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Experimental evaluation of tool wear and surface roughness under different conditions in high-speed turning of Ti6Al4V alloy

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Abstract

In high-speed machining of titanium alloys, due to their difficult-to-cut characteristics, tool performance and surface integrity are greatly influenced by the generated large amount of heat in the cutting zone. High cutting speeds lead to more severe abrasion, adhesion, and diffusion wear mechanisms and thus, decrease tool life rapidly. Therefore, the identification of an effective cooling/lubrication strategy is critical to enhance tool performance and surface finish. In this study, the effects of four different cooling/lubrication conditions (dry, conventional cutting fluid (CCF), minimum quantity lubrication (MQL), and cryogenic cooling) on tool wear and average surface roughness (Ra) in high-speed turning of Ti6Al4V alloy were investigated. Three cutting speeds (125, 250 and 350 m/min) were employed by keeping depth of cut (0.5 mm) and feed (0.1 mm) constant. For each condition, the variations of flank and crater wears with cutting length were determined. According to test results, high speeds caused an increase in temperature and this led to adhesive and abrasive wear mechanisms being effective simultaneously. Besides, the use of high speeds reduced the effects of coolants and/or lubricants. Due to the effective cooling and lubrication, lower Ra values were obtained under CCF conditions.

Keywords: Ti6Al4V alloy, high-speed machining, sustainable machining, tool wear.

Nomenclature

BUE	Built-up edge
CCF	Conventional cutting fluid
CNC	Computer numerical control
KT	Crater depth (μm)
LN_2	Liquid nitrogen
MQL	Minimum quantity lubrication
Ra	Average surface roughness (μm)
VB	Average band width of flank wear (μm)
V_C	Cutting speed (m/min)

1. Introduction

Ti6Al4V alloy is commonly employed in aerospace, aviation, biomedical, automotive, and energy industries due to its attractive characteristics such as good strength-to-weight ratio, superior corrosion resistance, high

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heat, fatigue, and creep resistance, and good biocompatibility. However, it is classified as one of the difficult-to-cut materials owing to its crystal structure (hexagonal close-packed), low thermal conductivity, high chemical affinity, high strength at high temperatures and low elastic modulus [1,2]. Difficult-to-cut characteristics of Ti6Al4V alloy lead to premature tool failure, longer machining time, poor surface quality and thus, excessive machining costs [3, 4]. Therefore, the studies on optimization of cutting conditions are among the main research topics to achieve a reduction in costs and improvement of efficiency in machining of Ti6Al4V alloy [5, 6]. As well-known, about 80% of the heat generated during cutting of Ti6Al4V alloy is retained in the cutting zone due to its low thermal conductivity [6]. In addition, transformation of more mechanical energy to thermal energy at high cutting speeds leads to further tool wear due to increasing friction and excessive heat generation at cutting zone. Therefore, cooling/lubrication strategies have a significant importance to enhance the tool life, finished part quality, and production rates. Recently, sustainable machining strategies such as minimum quantity lubrication (MQL) and cryogenic cooling have become increasingly important to decrease or eliminate the harmful effects of conventional cutting fluids (CCF) such as environmental pollution and health hazards and to enhance machining efficiency [7]. Silva et al. [8]. showed that MQL conditions provided better tool performance than dry conditions in high-speed turning of Ti6Al4V. According to Khatri and Jahan [9], when compared to dry and CCF conditions, a lower tool wear formation was achieved by using MQL machining in end milling of Ti6Al4V. The findings were associated with effective lubrication and moderate cooling effect of MQL environment. Some researchers point out that it is possible to achieve higher material removal rates with lesser tool wear, when machining Ti6Al4V alloy under cryogenic conditions [10–12]. Cryogenic cooling enhances the tool performance by reducing the cutting zone temperatures and chemical affinity of tool material to titanium workpiece material and thus, improves the machinability. Rotella et al. [13] showed that cooling/lubrication conditions are significantly affecting the surface quality in machining Ti6Al4V. According to their findings, cryogenic cooling is a more effective method than dry and MQL conditions to enhance surface quality. Khanna et al. [14] studied the sustainable cooling/lubrication strategy in machining Ti6Al4V. Their findings showed that cryogenic cooling provided a good balance between machining performance (cutting force, tool life, and surface quality i.e.) and sustainability. According to Agrawal et al. [15], in turning Ti6Al4V at different cutting speeds (70-110 m/min), cryogenic cooling improved the machinability in terms of tool life (up to 125%), surface roughness (up to 22.1%), power consumption (up to 23.4%), and also machining costs (up to 27%), especially at higher cutting speeds. Gupta et al. [16] showed that in machining Ti6Al4V at moderate cutting speeds (100, 150 m/min), when compared to dry cutting, LN_2 and LN_2+MQL machining environments significantly improved tool performance and surface quality.

The effects of different cooling and/or lubrication techniques on cutting performance is an important topic for researchers in machining of Ti6Al4V alloy [17,18]. The literature studies confirm that there is a need for further investigations to provide economical and efficient use of sustainable machining strategies. In addition, determination of optimal cutting conditions for difficult-to-cut materials will provide a significant contribution to the adaptation of green manufacturing into the industry, especially at high-speed machining conditions. Therefore, the main objectives of this study are to investigate the effectiveness of different eco-friendly cooling/lubrication methods on tool performance and surface roughness in high-speed turning of Ti6Al4V alloy. For this purpose, a number of tests were conducted at high cutting speeds from 125 m/min to 350 m/min under dry, CCF, MQL and cryogenic cooling conditions. The findings of the study were discussed in terms of tool wear and Ra depending on cutting length.

2. Material and method

In this study, Ti6Al4V bars with a length of 200 mm and a diameter of 63 mm are used as workpiece material. The experiments were performed using uncoated WC-Co inserts (CNMG 120408 K68, Kennametal Inc.) and a tool holder (PCLNR2020K12) with a rake, clarence, and approaching angle of -6°, -6°, and 95°, respectively. Turning tests were performed on a Spinner TC400 52 MC CNC lathe at cutting speeds of 125, 250, and 350 m/min, a feed of 0.1 mm/rev, and a depth of cut of 0.5 mm under dry, CCF, MQL, and cryogenic cooling/lubrication conditions. The maximum cutting speed recommended in machining Ti6Al4V with WC-Co tools is about 120 m/min [19]. The cutting speeds employed in this study were chosen to show the influences of cooling and/or lubrication environments on tool wear and Ra at higher cutting speeds. In case of CCF condition, the experiments were conducted using an emulsion of boron oil (10%) and water (90%). Liquid nitrogen (LN_2) was employed as a cryogen under cryogenic conditions. A copper nozzle (Ø2.5 mm) was used to apply LN_2 from pressurized LN_2 dewar to the cutting process. The pressure of the LN_2 dewar was set to 1 bar by means of a compressor. To prevent rapid vaporization of LN_2, copper hose was insulated. The tests were started after cryogen was sprayed through the nozzle in liquid phase. The employed setup of the cryogenic cooling system including materials and design can also be found in several research studies [20,21]. Under MQL conditions, vegetable oil was used at a flow rate of 100 ml/h and under 0.4 MPa air pressure using an Unist MQL system. All the cooling/lubrication agents were implemented to the cutting zone from the rake face of the cutting tool. Test setup is indicated in Figure 1.

During the tests, average band width of flank wear (VB) and crater depth (KT) were measured, and tool failure criteria (VB = 300 µm for flank wear and KT = 150 µm for crater wear) were selected in accordance with ISO 3685 (Figure 2a). Flank wear (Figure 2b) and crater depth (Figure 2c) were measured at a certain cutting length up to tool failure criteria by means of a digital microscope and a Nanovea optical profilometer, respectively. After flank wear and crater wear reached their failure criteria, the tests were stopped. After the examinations on tool wear, only some unexpected test results were repeated. In addition, SEM analyses were performed on worn tools by aiming to evaluate wear mechanisms. The Ra values were measured under all conditions depending on cutting length using the Nanovea optical profilometer.

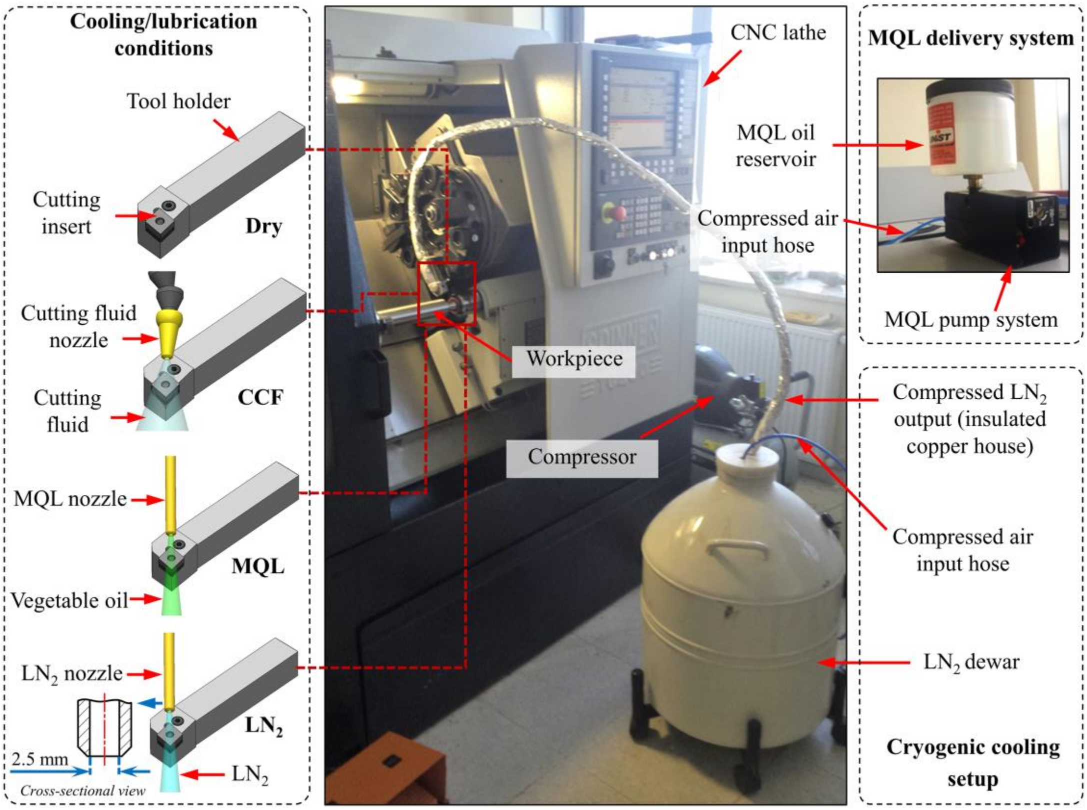

Fig 1. Experimental setup.

3. Results and discussions

3.1. Tool wear

Figure 3 indicates the variation of VB with respect to cutting length under different cutting conditions. The tool failure criterion for flank wear (300 µm) is shown with a horizontal dashed line in Figure 3. It is evident that minimal VB was observed at 125 m/min for all conditions. At 125 m/min (Figure 3a), cutting tools failed after about 650 m under dry and MQL conditions, 750 m under cryogenic condition, and about 1000 m under CCF condition. At the low cutting speed (125 m/min), the combined cooling/lubrication features of CCF improved the tool life (Figure 3). Application of CCF minimizes the friction and heat in the cutting zone simultaneously, and thus, suppresses the influences of abrasive, adhesive, and diffusion wear mechanisms. Similar tool performances of dry and MQL conditions confirmed that penetration of the oil particles did not take place effectively in MQL conditions due to high cutting temperatures and effect of centrifugal force during rotation motion. On the other hand, due to the limited lubrication effect of LN_2, shorter tool life under cryogenic conditions occurred in comparison to CCF conditions. However, when compared to the other cooling/lubrication conditions, a significant improvement was observed at 250 m/min (about 500 m cutting length) under cryogenic cooling conditions (Figure 3b). The other conditions exhibited similar tool performances (between 120-180 m). It can be said that increasing cutting temperatures at higher cutting speeds caused a decrease in the effectiveness of CCF conditions. The performance of CCF cutting condition was limited at high cutting speeds because it tends to vaporize at high temperatures and this condition minimizes the efficient penetration of CCF into the tertiary deformation zone [22]. On the other hand, the test results showed that effective cooling under cryogenic conditions was achieved, and thus the flank wear was minimal owing to the decrease in heat generation at the cutting zone.

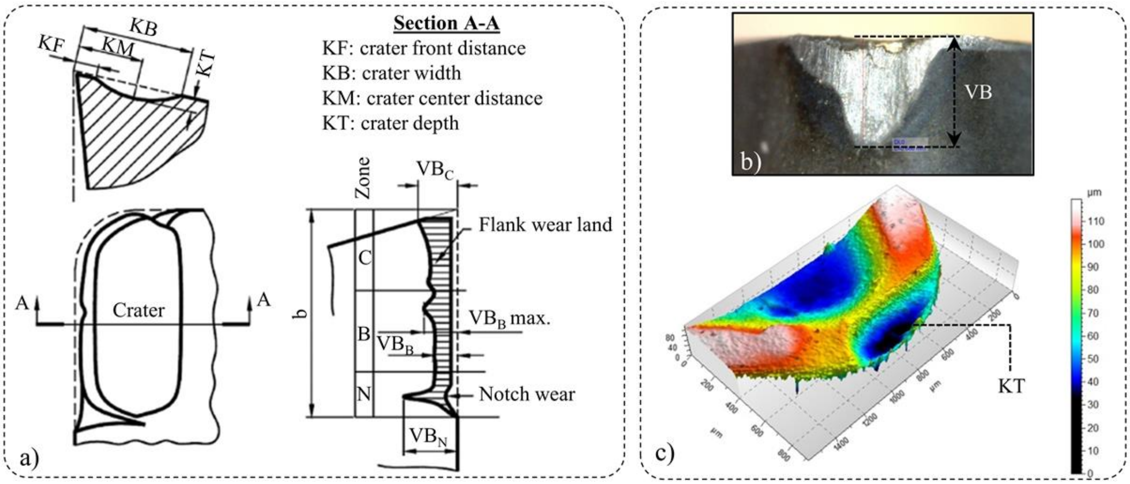

Fig. 2. a) Tool wear types according to ISO 3685 and measurement methods of b) flank and c) crater wears.

At 350 m/min, very close tool performances were observed (between 140-200 m cutting length) for all strategies (Figure 3c). The reasons for shorter tool life can be associated with elevated temperatures and high friction forces at the cutting zone at the high cutting speeds. Besides, interaction time between cooling/lubrication agent and workpiece material becomes shorter due to high strain rates at higher cutting speeds [23], thus the beneficial effects of the coolants and/or lubricants will be lesser. These cases led to a reduction of cooling and/or lubrication effects of employed strategies and caused diffusion and abrasive wear mechanisms (Figure 5). However, when compared with others, dry conditions showed the lowest tool flank wear at 350 m/min. The leading cause for this case is increasing temperatures at higher cutting speeds resulting in more ductile behavior of workpiece material and easier chip flow. Although increasing cutting temperatures also lead to thermal softening of cutting tool material, it can be said that this effect is lesser than the workpiece material. Therefore, it is thought that the effects of abrasive wear decrease. Besides, Lee and Lin [24] found that higher cutting temperatures caused a decrease in the microhardness values of Ti6Al4V alloy. Moreover, it is known that Ti6Al4V has lower tensile strength and hardness when high cutting temperatures are generated [25]. For these reasons, easier plastic deformation can be achieved with increasing cutting speeds when machining Ti6Al4V alloy. On the other hand, due to insufficient penetration of LN_2 into the cutting zone at high cutting speeds, the longer tool life was not observed at 350 m/min under cryogenic conditions.

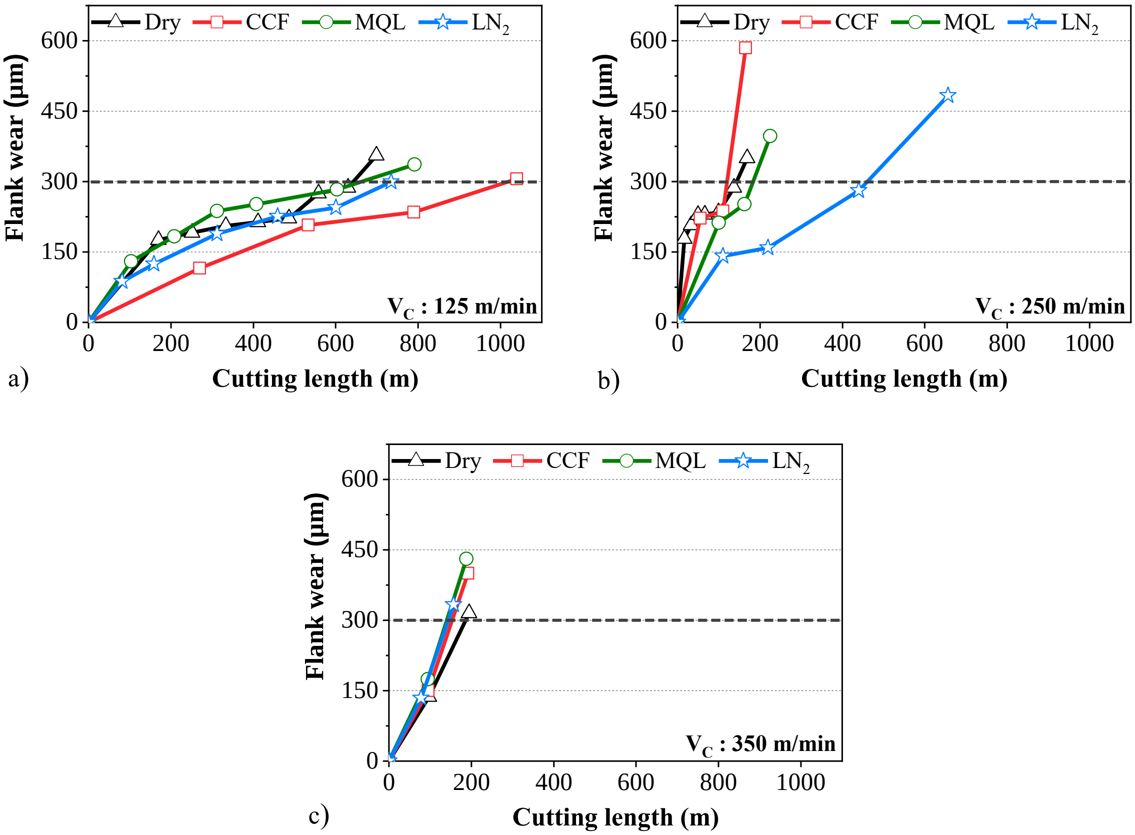

Fig. 3. The variation of flank wear with cutting length at a) 125, b) 250, and c) 350 m/min.

Crater depths at various machining conditions are shown in Figure 4. Tool failure criterion for crater wear (150 μm) is indicated with a horizontal dashed line in Figure 4. In general, similar trends to flank wear were observed. At 125 m/min under dry conditions (Figure 4a), combination of adhesive and abrasive wear mechanisms caused the shortest tool life (cutting length of 750 m) owing to absence of any cooling/lubrication media. However, similar crater depth values were obtained under CCF (1280 m) and cryogenic (cutting length of 1000 m) conditions. Cooling and/or lubrication feature(s) prevented formation of deeper a crater formation (Figure 5). Under MQL conditions, cutting tool reached to tool failure criterion after about cutting length of 1250 m. The primary reason for the usage of MQL technology is minimization of friction and heat. Therefore, it can be said that lubrication effect of MQL reduces the abrasive wear and increases the tool life in comparison to dry conditions, generally. However, due to its limited cooling effect, abrasion and diffusion occur, thus shallower crater depths could not be achieved (Figure 5). At 250 m/min, the shorter tool life (cutting length of 75 m) was observed under dry condition. The abrasive, adhesive and diffusion wear mechanisms are more effective at higher cutting speeds due to the increases in cutting temperatures and higher pressures on the rake face of the cutting tool. Crater wear depths at 250 m/min during CCF and MQL machining reached to tool failure criterion at almost the same cutting length. However, better results than dry and MQL (cutting length of 290 m) conditions were obtained under CCF conditions (cutting length of 360 m) owing to its efficient lubrication and cooling effects. As observed in the flank wear measurements, notable enhancement in tool life (about 900 m cutting length) was obtained under cryogenic conditions (Figure 4b). High cooling effect of LN_2 minimized diffusion wear mechanism which is a significant mechanism in formation of crater wear. At 350 m/min, the obtained results prove that effectiveness of cooling/lubrication media significantly decreases under high-speed conditions (Figure 4c). Although the obtained results were similar to one another (between 280-420 m cutting length), better tool life was observed under CCF conditions. As mentioned before, although high cutting temperatures reduce the effectiveness of cutting fluid, it is considered that cooling-lubrication features of the CCF are more effective on abrasive, adhesive and diffusion wear mechanisms than those of other conditions. On the other hand, shallower crater depth values were observed in LN_2 conditions owing to its efficient cooling feature in comparison to MQL (Figure 5). However, the results were very similar. Another interesting result is that the tool performance under dry condition was better than those cryogenic and MQL conditions. This result could be related to transfer of workpiece material on crater surface due to elevated temperature and high pressure during the machining (Figure 5). It is thought that crater surface could have such adhesions, and this leads to a decrease in crater depth under dry condition. In general, cryogenic cooling caused to chipping of the cutting edge (Figure 5). This can be attributed to the embrittlement of the workpiece material under cryogenic cooling conditions.

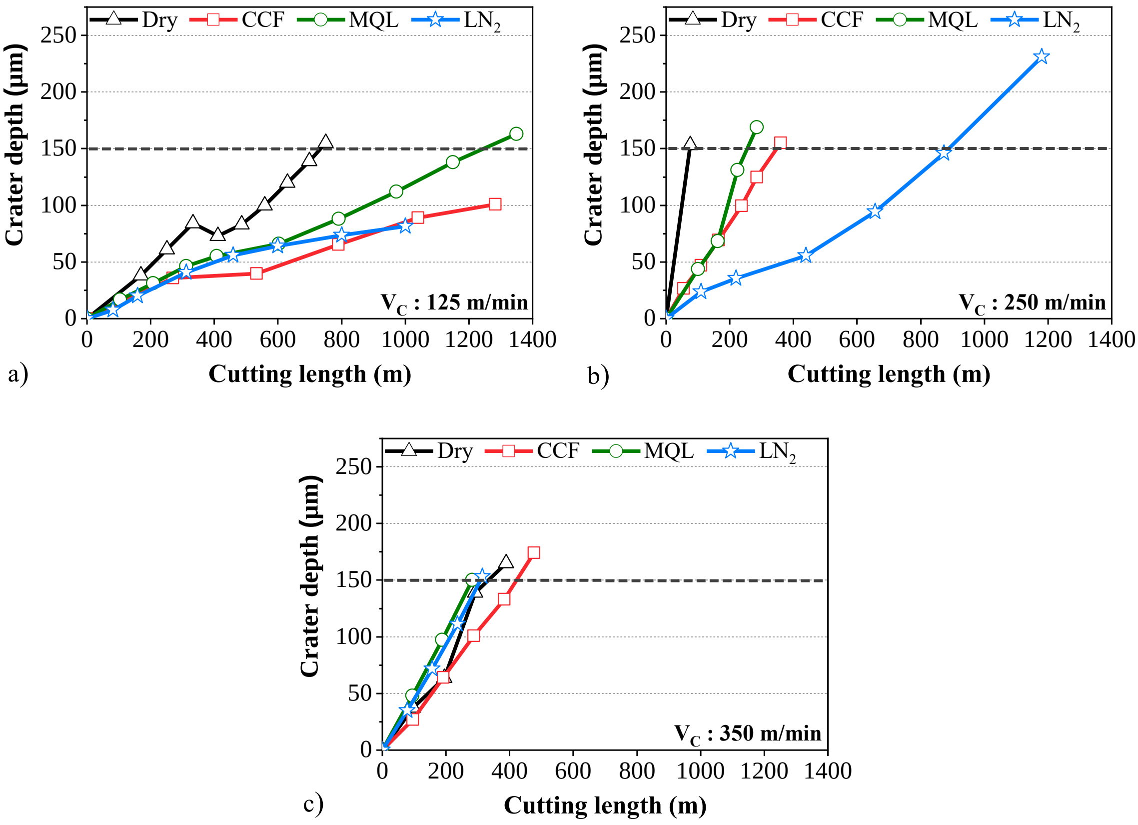

Fig. 4. The variation of crater depth with cutting length at a) 125, b) 250, and c) 350 m/min.

3.2. Surface roughness

The obtained Ra values depending on cutting length at 125m/min (Figure 6a) and 350 m/min (Figure 6b) at various cooling/lubrication conditions are given in Figure 6. In case of 125 m/min, when compared to other machining conditions, the lowest Ra values were obtained under CCF condition. This was attributed to lower tool wear and effective cooling-lubrication property of CCF. After a cutting length of 800 m an increase in Ra was observed under CCF condition. This can be explained by the formation of BUE (Figure 5). Under cryogenic cooling conditions, the Ra value significantly increased with increased cutting length. This can be associated with limited lubrication effect of LN_2 and excessive embrittlement of workpiece material under cryogenic conditions. Thus, higher cutting forces and vibrations can be observed and resulted in an unstable cutting process and higher Ra values [26]. In case of MQL condition, although lower Ra values than in dry condition were obtained until a cutting length of 400, due to the centrifugal force during rotation motion and increasing cutting temperatures with cutting length due to tool wear, the penetration of the oil particles into the cutting zone could not be reached. As a result, this led to increase in Ra. Moreover, under both MQL and LN_2 conditions, chipping was observed as shown in Fig. 5. Therefore, the sharp increase in Ra under these conditions can be associated with the formation of chipping. Figure 6b shows the variation of Ra values at the highest cutting speed (350 m/min). It is clear in Figure 6b that the obtained Ra values were similar for all cooling/lubrication conditions. Therefore, it can be concluded that due to high cutting temperatures at 350 m/min, the effectiveness of cooling/lubrication agents was not observed. It is clear from Figure 6b that the change of the cutting edge owing to tool wear through the cutting length of 400 m caused irregular variation of surface roughness such as better Ra values after a cutting length of 300 m when CCF was used. The improved surface roughness that occurred after some cutting lengths can be attributed to increased nose radius of tool with sudden tool wear.

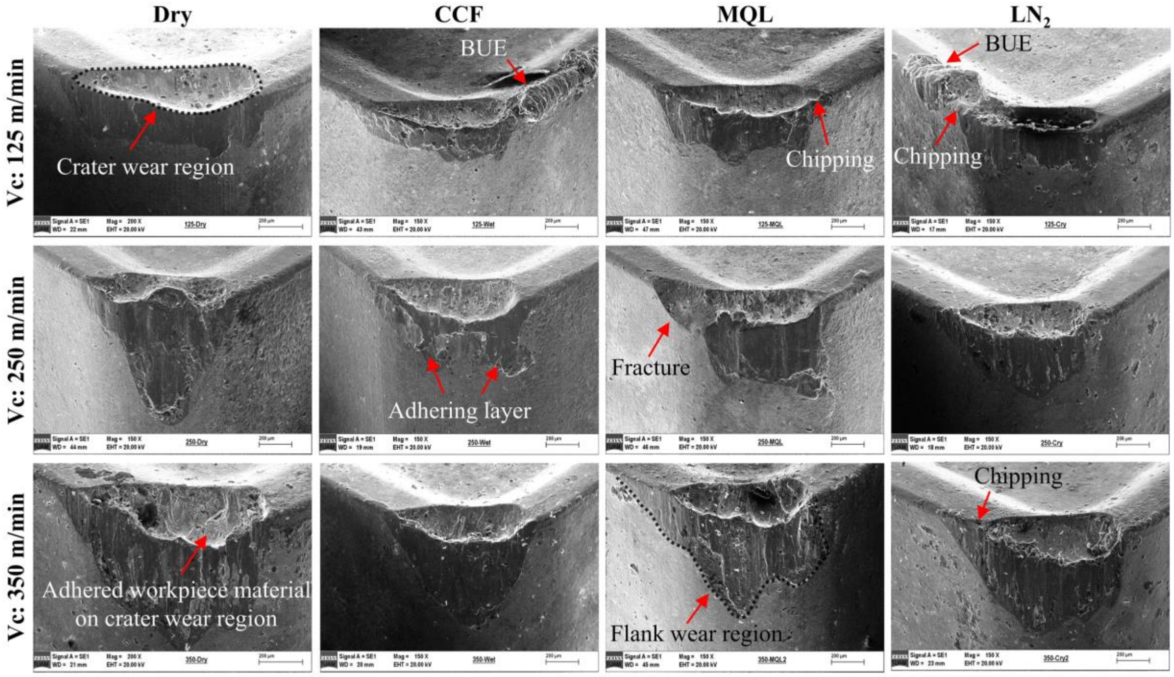

Fig. 5. SEM images of cutting inserts under different cutting conditions.

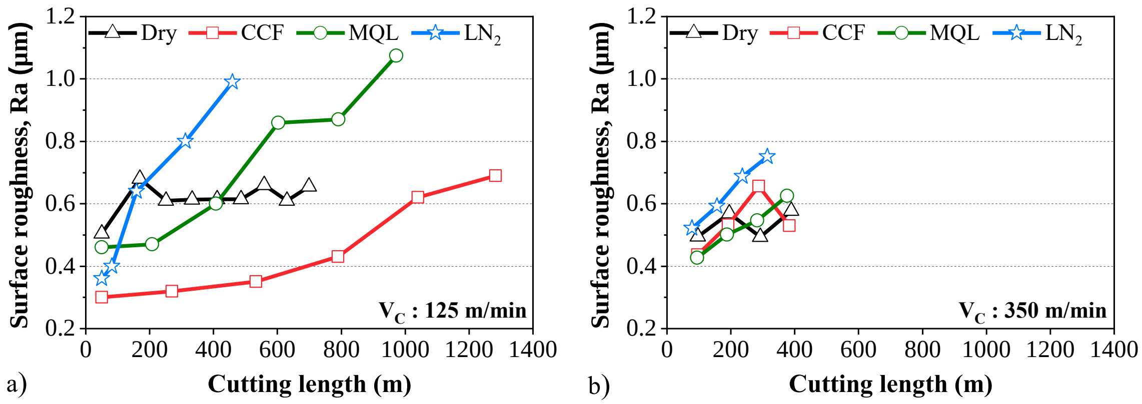

Fig. 6. The variation of Ra at a) 125 m/min and b) 350 m/min.

4. Conclusions

In this study, tool performances and Ra values under dry, CCF, MQL, and LN_2 conditions were investigated at high cutting speeds with uncoated carbide tools in turning of Ti6Al4V. The findings of this study are as follows:

- When considering VB, longer tool life (650-1000 m) was obtained at the lowest cutting speed value (125 m/min) in comparison to 250 m/min (120-500 m) and 350 m/min (140-200 m). Similarly, lower crater wear was observed at 125 m/min (750-1280 m) in comparison to cutting speeds of 250 m/min (75-900 m) and 350 m/min (280-420 m). However, as an interesting result due to thermal softening, hardness reduction, and lower strength of Ti6Al4V at high temperatures, better tool life was observed at 350 m/min in comparison to 250 m/min especially under dry conditions.
- The employed cooling and/or lubrication strategies affected tool wear mechanisms directly. However, at 350 m/min the effectiveness of cooling/lubrication agents reduced significantly.
- In general, absence of cooling/lubrication media under dry conditions led to premature failure of the cutting tools. Under CCF, effective cooling and lubrication improved the tool performance and generally uniform flank wear was observed. Similar trend was also obtained with MQL conditions but due to moderate cooling capacity, the obtained tool life was shorter than that obtained under CCF conditions, generally. On the other hand, an important progress in tool life was obtained under LN_2 conditions at 250 m/min due to efficient cooling with LN_2.
- At the lowest cutting speed (125 m/min) better Ra values (0.3-0.69 μm) were obtained under CCF conditions. On the other hand, similar Ra values ranging from 0.43-0.75 μm with cutting length were observed with different cooling/lubrication methods at the highest cutting speed (350 m/min) due to high cutting temperatures.

This study shows that it is possible to enhance cutting performance under cryogenic conditions. LN_2 can be regarded as an ideal solution in terms of cutting performance at especially medium-high speeds (250 m/min) in turning Ti6Al4V alloy.

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