Tribology Online

Japanese Society of Tribologists

https://www.tribology.jp/trol/

Vol. 18, No. 6 (2023) 385-395.
ISSN 1881-2198
DOI 10.2474/trol.18.385

Article

Effects of Hybrid Nanocooling-Lubricants MQCL on Machining Temperature and Tool Wear Mechanisms under Turning Process of Titanium Alloy

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Manuscript received 31 May 2023; accepted 22 August 2023; published 31 October 2023
Presented at the 9th International Tribology Conference, Fukuoka 2023, 25-30 September, 2023

Abstract

Minimum quantity lubrication (MQL) has performed optimum lubrication but poor cooling during turning process. Thus, hybrid nanocooling-lubricants for minimum quantity cooling-lubrication to achieve sufficient lubrication and cooling effect for high speed turning titanium alloy (Ti6Al4V) material. This study is targeted on the machinability performance of G-Al_2O_3 hybrid nanocooling-lubricants MQCL and conventional fluids cooling condition with variable cutting speeds at constant feed rate as input parameters to evaluate the machining temperature and cutting insert flank wear as quality responses. Scanning electron microscopy-energy dispersive X-ray (SEM-EDX) analysis was implemented to determine Ti6Al4V workpiece chemical elemental deposition on the cutting insert flank surface. Experimental results obtained that significantly increased of machining temperature from 206°C to 317°C based on type-*K* thermocouple wire measurement as the increment of cutting speeds from 120 m/min to 180 m/min. However, machining temperature decreased with the increasing of lubrication flow rate of MQCL 10 mL/min to 40 mL/min, then to the conventional fluids cooling condition. The comparison to conventional fluids cooling condition, the G-Al_2O_3 hybrid nanocooling-lubricants MQCL at the cutting speed of 120 m/min significantly increased tool life for 51% and cutting speed of 180 m/min for 28%, respectively. Furthermore, SEM-EDX has presented that titanium element deposited on cutting insert flank surface, which has shown micro-attrition, abrasion and adhesion wear leading edge chipping or fracture are identified as the main tool wear mechanisms.

Keywords

MQCL, machining temperature, hard-to-cut material, adhesion wear, abrasion wear

1 Introduction

Ti6Al4V workpiece considered as hard-to-cut material with (α+β) chemical compositions titanium alloy exhibited high strength-to-weight ratio and good hardness in mechanical properties, but the poor thermal conductivity of 7.2 W/mK prohibited the machinability of Ti6Al4V workpiece as high heat generation during machining, and chip adhesion accelerated cutting tool wear [1]. Comparatively short cutting tool life or high cutting edge wear in machining Ti6Al4V [2] is due to the generation of strong heat flux at the machining zone of workpiece-tool-chip interacting faces [3]. Hence, lubricant is crucial to implement to enhance the machinability of titanium alloy workpiece with optimum lubrication and adequate cooling for dissipation of heat. Minimum quantity lubrication (MQL) technology consisted pressurized air and lubricants of vegetable oil, ester oil and nanolubricants for machining of titanium alloy were reviewed [2-4]. MQL strategy consumed small quantity of lubricants between 50-500 mL/h in pressurized airflow straightly toward the workpiece-tool-chip interfaces using one or more nozzles. This MQL condition not only provided good lubrication as well as cooling effect [5] and also improve the machining performance of mechanical part [6].

Rahim et al. [7] conducted an experimental studied the machinability performance of ester oil MQL in the turning AISI-1045 steel workpiece. As comparative to dry cutting, the machining temperature, tool-chip contact length and chip thickness were measured under different machining process conditions. Their results showed that the application of MQL minimized the machining temperature up to 30% and lower tool-chip contact length than dry cutting. They concluded that MQL mist performed better penetration into the machining zone and improvement in machinability performance with ester oil due to low coefficient of friction under high pressure. Liu et al. [8] examined the machinability performance of ethanol mixed castor oil lubricants introduced to MQL system for the turning of hard-to-cut workpiece. They found that ethanol-castor oil blended lubricants MQL obtained longer tool life and better surface finish as compared to castor oil MQL. An investigation by Jamil et al. [9] measured blaser oil and hybrid ethanol-blaser oil under dry ice temperature MQL and dry cutting conditions for machining Ti6Al4V workpiece regarding cutting tool life. A comparison of tool life under hybrid ethanol-blaser oil-dry ice temperature MQL attained maximum tool life of 18 m, while the shortest tool life of 10.8 m under dry cutting condition. In analysis of cutting tool wear under hybrid ethanol-blaser oil in dry ice temperature MQL showed relatively low tool wear and less workpiece chemical elements of Ti6Al4V deposited on worn cutting edge. This evaluation proved that hybrid lubricants are optimal MQL lubricants in machining processes.

The remarkable application of nanolubricant as metalworking fluid is that it presents better cooling lubrication effect than conventional cutting fluid. Su et al. [10] demonstrated an experiment of nano-additives based polyol ester oil and vegetable oil through the MQL method in the machining of hard-to-cut workpiece. The findings indicated the superior thermophysical properties and machinability regarding lower machining temperature and cutting force compared to vegetable-based oil MQL. Next year, another experiment by Alimirzaloo et al. [11] applied a hybrid nanolubricants (CuO-Al_2O_3) based paraffin oil to compare with conventional fluids. The results obtained that the machinability performance of hybrid nanolubricants significantly improved by 40% in the machining process of an aluminum alloy. In another paper, Krishnamurthy et al. [12] studied the machinability performance of machining titanium alloy using ethanol blended conventional lubricant and cryogenic as cooling medium. They reported that ethanol blended conventional lubricant significantly reduced machining temperature and lower the cutting force of 65% during turning operation of Ti-6Al-4V workpiece. A smooth surface with the presence of microvoids coalescence and less shear strain were evaluated under ethanol blended conventional lubricant. The -OH group from ethanol blended conventional lubricant on the tool surface prevented adhesion of the workpiece element of Ti, Al and V on the flank surface. Aslantas and Cicek [13] investigated the effect of using different cooling lubrication strategies such as oil-water emulsion (conventional cutting fluid), MQL, ethanol and dry micro-milling of hard-to-cut Inconel 718 workpiece regarding tool wear and surface roughness. They indicated that minimal tool wear and better quality of surface roughness were obtained in the micro-milling process with MQL.

Since MQL is not completely developed and not fully replica of flood cooling. Thus, the small quantity flow of MQL system is insufficient to dissipate heat generation from machining zone, exclusively for machining a workpiece having poor thermal conductivity. Therefore, it would be advantage to understand the effect of novel hybrid nanocooling-lubricants. By considering the optimum cooling lubrication effect of G-Al_2O_3 hybrid nanocooling-lubricants MQCL mist spray, it could be proposed as a new cooling-lubricant as MQCL technology in manufacturing sector. The important objectives of this article are to study the performance of cooling lubrication on the machinability of titanium alloy workpiece regarding machining temperature, cutting tool life under several flow rates of MQCL with hybrid nanocooling-lubricants and cutting insert wear analysis with wear mechanism. The tool wear mechanisms are discussed using laser confocal microscope and SEM-EDX analysis and the results are compared with the results of conventional cutting fluid.

2 Materials and machinability characteristics experiment setup

In these turning experiments are conducted in lathe machine (ROMI C420, Germany) with maximum spindle rotation of 3000 RPM and feed rate of 10 m/min, respectively. The alloy of Ti6Al4V hard-to-cut bar rod materials with 38 mm X 400 mm (diameter X length) were applied as workpiece under turning process. The uncoated carbide cutting insert of CNMG 120408-H01 purchased from Korloy and the cutting insert is equivalent to standard number of DIN 4000-76-3 is implemented in the experiments. The cutting insert has 0.8 mm corner radius, 80o insert angle and detailed specifications are shown in Table 1. The experiments are conducted to determine the machinability characteristics of the proposed 1.5% volume concentration of hybrid nanocooling-lubricants with the nanoparticles ratio of graphene to aluminium oxide (60:40) under minimum quantity cooling lubrication (MQCL) condition. The G-Al_2O_3 hybrid nanocooling-lubricant was studied [14] and prepared by using nanoparticles dispersion method, then it subjected to an ultra-sonication process for at least 2 hours, recommended by Hamid et al. [15]; Sharif et al. [16] and Lim et al. [17]. The complete turning conditions are setup throughout the whole experiments. Table 2 presents the machining parameters and the responsive variables are measured in each experiment.

For measuring machining temperature during turning

Table 1 The geometry and specifications of tungsten carbide insert

Cutting edge length, *L* (mm)	Corner radius, *r* (mm)	Angle, α (°)	Thickness, *t* (mm)	Weight, *W* (kg)	Coating
12.90	0.80	80	4.76	0.0089	Uncoated

Table 2 Machining conditions of turning operation

Parameter	**Value**
Cutting speed, V_c (m/min)	120 - 180
Feed rate, *f* (mm/rev)	0.2
Depth of cut, a_p (mm)	1.0
Initial workpiece diameter, D_o (mm)	38
Workpiece length, *L* (mm)	300
Lubrication conditions	1. Conventional fluids with flood cooling method 2. Hybrid nanocooling-lubricant with 10 and 40 mL/min MQCL method

process, a type-*K* thermocouple wire of 1.0 mm diameter was deposited on rake surface of the insert with the help of epoxy. The thermocouple sensor has a temperature measurement ranging from −50°C to 1200°C with a standard type error in approximately 1.5°C, which is only 0.2%. Moreover, a thermographic infrared camera from Fluke (Ti480) was equipped to capture the contact temperature of the insert-workpiece interfaces [18, 19], while type-*K* thermocouple wire was attached to the insert to measure the cutting insert material temperature during turning operation [20, 21]. The heat signals produced during the turning process was detected by the type-*K* thermocouple wire and captured by a PICO DAQ system for data analysis. Figure 1 depicts the heat generated and detected by using thermographic camera, and peak temperature recorded through computer during turning process.

The cutting insert wear was observed by using a Laser Confocal Microscope (LEXT OLS5000, Olympus) and Energy-dispersive X-ray spectroscopy (TM3030 Plus, Hitachi) was used to evaluate the interaction of the hybrid nanocooling-lubricants with the worn insert surface. According to the tool life criteria of ISO-3685 standard [22], the average flank wear attained 300 μm or maximum 500 μm at the cutting insert could be used to discard. To established the relationship between tool life inversely proportional to cutting feed rate and a relation between tool life and cutting length as shown in Eq. (1) [9].

$$T_l = {}^{L_c}\!/_{V_f} \tag{1}$$

Where T_l is the cutting tool life (min), L_c is the cutting length (mm) and V_f is the cutting feed rate (mm/min). Equation (2) describes the cutting feed rate involving the cutting speed, V_c (m/min), the feed rate , f (mm/rev), the diameter of the workpiece, D (mm) and a constant of π in relationship:

$$T_l = \frac{L_c \times \pi \times D}{f \times V_c \times 1000} \tag{2}$$

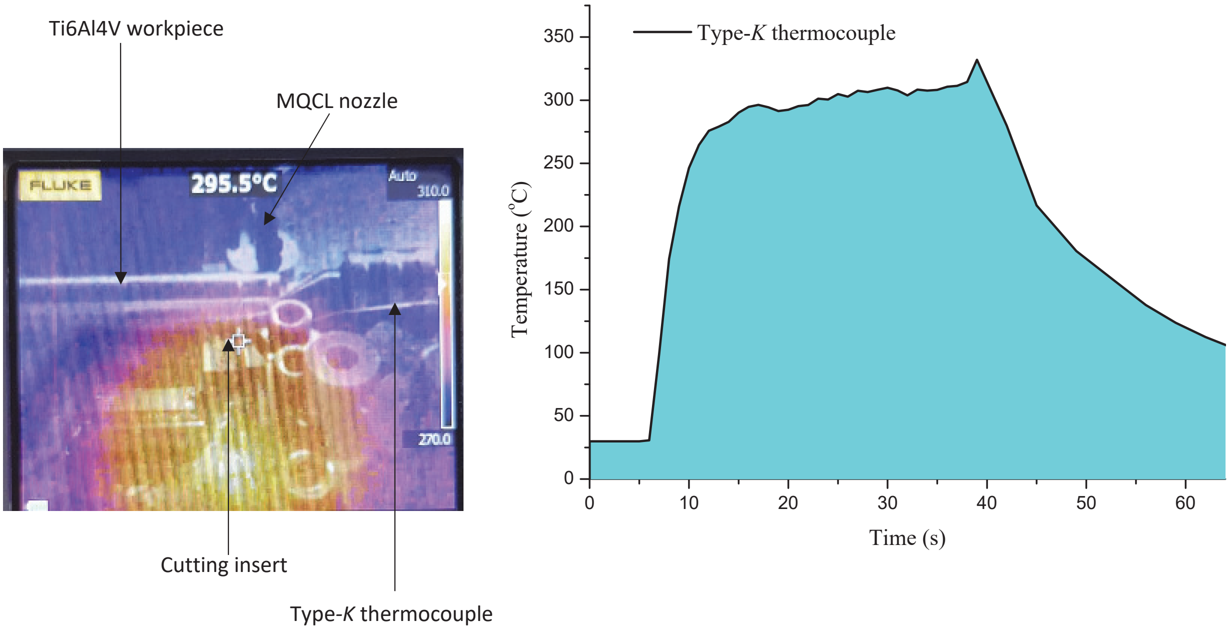
The growth of the cutting insert flank wear with the increment of cutting length was evaluated and the tool wear mechanism was determined. Figure 2 demonstrates the procedure of turning process for each experiment.

3 Results and discussion

In this section, the machinability performance measure such as machining temperature and cutting insert lifespan using different cooling lubrication strategies were evaluated and discussed to examine the performance of tribology on the cutting inert. Turning process experiments have been demonstrated under variable flow rates of MQCL based G-Al_2O_3 hybrid nanocooling-lubricants and conventional fluids with flood cooling conditions, and results of all cooling lubrication conditions have been studied and explained in the following subsections.

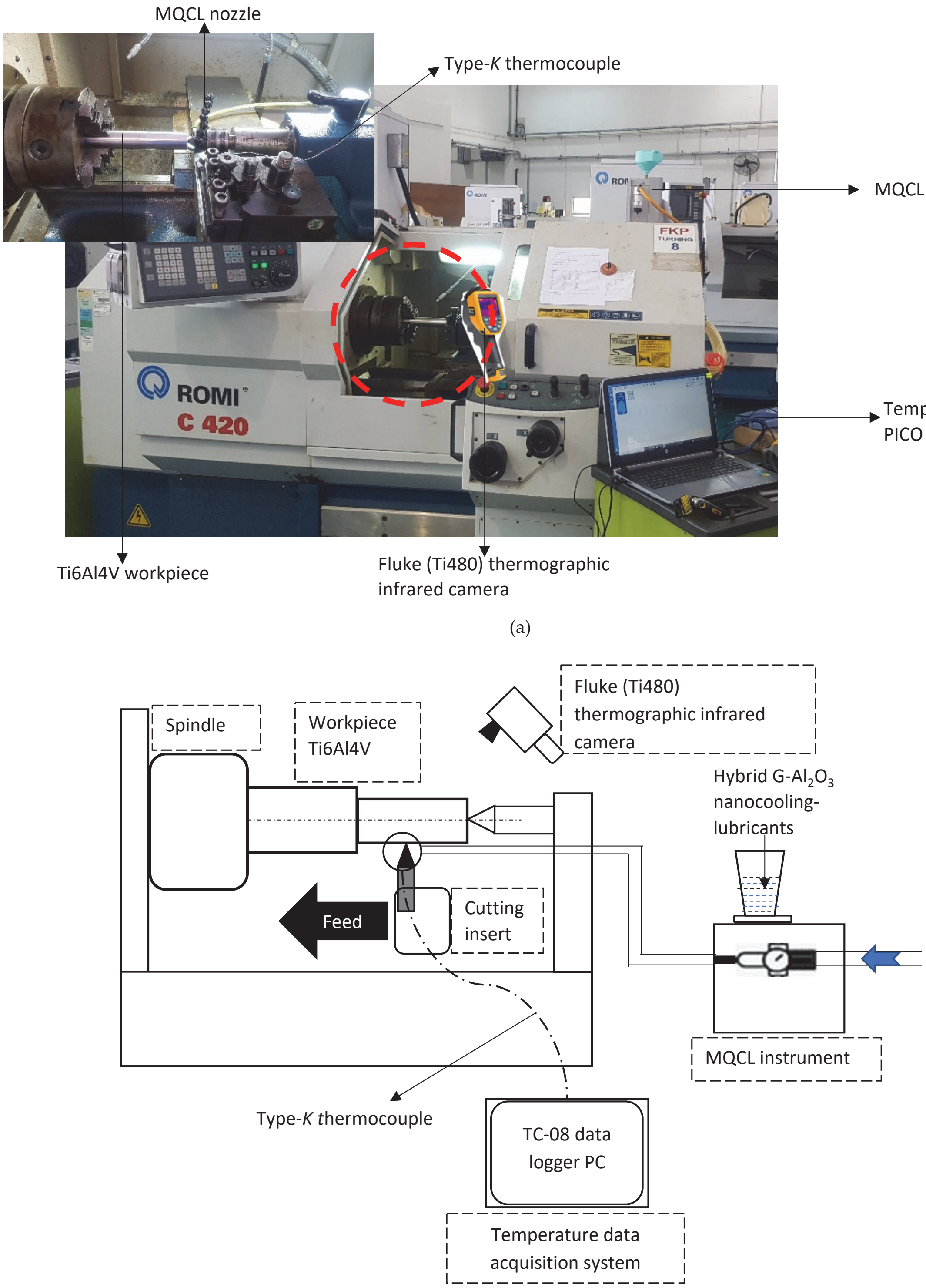
3.1 Machining temperature

Machining heat was mainly generated at primary machining zone of plastic deformation process and frictional or sliding deformation at the tool-chip interfaces in secondary machining zone. Figure 3 describes the cutting peak temperature results during the turning operation of titanium alloy (Ti6Al4V) experiment measured using Fluke thermography camera and type-*K* thermocouple wire. In the experiment, a significant increased of machining temperature from 206°C to 317°C based on type-*K* thermocouple wire measurement as the increment of cutting speed from 120 m/min to 180 m/min. However, machining temperature decreased with the increasing of lubrication flow rate from MQCL 10 to 40 mL/min up to the conventional fluids with flood cooling under every single cutting speed condition. The Fluke thermography camera could not accurately detect the machining temperature of three testing experiments under conventional fluids with flood cooling condition for all cutting speeds from 120 – 180 m/min



(a) (b)

Fig. 1 Machining temperature during turning process; (a) Thermographic image with temperature data; (b) peak temperature collected using type-*K* thermocouple wire



(a)

(b)

Fig. 2 Experimental setup of turning process; (a) On-machine assembly for output variables measurements; (b) Schematic for turning process

due to this device detected temperature of cooling lubricants and side surface temperature of workpiece [23, 24]. The data obtained that the peak machining temperature recorded by type-*K* thermocouple wire were always higher as compared to the Fluke thermography camera and deviated approximately 1.5% to 8.0% deviation under MQCL (near dry machining) condition and more than 100% deviation under conventional fluids with flood cooling condition. The reason that the type-*K* thermocouple wire attached to the cutting insert allowed heat transfer due to conduction from primary and secondary machining zone of workpiece-tool-chips interfaces reaching the thermocouple measuring sensor [18, 20]. Furthermore, the

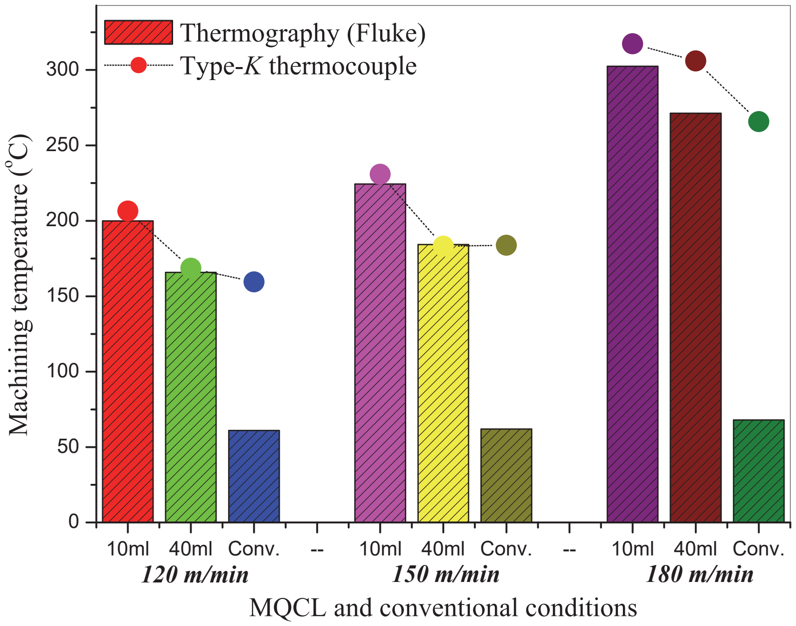


Fig. 3 Machining temperature under several cutting speeds and different MQCL conditions

vapour in the surrounding of the machining workpiece due to evaporation effect under MQCL condition [25], and under flood cooling condition, the conventional fluids highly covered the workpiece surface to influence the detection of temperature by Fluke thermography camera.

The minimum machining temperature was obtained at approximately 159°C under conventional fluids with flood cooling condition with cutting speed of 120 m/min. Oppositely, the maximum heat generated at cutting speed of 180 m/min under MQCL flow rate of 10 mL/min was found at temperature of 317°C. The application of G-Al_2O_3 hybrid nanocooling-lubricants MQCL maintained optimum machining temperature peak or heat dissipation at machining conditions of 120 to 150 m/min due to heat transfer performance of Al_2O_3 and graphene nanoparticles homogeneously suspended in base spent lubricants/EG solution for cooling and lubrication effect. A fine mist of hybrid nano-cooling lubricants transferred away some of the heat by conduction and convection of nanoparticles and base solution, respectively; and a small amount of heat was carried away with evaporation of base solution at elevated temperature condition [26]. Furthermore, hybrid G-Al_2O_3 nanoparticles in base solution could serve as colloidal lubricants [27] made a protective tribo-film associated with minimizing frictional heat generation due to the sliding of the cutting insert on the workpiece material of titanium alloy. Although less amount of hybrid nanocooling-lubricant was implemented, relatively high viscosity allowed it to stick longer at the machining zone with a relatively high specific heat of EG oil, the G-Al_2O_3 hybrid nanocooling-lubricant was most effective.

The huge amount of heat generation at the high level of cutting speed 180 m/min due to high speed shear deformation of titanium alloy workpiece which exhibited low thermal conductivity property. Therefore, the heat remained at the machining zone due to low thermal conductivity and produced high thermal stresses at the machining zone with extreme high cutting speed [28]. At the highest machining temperature, the effectiveness of G-Al_2O_3 hybrid nanocooling-lubricants significantly decreased due to degradation and desorption of tribo-film thinner on the surface. Hence, the destruction of tribo-film consequence in terms of high heat generation. The lower machining temperature under hybrid nanocooling-lubricants with the flow rate of 40 mL/min could be associated with the high thermal conductivity of Al_2O_3 nanoparticles (36 W/m.K^{-1}) performed conduction and convection heat transfer as cooling effect and graphene nanoparticles contributed for lubrication effect. The mist spray of MQCL system with pressure allowed the droplets penetrated to the hot workpiece-cutting insert interface and resulted for heat dissipation. The G-Al_2O_3 hybrid nanocooling-lubricants penetrated the machining zone, which provided adequate cooling and lubrication, and minimize the sliding of the cutting insert with the workpiece [45].

3.2 Cutting insert lifespan under various cooling lubrication conditions

Cutting insert life was significantly influenced by cutting speed and machining temperature which strongly co-related [29]. Under high level of cutting speed, a lubricant failed to penetrate closer to the cutting region and a high rate of material deformation converted into an elevated machining temperature that damaged the cutting edge to reduce cutting insert lifespan [9]. Figure 4 indicates a comparison of different cooling lubrication conditions on cutting insert life and cutting length were conducted at the same cutting speed. The increment of cutting speed from 120 m/min to 180 m/min under hybrid nanocooling-lubricants with MQCL method and conventional fluid cooling condition resulted shorter cutting insert lifespan. The maximum cutting insert lifespan reached before insert removing at maximum of 500 μm wear on the flank surface of cutting edge. In a cutting speed of 120 m/min, hybrid nanocooling-lubricant was introduced to MQCL flow rate set at 40 mL/min obtained the highest cutting insert lifespan up to 12.7 min or cutting length of 2700 mm, followed by 10 mL/min flow rate of MQCL hybrid nanocooling-lubricants of 10.6 min with 2250 mm cutting length and a minimum of 8.4 min cutting insert life (cutting length of 1800 mm) under conventional fluid cooling condition. The maximum improvement for cutting

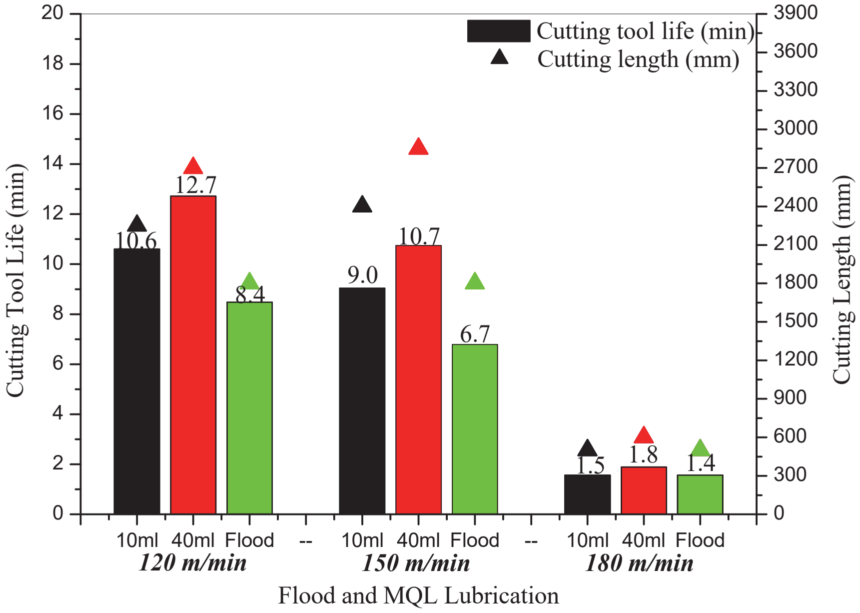


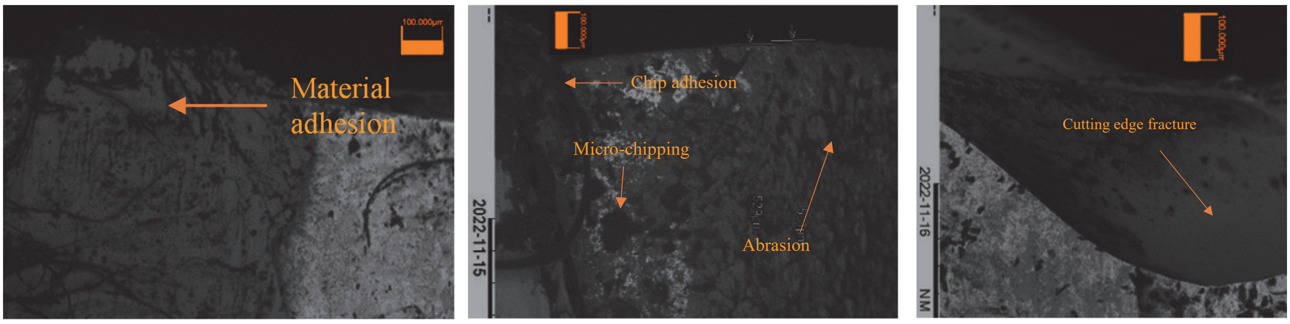
Fig. 4 Cutting tool life and cutting length under different cooling lubrication conditions at several cutting speeds

insert lifespan was evaluated to be enhanced by approximately 51% between 40 mL/min MQCL hybrid nanocooling-lubricants compared to conventional fluid cooling method under machining parameters of 120 m/min cutting speed, a feed rate of 0.2 mm/rev and 1.0 mm depth of cut. However, at the maximum level of cutting speed of 180 m/min attained lowest cutting insert life of 1.4 min with 300 mm cutting length under conventional fluid cooling condition. The cutting insert lifespan of 1.5 min with a cutting length of 450 mm under 10 mL/min flow rate, while cutting length of 600 mm with cutting insert life of 1.8 min under 40 mL/min flow rate of MQCL hybrid nanocooling-lubricants. The enhancement was measured to be improved by 20% and 28% under MQCL hybrid nanocooling-lubricants between the flow rates of 40 mL/min with 10 mL/min and compared to conventional fluids cooling condition, respectively. The conventional fluid had poor cooling lubrication ability due to vaporize at high machining temperature with high heat generation in the cutting region at high level of cutting speed. Likewise, the MQCL hybrid nanocooling-lubricants exhibited excellent performance in cutting insert life improvement for all cutting speeds due to inherent and intrinsic properties making it enhanced tribological interaction between the cutting insert-chip interface [30, 31].

3.3 Cutting insert flank wear and wear mechanism analysis

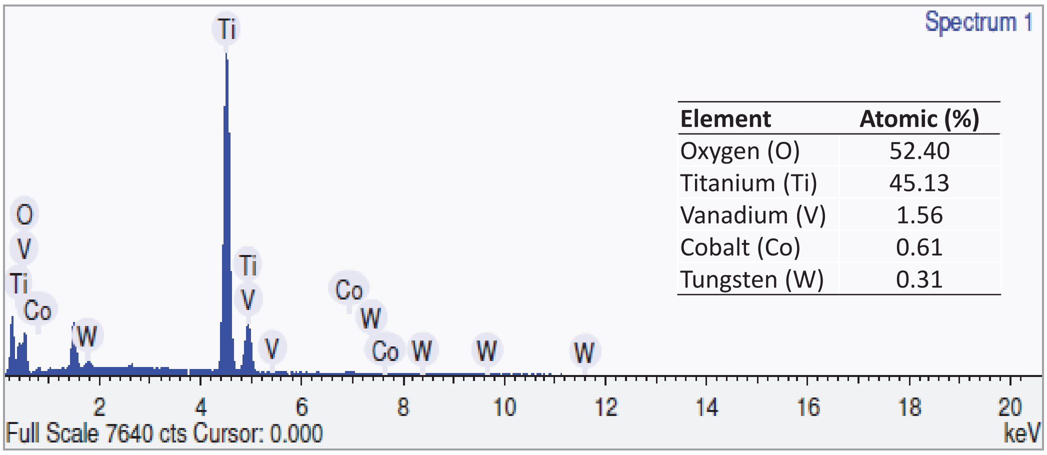
The flank wear showed on the insert flank surface of cutting edge along the length of tool-workpiece sliding interfaces resulted in the formation of a wear land [32]. Figures 5, 6 and 7 illustrates the typical cutting insert failure mode at the insert flank surface under conventional fluids cooling and hybrid nanocooling-lubricants in MQCL flow rate of 10 mL/min to 40 mL/min conditions for a cutting length of 300 mm. For conventional fluids cooling condition with the machining parameters of 120 m/min cutting speed, a feed rate of 0.2 mm/rev and 1.0 mm depth of cut presented by LEXT images are shown in Fig. 5(a)(i). The severe adhesion of Ti6Al4V workpiece removal material was clearly seen on the cutting insert flank surface. This condition could be happened due to high temperature at the machining region and the sticking of Ti6Al4V removal material that covered the insert surface underneath. Moreover, the average flank wear was measured as 529 μm together with abrasive wear, chip adhesion and micro-chipping on the insert surface at a cutting speed of 150 m/min with constant machining condition as depicted in Fig. 5(a)(ii). The deposited micro-chip on the cutting insert flank surface and abrasion seemed to be major wear processes. This welded adhesive chip of titanium alloy workpiece material resulted micro-chipping on the cutting edge surface in order to cause the exacerbation of flank wear until it reached the cutting insert failure criterion. While the abrasive wear was characterized by the forcible sliding contact with hard particles between the sliding interfaces and the appearance of small flats on the flank surface by protruding carbide grains [33]. During a cutting speed of 180 m/min, Fig. 5(a)(iii) shows cutting insert fracture on the cutting edge which occurred cavity due to dislodge of cutting insert carbide particles. The fracture was resulted by titanium alloy workpiece material adhesion on the cutting edge. The SEM-EDX spectrograph as Fig. 5(b) presents high concentration of Titanium (Ti) element of 45.1 *au*% which belonging to the workpiece of Ti6Al4V on the worn flank surface. The presence of Oxygen (O) element on the main cutting edge might be attributed to exposure to the atmosphere as the turning process is done in open air that occurrence of oxidation reaction. The existence of Oxygen (O) element is also reported by Hu and Chou [34] and Najiha et al. [33]. The selected zone obtained the elements of Titanium (Ti) and Vanadium (V) on the edge of cutting insert to prove the transferring of material. The Cobalt (Co) and Tungsten (W) elements of 0.61 *au*% and 0.31 *au*% ,respectively, were also detected on the flank surface due to the decomposition of tungsten carbide cutting insert [33] and diffusion of carbide insert because the conventional fluids did not provide adequate cooling lubrication effect at high level cutting speed for turning a hard-to-cut material of Ti6Al4V workpiece [26].

The Fig. 6(a)(i) exhibits LEXT micrograph for the flank surface of cutting edge in machining conditions with a



(i) 120 m/min (ii) 150 m/min (iii) 180 m/min

(a)



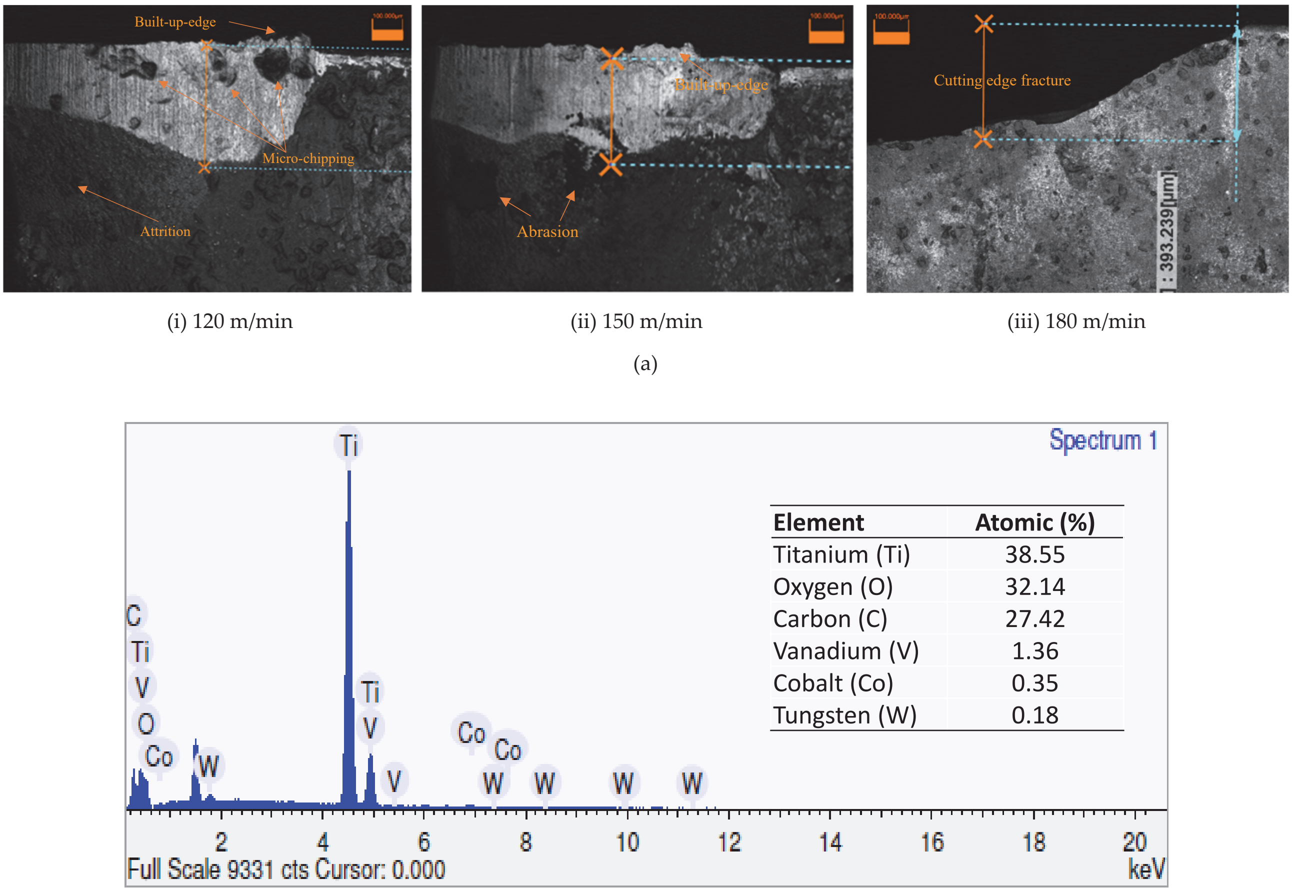
Element	Atomic (%)
Oxygen (O)	52.40
Titanium (Ti)	45.13
Vanadium (V)	1.56
Cobalt (Co)	0.61
Tungsten (W)	0.31

(b)

Fig. 5 Typical flank wear under conventional fluids cooling condition at constant feed rate, f = 0.2 mm/rev and depth of cut, α_p = 1.0 mm; (a) Different cutting speeds; (b) SEM-EDX pattern for element composition

cutting speed of 120 m/min, a feed rate of 0.2 mm/rev, 1.0 mm depth of cut and a hybrid nanocooling-lubricants based G-Al_2O_3 nanoparticles with MQCL flow rate of 10 mL/min appeared attrition wear and micro-chipping on the worn flank surface (average 246.9 μm) were major wear phenomenon. This phenomenon could be justified the high strain rate and concentrated heat generation that smearing of titanium on the flank surface in order to the removal of cutting insert substrate material from the cutting edge [35]. The minor formation of built-up-edge found on the cutting edge negatively changed the cutting insert geometry due to increment of the machining temperature that chips sticked to the cutting edge. The built-up-edge was unstable and provided for tool chipping [36]. During 150 m/min cutting speed with similar turning condition, the average flank wear of 253.5 μm was evaluated on the cutting insert flank surface together with abrasion wear and built-up-edge as illustrated in Fig. 6(a)(ii). These findings highly related to high cutting speed and high heat generation. Under high machining temperature and high pressure environment, the chips likely to stick to the main cutting edge. The possibility of chip welded on the cutting edge increased the main cutting edge substrate to expose during turning operation [37]. While sudden fracture on the cutting edge has been observed at the cutting speed of 180 m/min turning condition as shown in Fig. 6(a)(iii). The cutting edge fracture was negatively contributed by workpiece material adhesion on the main edge, hence whole elimination of the cutting edge. This was associated with the elevated machining temperature, and ultimately softening of the cutting insert-tip, which exposed insert substrate and material flow making the cutting edge sudden fracture. Zhang et al. [38] concluded that a similar phenomenon of flank wear initially before the cutting edge blunt completely and later a sudden fracture on the cutting edge caused the end of the tool life. The micro-zone is selected for SEM-EDX spectrograph analysis as depicted in Fig. 6(b). The presented of Carbon (C) element of 27.4 *au*% and Oxygen (O) element of 32.1 *au*% on the cutting insert flank surface with the reduction of approximately 17% of Titanium (Ti) element of 38.5 *au*% as compared between the hybrid nanocooling-lubricants based graphene and oxide nanoparticles under 10 mL/min flow rate MQCL with conventional fluids cooling machining condition. The deposited Titanium (Ti) element in abundance and small amount of Vanadium (V) element (1.36 *au*%) on worn cutting edge. Furthermore, Tungsten (W) element of 0.18 *au*% was reduced roughly 72% as compared to conventional fluids cooling condition with the exposing of cutting insert substrate during turning process.

In the combination machining parameters of a feed rate 0.2 mm/rev, a depth of cut 1.0 mm, a cutting speed 120 m/min and a G-Al_2O_3 hybrid nanocooling-lubricants of MQCL flow rate set at 40 mL/min was shown in LEXT micro-image as Fig. 7(a)(i). A maximum flank wear of 131.4 μm was evaluated on the worn cutting insert surface, while micro-attrition, micro-adhesion and micro-chipping were clearly seen on the worn flank surface. The



(i) 120 m/min

(ii) 150 m/min

(iii) 180 m/min

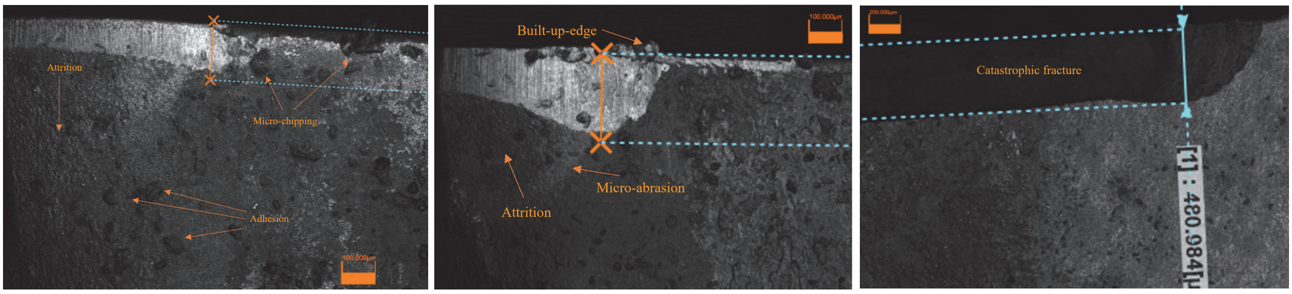
(a)

Element	Atomic (%)
Titanium (Ti)	38.55
Oxygen (O)	32.14
Carbon (C)	27.42
Vanadium (V)	1.36
Cobalt (Co)	0.35
Tungsten (W)	0.18

(b)

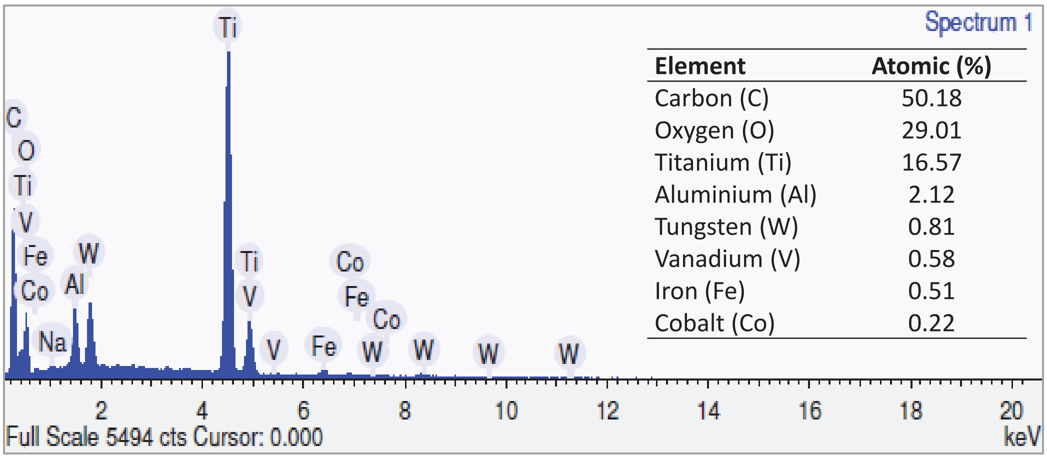
Fig. 6 Typical flank wear under hybrid nanocooling-lubricants of MQCL flow rate of 10 mL/min machining condition at constant feed rate, $f = 0.2$ mm/rev and depth of cut, $\alpha_p = 1.0$ mm; (a) Different cutting speeds; (b) SEM-EDX pattern for element composition

micro-attrition or dull flank surface ploughing effect due to the Ti6Al4V chip micro-welding or smearing on the carbide cutting insert [33]. It was crucial to reveal that compared to conventional fluids cooling condition prevented the abundance of chips adhesion on the cutting insert flank surface. Micro chipping could be attributed to the characteristic behavior of concentrated heat generation with high level of cutting speed which led to the removal of cutting insert substrate material from the main cutting edge [39]. As G-Al_2O_3 hybrid nanocooling-lubricants introduced into MQCL system to spray mist droplets as superior cooling and lubrication medium due to conduction among the nanoparticles, convection and evaporation processes occurred between the cutting insert-lubricant-workpiece. Hence, this could be reported that G-Al_2O_3 hybrid nanocooling-lubricants in MQCL system contributed to prolong cutting insert life with longer machining time under high level cutting speed of turning hard-to-cut (Ti6Al4V) workpiece. Furthermore, at 150 m/min cutting speed with G-Al_2O_3 hybrid nanocooling-lubricants under MQCL flow rate of 40 mL/min to compare to conventional fluids cooling that the enhancement of cutting insert flank surface approximately 127% by reducing the flank wear to 233.4 μm. The main reason that the existing of nanoparticles boundary as ball bearing effect by the graphene and aluminum oxide nanoparticles on the two interacting surfaces, that resulted to reduce contact between asperities on the two sliding surfaces. The presence of nanoparticles between the interacting frictional surfaces considerably reduced the contact between the interacting surfaces by rolling mechanism effect [40] from alumina nanoparticles and formation of tribo-film on the contacting surface due to graphene nanoparticles absorbed on the metal surface as protective coating [41]. Wu et al. [42] noticed that the formation of tribo-film and ball bearing effect of nanolubricants responsible for efficient tribology due to the spherical nature of nanoparticles easier to transform into miniature ball bearing for rolling mechanism at two contacting surfaces. Figure 7(a)(ii) displays micro-attrition followed by micro-abrasion on the cutting insert flank surface due to the optimum lubrication and cooling ability of G-Al_2O_3 hybrid nanocooling-lubricants enabled the prevention of any catastrophic fracture at the main cutting edge at high level of cutting speed. However, minor built-up-edge formation could be observed in LEXT micrograph. This could be explained that as compared to conventional fluids cooling condition, minor built-up-edge and micro-abrasion on the main cutting edge under hybrid nanocooling-lubricants MQCL condition. The reasons that the cushion effect of fine mist cooling and excellent viscosity of G-Al_2O_3 hybrid nanocooling-lubricants under high strain rate and pressure in order to provide optimum lubrication at the interacting surfaces to reduce the rubbing effect and heat dissipation [43]. Figure 7(a)(iii) shows catastrophic edge fracture was major wear phenomenon of the carbide insert. The cutting edge was significantly altered at high cutting speed of 180 m/min in the turning operation of Ti6Al4V workpiece material under hybrid nanocooling-lubrication of



(i) 120 m/min (ii) 150 m/min (iii) 180 m/min

(a)



Element	Atomic (%)
Carbon (C)	50.18
Oxygen (O)	29.01
Titanium (Ti)	16.57
Aluminium (Al)	2.12
Tungsten (W)	0.81
Vanadium (V)	0.58
Iron (Fe)	0.51
Cobalt (Co)	0.22

(b)

Fig. 7 Typical flank wear under hybrid nanocooling-lubricants of MQCL flow rate of 40 mL/min machining condition at constant feed rate, $f = 0.2$ mm/rev and depth of cut, $\alpha_p = 1.0$ mm; (a) Different cutting speeds; (b) SEM-EDX pattern for element composition

MQCL condition. The catastrophic edge fracture due to high strain rate and high machining temperature, accompanied by work hardening that accelerated the cutting insert failure. At elevated machining temperature, the melting process occurred at the main cutting edge and exposed followed by damaging the cutting edge substrate almost equal to the approached depth of cut. This ultimate cutting insert failure due to melting process was frequently occurred at carbide insert under high level cutting speed of machining Ti6Al4V hard-to-cut workpiece [44]. The randomly selected micro-zone of SEM-EDX spectrograph presented deposition of Titanium (Ti), Aluminum (Al), Vanadium (V) and other chemical elements related to cutting insert material such as Tungsten (W) element were identified as in Fig. 7(b). The minimum peak of Titanium (Ti) element of 16.5 *au*% and Vanadium (V) element of 0.5 *au*% under MQCL with G-Al_2O_3 hybrid nanocooling-lubricants at flow rate of 40 mL/min, that compared to conventional fluids cooling condition with Titanium (Ti) and Vanadium (V) elements of 45.1 *au*% and 1.6 *au*%, respectively, deposited on the main cutting edge. The less deposition of Titanium (Ti), Aluminum (Al) or Vanadium (V) on the cutting edge could be associated with superior cooling and lubrication by the high penetration capability of pressurized MQCL based hybrid nanocooling-lubricants that delivered sufficient lubrication and cooling to the border of elements deposition during turning process. Therefore, under G-Al_2O_3 hybrid nanocooling-lubricants with MQCL system, only few Titanium (Ti) element and Vanadium (V) element depicted less adhesion and flank wear on the cutting insert flank surface.

4 Conclusion

In conclusion, this study achieved several objectives:

- Experimental results revealed that the machining temperature significantly increased from 206°C to 317°C based on type-*K* thermocouple wire measurement as the cutting speed increased from 120 m/min to 180 m/min. However, the machining temperature decreased with the increasing of lubrication flow rate of MQCL from 10 mL/min to 40 mL/min, then to the conventional fluid cooling condition. Cutting speed and feeds of more than 150 m/min and 0.25 mm/rev, respectively, lead to cutting insert failures.
- Compared with conventional fluid cooling condition, the G-Al_2O_3 hybrid nanocooling-lubricants MQCL at the cutting speed of 120 m/min significantly increased cutting tool life to 51% and cutting speed of 180 m/min to 28%.
- SEM-EDX presented that titanium element deposited on cutting insert flank surface, which has shown micro-attrition, abrasion and adhesion wear leading edge chipping or fracture, was the main cutting insert wear mechanism.

Acknowledgements

The authors are grateful to the Universiti Malaysia Pahang (UMP) for financial support. This work was supported by the UMP grant RDU 223004.

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