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Wear Performance Evaluation of Minimum Quantity Lubrication With Exfoliated Graphite Nanoplatelets in Turning Titanium Alloy

This paper evaluates the performances of dry, minimum quantity lubrication (MQL), and MQL with nanofluid conditions in turning of the most common titanium (Ti) alloy, Ti-6Al-4 V, in a solution treated and aged (STA) microstructure. In particular, the nanofluid evaluated here is vegetable (rapeseed) oil mixed with small concentrations of exfoliated graphite nanoplatelets (xGnPs). This paper focuses on turning process that imposes a challenging condition to apply the oil or nanofluid droplets directly onto the tribological surfaces of a cutting tool due to the uninterrupted engagement between tool and work material during cutting. A series of turning experiments was conducted with uncoated carbide inserts, while measuring the cutting forces with a dynamometer under the dry, MQL and MQL with nanofluid conditions supplying oil droplets externally from our MQL device. The inserts are retrieved intermittently to measure the progress of flank and crater wear using a confocal microscopy. This preliminary experimental result shows that MQL and in particular MQL with the nanofluid significantly improve the machinability of Ti alloys even in turning process. However, to attain the best performance, the MQL conditions such as nozzle orientation and the concentration of xGnP must be optimized.
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Keywords: MQL, Ti-6Al-4V, turning, xGnP-based nanofluid, cutting force, flank wear, crater wear

Introduction

Recently, lightweight metals have drawn extensive attention in many applications in aviation and automotive industries to boost the fuel economy and reduce the carbon dioxide emission. Among the lightweight metals, titanium (Ti) alloy is ideal for many of these applications because of the extraordinary strength/weight ratio and the high operating temperature [1,2], which are not offered by the other light metals. Table 1 compares the strength/weight ratios and the maximum service temperatures of the lightweight metals [3].[2]

Despite these advantages, the material cost and machinability issues are the main obstacles in adopting Ti alloys for a wide range of applications. This paper focuses on improving the machinability of Ti alloys with the minimum quantity lubrication (MQL) with oil or nanofluid. The poor machinability of Ti alloys comes from their low thermal conductivities [4,5], which causes the heat to be trapped, instead of dissipating into the work material, near the cutting edge during machining. Even at a moderate cutting condition, the maximum temperature on the rake face of the tool can reach well over 1000 °C [6]. Such high temperature on a cutting tool significantly reduces the mechanical strength of a cutting tool. Moreover, due to the high chemical affinity with all available tool materials, the tool/work/chip interfaces are characterized by not only the high friction but also the adhesion layers formed while machining. As the adhesion layers are intermittently detached, the fragments of the tool body are detached as well. This phenomenon is known as attrition wear. Consequently, the machining cost of Ti alloys in general can increase up to four times of that of ferrous alloys [7].

In machining ferrous alloys, the machinability has significantly improved by applying wear-resistant ceramic coatings on carbide inserts. However, in machining Ti alloys, these coatings do not significantly improve the machinability. Moreover, with the high cutting temperature, flood cooling provides the reasonable means to extract the heat, which is commonly applied when machining Ti alloy in many industrial applications. The flood cooling also has the added benefit of improving the surface finish and tool life. However, due to the health/environmental concerns and the eventual disposal cost of cutting fluid [8–10], MQL was proposed as an ecologically viable machining solution. Even though MQL may not provide adequate cooling when machining Ti alloys, it can provide the ample lubrication by applying the oil droplets

Table 1 Properties of lightweight metals

Materials	Strength/weight ratio (kN m/kg)	Operating temperature (°C)
Ti-6Al-4V (titanium alloy)	260	350–400
AZ63 (magnesium alloy)	109	120 [3]
6061-T6 (aluminum alloy)	115–130	130

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[2]http://www.matweb.com/
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generated by compressed air. This paper explores MQL as an alternate enhancement technology for turning Ti alloys and studies the capability and limitation of this technology for the turning process where the uninterrupted engagement between tool and work material during cutting offers a severe challenge in supplying oil/nanofluid droplets at the tool/work/chip interfaces.

MQL-based machining uses a minute amount of oil (typically between 5 and 500 cc/h), which is transformed into micron-sized droplets by applying compressed air. These droplets are applied directly onto the tool/work/chip interfaces to enhance various machining processes. Heinemann et al. [11] carried out deep hole drilling experiments on AISI 1045 steels with three media such as synthetic ester, synthetic ester with 20% alcohol, and oil-free synthetic lubricant with water, while applying external MQL. The best results were obtained with the oil-free synthetic with water due to the high cooling capacity and low viscosity. Yoshimura et al. [12] reported the device to generate the water droplets covered with oil film and carry out MQL experiments. The results showed that the combination of oil and water as MQL media with improved cooling ability reduced the cutting force.

More recently, MQL machining with nanofluid has been applied to enhance the machinability. Shen et al. [13] carried out the MQL grinding experiment with the nanofluid mixed with MoS_2 nanoparticles and reported the considerable reduction in cutting force. Park et al. [14] reported the outstanding results on flank wear with vegetable oil mixed with small concentrations of exfoliated graphite nanoplatelets (xGnPs) in the milling process of AISI 1045. Spherical nanoparticles were used to enhance the ball/rolling bearing effects. Nano-diamond, nano-alumina, and fullerene (C_{60}) are the representative spherical nanoparticles. Lee et al. [15] observed the reduction in cutting forces and the improvement in the workpiece surface qualities during microgrinding process using MQL with nano-diamond and alumina particles and found that the size and concentration of the nanoparticles are important parameters. They also investigated the thermal effects of nano-diamond during microgrinding process using MQL [16]. With experimental and computational fluid dynamics results, they reported on the tribological benefits and high heat transfer enhanced by the nano-diamond particles in reducing the temperature on the workpiece surface.

The research works described above show the improved machinability when MQL with nanofluid is used for drilling, milling, and grinding. However, its effectiveness in turning process has not been studied extensively. Even though the effectiveness of MQL may be questionable due to the uninterrupted engagement of the workpiece on cutting tool, limited numbers of research works on turning process with MQL with or without nanofluid were reported with conflicting results. Attanasio et al. [17] performed the turning experiment on normalized 100Cr6 steel with $TiN/Al_2O_3/TiCN$-coated insert in MQL condition of ester oil with extreme pressure additives (COUPEX EP46). The results showed that the tool life was improved when the nozzle is applied on the flank face. On the contrary, Bruni et al. [18] conducted MQL turning experiments on AISI 1040 steel with vegetable oil at the cutting speed of 235 m/min, and the results, however, showed no improvement in tool wear and surface quality compared with the dry condition. Dhar et al. [19] turned AISI-1040 steel with MQL of Mobil Cut-102, and both the cutting force and flank wear were reduced compared with the dry condition. Khan et al. [20] reported the turning experiment on AISI 9310 alloy steel with vegetable oil based MQL in the wide range of high cutting speed from 223 to 483 m/min, and the result showed the reduction in cutting temperature and flank wear and the elimination of built up edge. Other various turning experiments were carried out on various ferrous alloys showing the reduction in cutting force, temperature, and surface roughness with MQL [21–26]. Thus, some of the literature mentioned do not always provide the conclusive evidence if MQL can provide the effective enhancement in turning process, and more importantly the effectiveness of MQL depends extensively on the machining and MQL conditions.

Furthermore, a very limited research work reported on turning process of Ti alloy especially with MQL and MQL with nanofluid, and many detailed processing parameters and machining conditions are not well established. Revankar et al. [27] conducted the MQL turning of Ti-6Al-4V alloy using the polycrystalline diamond tool and optimized speed, feed rate, and lubricant flow rates for better surface finish. Raza et al. [28] performed turning experiments with Ti-6Al-4V alloy under many conditions such as dry, MQL, minimum quantity cooled lubrication (MQCL), cooled air, flood, and cryogenic conditions. The results show that MQL and MQCL conditions turn out to be feasible alternatives at low feed and speed conditions. Liu et al. [29] also performed a series of turning experiments of the nanocomposite-AlCrN/amorphous-Si_3N_4 coated insert on Ti-6Al-4V alloy with a wide range of cutting conditions by applying vegetable oil based MQL on flank side to find an optimal cutting condition for minimizing surface roughness. Gupta and Sood [30] and Gupta et al. [31] performed MQL turning process of Ti-6Al-4V alloy with few nanofluid (the 3 wt% concentration of nano-scale graphite, MoS_2, and Al_2O_3 in vegetable oil). Among the machining parameters, the best surface finish and the minimal tool wear were found to be at low cutting speed, low feed rate, high approach angle, and graphite-based nano-fluids. Recently, Sartori et al. [32] carried out MQL experiments with varying concentrations of solid lubricants, graphite, and polytetrafluoroethylene particles in water and vegetable oil to improve the machinability of Ti-6Al-4V in finish turning in one cutting condition (cutting speed of 80 m/min, feed rate of 0.2 m/rev, and depth of cut is 0.2 mm). The nose wear results showed that all MQL experiments reduced the wear to 35–50%.

This paper discusses our results from our turning experiment of Ti-6Al-4V alloy in the solution treated and aged (STA) microstructure under dry, MQL, and MQL with nanofluid conditions. Apart from the nanofluid with various nanoparticles, which are used by Lee et al. [15,16] and Gupta and Sood [30] and Gupta et al. [31], we found that nanofluid made of xGnPs with certain aspect ratios (high diameter/thickness ratio due to their nanoscale thickness) was necessary to provide the significant advantages in MQL. This paper reports on our turning experiments to determine if MQL is indeed effective in turning Ti alloys at high cutting speed. The results were significantly depended on the orientation of the MQL nozzle as the orientation and pressure of the coolant applied dictates its effectiveness in improving tool life in the flood condition [33]. Therefore, the optimal nozzle orientation must be first defined for the turning conditions employed, and an additional series of MQL turning experiments with the optimum nozzle orientation is conducted to compare the performances of various nanofluid with varying concentration of xGnPs. The experimental results of cutting force and tool wear show that MQL is effective, and MQL with nanofluids is even more effective in improving the machinability when turning Ti alloy.

Turning Experiments Materials

In the experiments, a Ti-6Al-4V (Al, 6 wt%; V, 4 wt%; and Ti, 90 wt% with Fe max 0.25 wt% and O max 0.2 wt%) round bar with the diameter of 127 mm and the length of 648 mm in the STA microstructure [34] was used as a workpiece. The microstructure captured by scanning electron microscopy (SEM) in the backscattered electron imaging mode is shown in Fig. 1, which consists of fully equiaxed alpha grains (dark color) and lamellar phase (light color) with alternating layers of alpha and beta phases [35]. The microstructures of Ti-6Al-4Vs typically consist of various combinations of the alpha and lamellar phases. The STA microstructure is a good representation of Ti-6Al-4V with the similar contents of both alpha and lamellar phases. Due to the presence of the lamellar phase, both flank and crater wear become significant at the high cutting speed used in this experiment [35].

Uncoated carbide inserts (SCMW 432-H13A, Sandvik Coromant, Hebron, KY) with the rake and relief angles of 0 deg and 7 deg, respectively, were chosen. These inserts, whose average size of

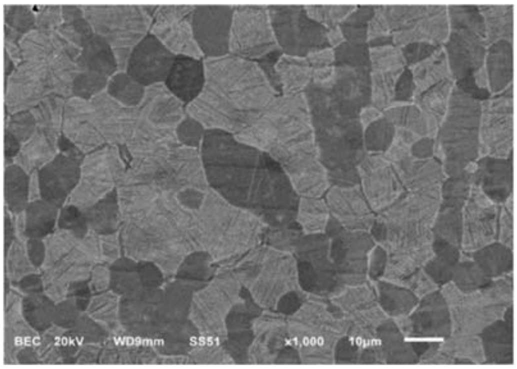


Fig. 1 Microstructure of Ti-6Al-4 V in the STA condition

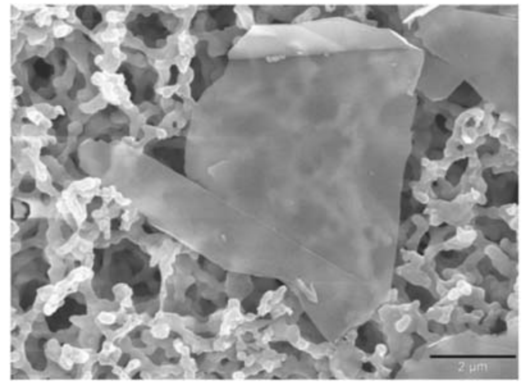
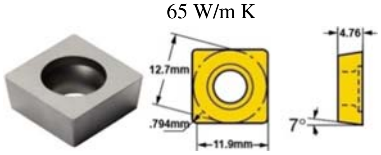


Fig. 2 SEM image of xGnP [37]

Table 2 Specification of the uncoated carbide insert used

Grade	H13A
Substrate	WC + Co (6 wt%)
Thermal conductivity	65 W/m K
Dimension	 [37]

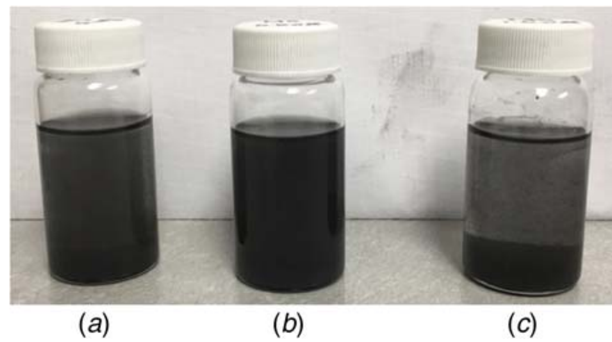


Fig. 3 Stability in mixtures of oil: (*a*) 0.1, (*b*) 0.5, and (*c*) 1.0 wt% xGnP M5 after 72 h

the carbide grains is 1 μm, do not have any chip breaker to minimize the cutting temperature variations on the rake face. The detailed specification of the insert is given in Table 2.[3]

The rapeseed-based oil (Coolube 2210, Unist Inc., Grand Rapid, MI) with the flash temperature of 200 °C was applied to generate MQL mist. The xGnPs are produced by XG Science, Inc. (Lansing, MI) from graphite intercalated compounds through the reaction in acids and their proprietary exfoliation process using a microwave method in order to obtain the size reduction (mostly thickness) [36]. Based on the previous success on the milling process [37],[4] the xGnP-M5 (or simply M5) grade was chosen and mixed with the oil to generate the nanofluid for MQL. Figure 2 shows the SEM image of M5 grade with the diameter of 5 μm, the thickness of 6–8 nm, and the surface area of 120–150 m^2/g. The mixing with the oil was performed with the magnetic stirrer (1120049SH by Fisher Scientific Inc.) at 700 rpm for 30 min and then sonicated using CPX 15337427 (Fisher Scientific Inc.) for 1 h to produce the stable nanofluid. The stabilities of the nanofluid with 0.1, 0.5, and 1.0 weight (wt%) of xGnP M5 grade were observed after 72 h as shown in Fig. 3. The stable mixtures were attained with the nanofluid with 0.1 and 0.5 wt% of xGnPs but not with 1.0 wt% of xGnPs, which must then be applied in MQL experiment before the segregation of xGnPs.

Experimental Setup. The straight turning experiments were conducted on our CNC Lathe (TL01, Haas Automation Inc., CA). The uncoated carbide inserts were mounted with the screw on the tool holder (SSBCR-2525M-12, Sandvik Coromant, Hebron, KY). The MQL dispensing system Uni-MAX (Unist Co., Grand Rapid, MI) was used to deliver the oil or nanofluid mist with the compressed air to the work–insert interface externally through its nozzle. The cutting forces in three directions were measured during the turning tests with Kistler stationary dynamometer (Kistler Instrument Corp., Amherst, NY). The cutting forces from the inserts mounted on Kistler tool holder type 9403 for the 25 × 25 shank cutting tool were measured by Kistler Piezo-Multicomponent Stationary Dynamometer type 9257B. The Kistler Multichannel Charge Amplifier type 5070A was used to amplify the input charges generated from the dynamometer. The channel sensitivities of the multichannel charge amplifier were set for −7.854, −7.818, and −3.727 pC/N corresponding to the cutting forces in the *x*, *y*, and *z* directions, respectively. The amplifier signal was obtained and converted using the Kistler acquisition system type 5697A, and Kistler Dynoware type 2825A was used to store the force data in a computer. The force data acquisition was set at the rate of 100 sample/s. The experimental setup is shown in Fig. 4. Even though two nozzles were shown in Fig. 4, this paper examines the isolated impact of applying MQL at either rake or flank surface, and only one of two nozzles was implemented.

Experimental Design and Conditions. Turning experiments of Ti-6Al-4V workpiece are conducted in three distinct conditions, dry, MQL, and MQL with nanoplatelets (0.1, 0.5, 1.0, and 2.0 wt% of xGnP in M5 grade) to compare their performances. The advantage of the external MQL is that the location and orientation of the nozzle can be optimized. The nozzle distance is predetermined to be optimum at the distance of 5 cm based on our previous work [14]. The nozzle orientation defined by pitch and yaw angles is illustrated in Fig. 5. The pitch angle is the angle between the feed rate direction (or *x*-direction in Fig. 5) and the projection of the nozzle direction onto *XY* plane. In this study, the yaw angle of the nozzle is set at three distinct angles, 15 deg, 30 deg, and 45 deg and denoted to be Y15, Y30, and Y45. Three distinct pitch angles of 15 deg, 45 deg, and 75 deg tested are denoted as RN15, RN45, and RN75, respectively, while the pitch angle of −85 deg is denoted as FN.

Due to the space limitation on the flank side, only one FN condition set at the pitch angle of −85 deg, which represents the nozzle pointing at the flank surface, was feasible. Because

[3] https://www.sandvik.coromant.com/en-gb/products/pages/productdetails.aspx?c=SCMW%20432%20%20%20%20%20%20%20%20%20%20%20%20H13A

[4] https://xgsciences.com/materials/graphene-nano-platelets/

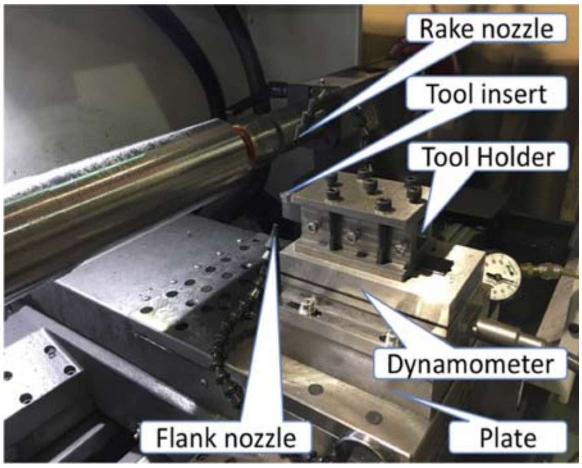


Fig. 4 Experimental setup

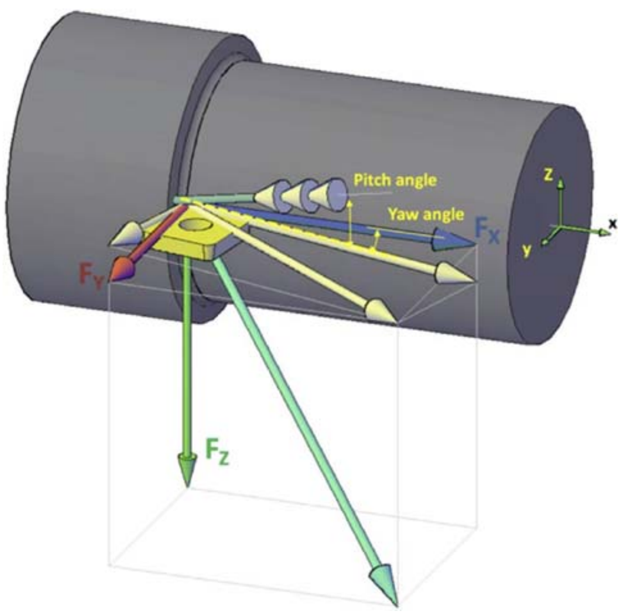


Fig. 5 The cutting forces measured and the orientation of MQL nozzle in turning center

RN15Y15 provides the best performance in terms of tool wear, further MQL experiment with various nanofluid was restricted to RN15Y15. Four distinct nanofluid with xGnPs (M5 grade) concentrations of 0.1, 0.5, 1.0, and 2.0 wt%, denoted as RN15Y15wt0.1, RN15Y15wt0.5, RN15Y15wt1.0, and RN15Y15wt2.0, respectively, were used to determine the optimum concentration of xGnP (M5 grade) in nanofluid. The complete list of the MQL experiments is provided in Table 3.

The uncoated carbide insert was mounted by the screw on a tool holder SSBCR-2525M (Sandvik Coromant, Hebron, KY) with the rake angle of 0 deg. As shown in Fig. 4, the large plate was added to support the dynamometer to level the tool tip with the centerline of the workpiece during the straight turning experiments. For each experimental condition, the surface cutting speed, depth of cut, and feed rate are fixed at 122 m/min, 1.2 mm, and 0.127 mm/rev, respectively. For the MQL, the flow rate and pressure of the MQL mist were 1.5 ml/min and 0.055 MPa (8 psi) based on our previous work [14], which determined the optimum pressure to deposit most of the droplets onto the tribological surfaces of the insert. The MQL conditions are summarized in Table 4.

Table 3 Experimental design of MQL experiments

Cases	Conditions	Pitch angle of nozzle	Yaw angle of nozzle
Dry	Dry	—	—
FNY15	MQL	−85 deg (flank nozzle)	15 deg
RN15Y15	MQL	15 deg (rake nozzle)	15 deg
RN15Y30	MQL	15 deg (rake nozzle)	30 deg
RN15Y45	MQL	15 deg (rake nozzle)	45 deg
RN45Y15	MQL	45 deg (rake nozzle)	15 deg
RN75Y15	MQL	75 deg (rake nozzle)	15 deg
RN15Y15 wt0.1	MQL with 0.1 wt% xGnP M5	15 deg (rake nozzle)	15 deg
RN15Y15 wt0.5	MQL with 0.5 wt% xGnP M5	15 deg (rake nozzle)	15 deg
RN15Y15 wt1.0	MQL with 1.0 wt% xGnP M5	15 deg (rake nozzle)	15 deg
RN15Y15 wt2.0	MQL with 2.0 wt% xGnP M5	15 deg (rake nozzle)	15 deg

Table 4 External MQL spraying conditions

Lubricant	Dry, vegetable oil (Coolube 2210), lubricant enhanced by xGnP 0.5 wt%
Air pressure	8 psi
Flow rate	1.5 ml/min
Hole diameter of nozzle	3.2 mm
Pitch angles of nozzle	15 deg, 45 deg, 75 deg (rake), and 5 deg (flank)
Nozzle distant	50–60 mm

Tool Wear Analysis. After turning certain cutting lengths, the Ti-adhesion layers on the inserts are etched by hydrofluoric acid (52 wt%) to capture the extent of both flank and crater wear with Olympus Fluoview FV1000 Confocal Laser Scanning Microscopy (CLSM) using reflect laser z-stack with the magnification of 20× and the step size of 1 μm The CLSM data including conjugal focal plane images are overlapped to generate the height encoded images (HEI) (Fig. 6(*a*)). The noise from the HEI must be removed using the wavelet-based algorithm developed in MATLAB [38]. Three-dimensional images are constructed as shown in Fig. 6(*b*). In Figs. 6(*c*) and 6(*d*), the two-dimensional profiles in crater wear with 75 deg from *x*-axis (along the chip flow) were extracted, while the profile representing flank wear was processed similarly with the vertical profiles.

Results and Discussion

Cutting Forces. A sample dynamometer reading representing the three force signals in *x* (feed), *y* (radical), and *z* (tangential) directions were presented in Fig. 7(*a*). The results from our dry condition are similar to the force data in dry condition reported by Sun et al. [39]. The averages of the measured forces and the variations in the cutting forces in three directions are calculated and presented in Figs. 7(*b*) and 7(*c*), respectively, for all cases. As will be explained, the best tool wear result was observed with RN15Y15, which is chosen as the reference to compare the effect of the concentration of M5, represented by four additional data, 0.1%, 0.5%, 1.0%, and 25% in weight. The M5 grade of xGnPs has performed the best among many grades. Many other xGnP grades with nanoscale thickness and other thicker graphite platelets with microscale thickness were used in our previous work [37]. Interestingly, the graphite platelets with microscale thickness will accelerate tool wear.

As shown in Fig. 7(*b*), the average cutting forces in the x, y, and z directions in the dry condition are 253 N, 165 N, and 409 N, respectively, while the three average forces in all MQL conditions ranging between 184 and 225 N, 135 and 158 N, and 322 and

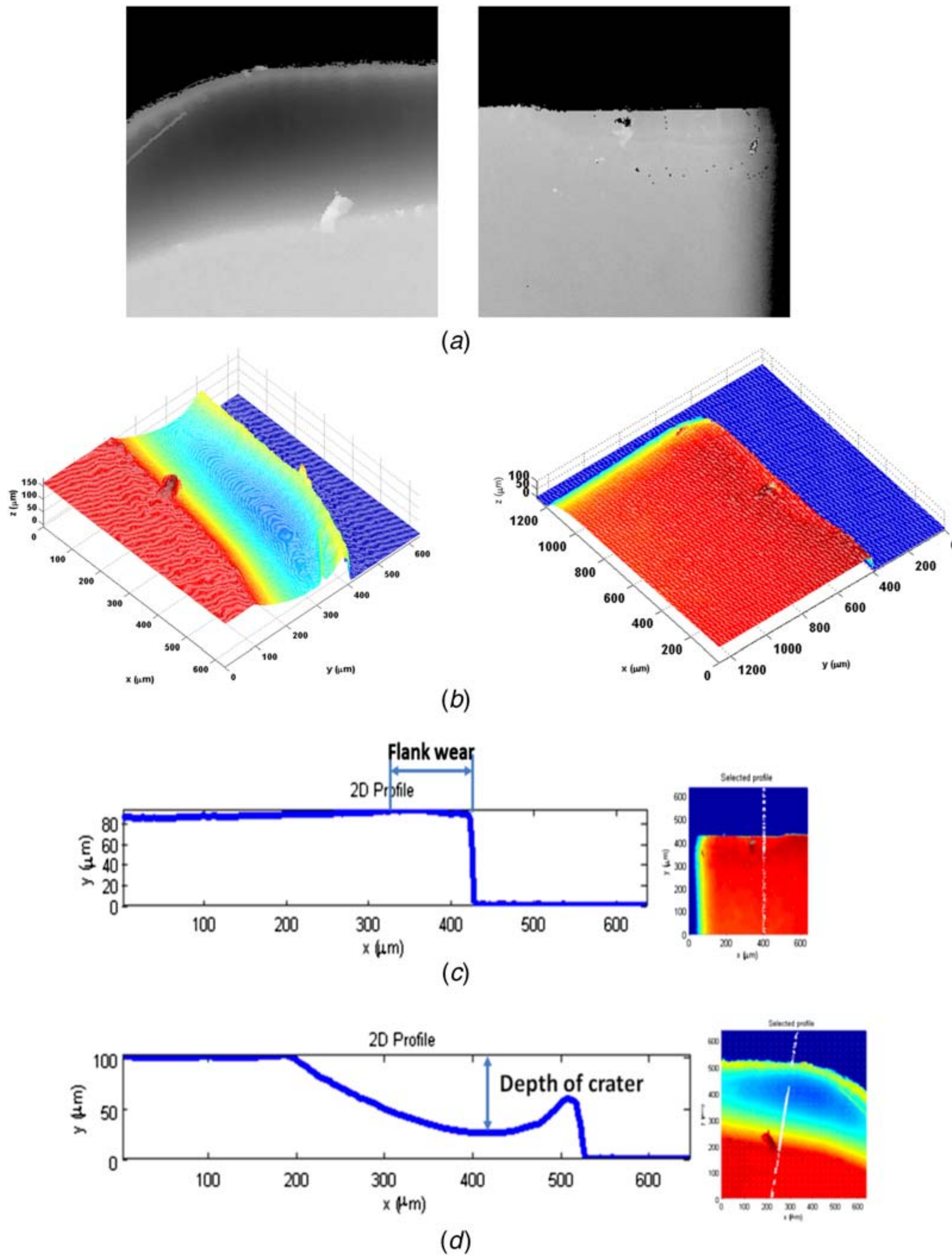


Fig. 6 Tool wear analysis with 3D confocal images: (*a*) HEI image, (*b*) 3D confocal image, (*c*) 2D profile of flank wear, and (*d*) 2D profile of crater wear

352 N, respectively, are consistently reduced. With the variation of the pitch angle of the MQL nozzle, the average cutting forces in RN45Y15 show slightly smaller than those of RN15Y15 and RN75Y15. Regarding the yaw angle, the average cutting forces of RN15Y45 were reduced slightly compared with those of RN15Y15 and RN15Y30. With the nanofluid of 0.5% of M5 (RN15Y15), the forces in x, y, and z directions were decreased by 15.1%, 9.7%, and 7.7%, respectively, compared with RN15Y15. As shown in Fig. 7(*b*), the cutting forces in x and y directions have in general decreased with the presence of xGnPs.

Figure 7(*c*) shows the variations in the cutting force measurements. Clearly, the variations in the dry condition are substantially higher in all three directions than any MQL conditions. The variations in cutting forces (in x, y, and z directions) in dry condition are 128N, 169N, and 291 N, and those in MQL conditions range between 72N and 92N, 87N and 117N, and 111N and 159N, respectively. Both the average and the variation in cutting forces in three directions in dry condition are significantly higher than those in MQL condition with the lubrication provided by the oil or nanofluid droplets landed between tool–work interfaces. These force data imply that the cutting time of any MQL condition lasted much longer than that of dry condition. More importantly, the MQL with nanofluid further reduce the cutting forces, expecting better performances.

Tool Wear. To present the progress of tool wear, the average flank land (V_B) and maximum crater depth (K_t) as a function of

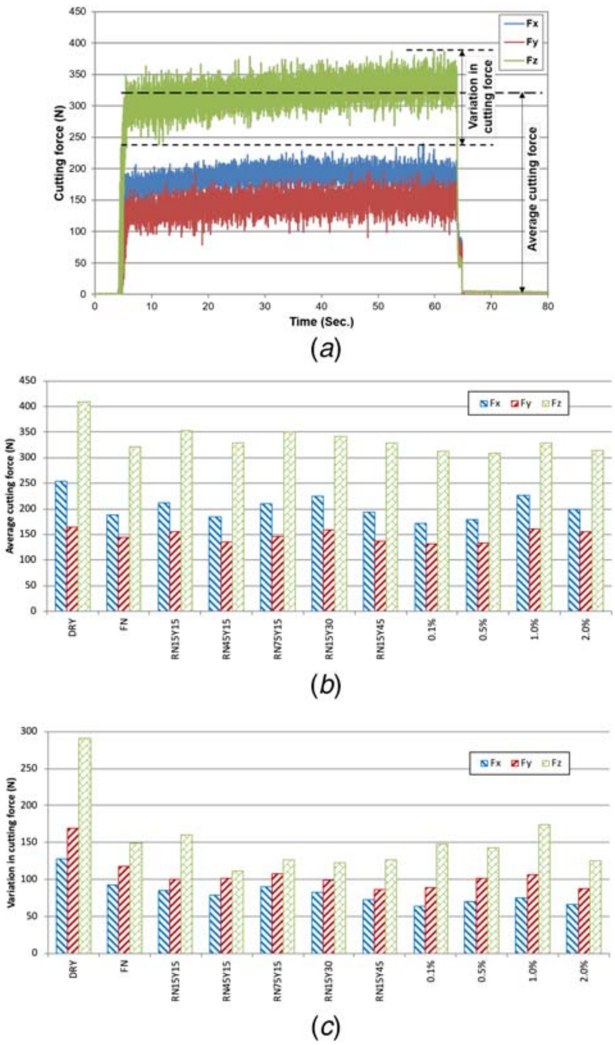


Fig. 7 Cutting forces in *x*, *y*, and *z* directions under various conditions: (*a*) force signals from dynamometer, (*b*) average cutting forces, and (c) variation in cutting force

cutting length under dry and various MQL conditions are presented in Figs. 8(*a*)–8(*d*) based on our confocal measurements. The characteristic progress of flank wear is that, after the initial wear, the steady-state wear takes place followed by the abrupt acceleration in wear, which in this case is caused by the attrition wear mentioned earlier, while the crater wear depth steadily increases in each condition without any distinct difference among various conditions till the attrition wear fractures the inserts. Typically, the tool life criterion is defined as the average flank wear land reaching 300 μm [40,41]. Thus, the turning experiments were continued until the flank wear land reaches 300 μm.

In dry condition, the flank wear of 300 μm reached when the cutting length reached 265 m. Among various pitch angle conditions in the MQL experiments, the cutting length in RN15Y15 reached 380 m, which is significantly longer than those of FN, RN45Y15, and RN75Y15 at 310, 325, and 360 m, respectively. Comparing the various yaw angles in the MQL experiments, RN15Y15 achieved a longer cutting length than those of RN15Y30 and RN15Y45, which measured 292 and 326 m, respectively. Therefore, this study concludes that the nozzle orientation represented by the pitch angle of 15 deg and the yaw angle of 15 deg was optimal in terms of flank wear. It is interesting to note that, in the FN condition where the oil mist is sprayed on the flank face, the flank wear did not necessary reduced compared with the other MQL conditions where the oil mist was applied on the rake face. Conversely, the crater wear obtained from the FN condition is comparable to dry and the other MQL conditions where the oil mist was applied on the rake face.

Clearly, among the MQLs with nanofluid, flank wear in the MQL with the nanofluid with 0.5 wt% of M5 were significantly diminished compared with the other conditions tested, attaining the cutting length of 520 m before reaching the tool life criterion. Thus, we can conclude that the tool life is substantially improved with the introduction of xGnPs (M5). The concentration of 0.5% M5 shows the most promising improvement, being capable of reaching additional 255 m of cutting length.

The main flank wear mechanism was established to be the abrasion by the "hard" orientation of the alpha clusters in our previous work [35]. With the presence of oil droplets in MQL experiments, the friction between tool and work material is expected to be reduced, and with the presence of xGnPs, we expect to provide the lubrication even at high cutting temperature. This is evident by the fact that the tool life in the MQL with the nanofluid with 0.5% M5 lasted nearly twice longer than that of the dry condition.

For crater wear, the main wear mechanism is solubility/diffusivity [42,43] due to the higher temperature at the rake face compared with that of the flank surface. With MQL, the rake temperature may be slightly reduced with the application of oil droplets and compressed air. However, at the cutting speed of 122 m/min, the cutting temperature at the rake face can reach over 1000 °C [6]. At such temperature, the oil droplets are simply vaporized as soon as they landed on the hot rake surface. As evident in Fig. 8(*d*), among the MQL conditions with the various concentrations of xGnPs, 0.1, 0.5, 1.0, and 2.0 wt%, the best performance was also achieved with the concentration of 0.5 wt%, while the other three concentrations have reduced the crater wear initially. However, these inserts did not last long due to the fractures started at the flank side. Therefore, the presence of xGnPs with a certain threshold concentration is critical in reducing both flank and crater wear.

Conclusion

This paper presented the preliminary study of turning Ti alloy in dry, MQL, and MQL with xGnPs. In particular, many MQL conditions including nozzle orientation (various pitch angles: FN, RN15, RN45, and RN75 and various yaw angles: Y15, Y30, and Y45) and lubrication conditions (dry, MQL, MQL with 0.1, 0.5, 1.0, and 2.0 wt% of M5 grade of xGnPs) were considered in the experiments. Based on the cutting forces and tool wear measured in this study, the following conclusions are drawn:

(1) The average cutting forces and the variations in cutting forces were considerably reduced in the case of MQL and MQL with our nanofluid compared with dry condition. However, among the MQL and MQL with xGnPs conditions, the difference in the cutting forces is not discernable.
(2) MQL was not expected to make a significant enhancement when turning Ti alloys at high cutting speed (122 m/min) due to the high cutting temperature on the inserts. However, our experimental results show up to 50% improvement in tool life with traditional MQL and up to 100% improvement in tool life with MQL with xGnPs. Such improvement is significant when the coated inserts do not significantly improve tool life when machining Ti alloys.
(3) Flank wear was reduced by applying MQL and significantly reduced by MQL with xGnPs compared with the dry condition. The maximum cutting length based on the standard flank wear was extended by approximately 40% with MQL and 100% with MQL and 0.5 wt% of xGnPs. However, despite the less distinguishable difference in crater depth among various MQL conditions (FN, RN 15, RN45, and RN75), the addition of xGnPs in the MQL oil media, which can survive at the high crater temperature, has reduced the crater wear depth by 20% with MQL and

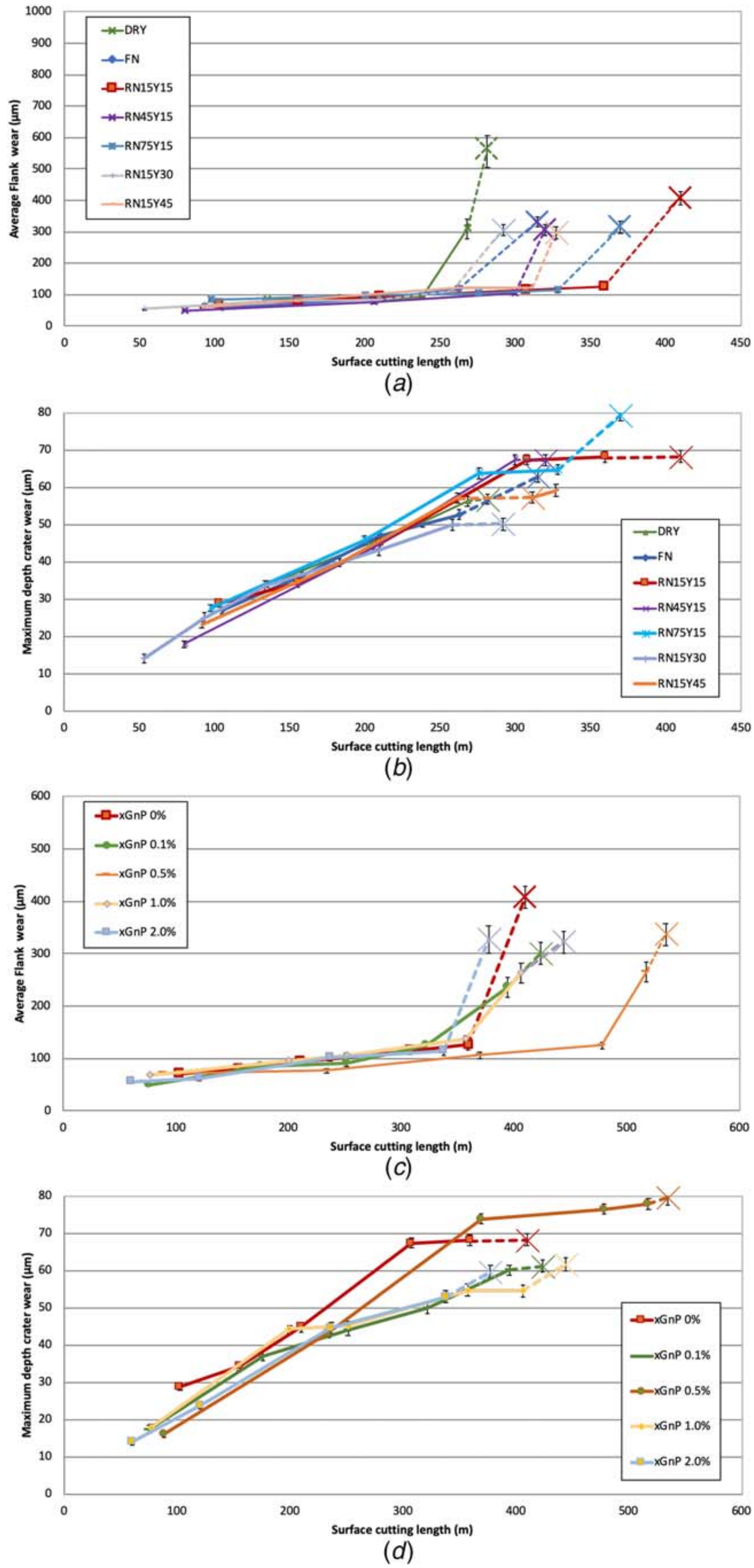


Fig. 8 Tool wear under various conditions: (*a*) flank wear in various nozzle orientations, (*b*) crater wear in various nozzle orientations, (*c*) flank wear in four xGnP concentrations in nanofluid, and (*d*) crater wear in four xGnP concentrations in nanofluid

1.0 wt% of xGnPs. More importantly, the presence of xGnPs in general increased the cutting length despite the slight increase in crater depth.

(4) It is important to note that the effectiveness of MQL and MQL with xGnPs is dictated by the orientation of the nozzle. The orientation of nozzle MQL rake positions, the pitch angle of 15 deg and yaw angle of 15 deg, was the most optimum orientation of the MQL nozzle in reducing flank wear.

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