
(4) Lower rates of cutting tool flank wear can be obtained by either increasing nanoparticles' concentration from 0.5% to 3% and/or reducing their sizes from 50 to 10 nm.
(5) With the low cost and excellent performance of TiO_2 nanofluids in decreasing cutting forces, temperatures, and cutting tool wear, it can be concluded that both MQL and MQCL techniques can be successfully mixed with TiO_2 nanofluids to improve machining performance and to reduce the total manufacturing cost of a component.

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