

Tool wear patterns and their promoting mechanisms in hybrid cooling assisted machining of titanium Ti-3Al-2.5V/grade 9 alloy

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ABSTRACT

Hybrid lubri-cooling is a latest technology that provides synergistic cooling and lubrication effect in the machining area especially in the cutting of titanium and its alloys. In this current study, cryogenic-LN₂, minimum quantity lubrication (MQL), and hybrid cryogenic LN₂-MQL are applied and compared against dry medium in perspective of in-depth analysis of tool flank wear, EDS mapping, and intensity of tool wear. Experimental results showed that in comparison with dry, hybrid LN₂-MQL substantially reduced the tool flank and rake wear followed by LN₂, MQL, and dry conditions, respectively. Additionally, the SEM and EDS analysis depicted relatively less severe wear and chemical elements adhesion on the tool's main cutting edge, while turning titanium alloy under a hybrid LN₂-MQL lubri-cooling environment. In addition, the dry condition has maximum value of tool wear progressions i.e., 1.04 mm and hybrid LN₂-MQL have 0.06 mm while machining titanium alloys. When tool wear is evaluated from a tribological point of view, the reduction in flank wear value compared to dry machining is 89.4 %, 92.3 % and 94.2 % owing to MQL, LN₂, MQL and hybrid LN₂-MQL cutting strategies. In terms of crater wear, the improvement was 87.7 %, 90.4 % and 90.8 % thanks to MQL, LN₂, MQL and hybrid LN₂-MQL.

1. Introduction

Titanium and its alloys have brilliant mechanical and physical features which put such compounds into the group of first priority materials in many areas such as aerospace and biomedical sectors thanks to various features such as high strength, high corrosion and oxidation resistance and biocompatibility [1]. The most problematic issue is the typical characteristics of this material class such as insufficient thermal conductivity, poor elastic modulus and a tendency to chemical reactivity which lowers the machinability index [2]. Therefore, these alloys are categorized under the difficult-to-cut material group. The primary reason for this is rapidly increasing frictional force and resultant heat generation around the cutting zone which deteriorates the initial form of the tool geometry [3]. The deformation observed is called wear which emerges at cutting edges and faces [4]. Since the tool wear is a natural

case, complete prevention is not possible while some retarding factors like lubri-cooling are valid as reported many times previously [5].

Using the cutting tools for remaining useful lifetime with high performance is a major goal to maximize productivity and minimize losses. Meeting such expectations heavily depends on discovering the governing wear formation and triggering mechanisms on the cutting tool [6]. As being chemically reactive material, titanium has a high tendency to join the tool as an expected result of high temperatures [7]. This type of wear mechanism turns into build-up edge and/or build-up length at the rake face [8]. It was reported that several mechanisms namely adhesion, abrasion and diffusion were detected as the underlying reason for flank wear development while machining titanium alloy [9]. As being a determinative function of the durability at elevated temperatures, high strength and hardness cause excessive cutting forces which end up in intense plastic deformation [10]. Thus, severe attrition around the

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contact areas leads to flank wear, micro/macro chipping, or failure [11]. Also, the peeling effect was observed and extinguished the coating material as a result of severe cutting conditions [12]. According to some findings, cutting mechanism is characterized by transitive plowing-shearing events while machining titanium alloys [13]. The authors discussed the developing wear structure on cutting tools and decided that conventional cooling was not effective in eliminating crater wear [14]. Odelros et al. [15] determined that crater wear is the primary type of deformation on the cutting tools during the wet turning of titanium which turns into plastic deformation and breakage at the next stages of machining. A group of researchers focused on the levels of cutting parameters and their triggering effect on wear developments [16]. Accordingly, within certain ranges of cutting speed, crater wear was the limiting factor of tool life. Plus, it was stated that diffusion of the main elements such as W, C, and Co to the chip is one of the promoting mechanisms of poor tool life [17]. As seen, all of the known wear mechanisms play an active role in featured wear types like flank, crater, nose, build-up-edge, notch, chipping and breakage. All of these wear patterns are responsible for reduced tool life in some way [18]. Therefore, innovative methods are required to overcome the excessive and quickly-developed wear textures. Hong et al. [19] observed the impact of cryogenic environment on tool life evaluating the nozzle number and position on machining of titanium alloys. According to their findings, the productive way is using two nozzles simultaneously which improves tool life five times compared with a conventional method. Silva et al. [20] evaluated different coolant pressures for upgraded machinability of titanium alloy. They reported that adhesion and abrasion mechanisms were detected as governing which can be eliminated with higher pressures effectively and elongate tool life. Focusing on the importance of these alloys in the space industry, Shokrani et al. [21] proposed a hybrid method for these alloys which combines MQL and cryogenic environments. They indicated that such a hybrid approach gave the best cutting performance and increased tool life 30 times. Yi et al. [22] utilized nanofluid-assisted cutting to enhance the machinability characteristics of titanium. Seemingly, upgraded build-up-edge formation on the upper face of the insert was observed and less wear development on the clearance face was obtained with new technology compared with a conventional method. Jamil et al. [23] determined the performance of sub-zero cooling and near dry-assisted machining of titanium alloys. According to their outcomes, longer tool life was possible with a cryogenic environment which was pursued by MQL and dry approaches. Hu et al. [24] integrated the MQL system into the milling operation for tool wear monitoring of titanium alloy. Such a strategy was found as an efficient road to the prediction of tool wear state at any time during the cutting of titanium. Revuru et al. [25] optimized the cutting parameters for improved machining of titanium using statistical methods under varied cooling and lubricating environments. They indicated the importance of cutting fluid type in the performance enhancement of titanium machining. The other pioneered work on hybrid cooling system is also shown in Table 1.

As can be seen from the literature review and from Table 1, there are many papers published in the literature about eliminating tool wear and elongating tool life of titanium alloys using cooling and lubricating strategies. However, there is no work encountered on the machinability of Grade/9 to this date which represents an important gap in the field considering the place of the material in the sector. Thus, it was intended with this study to contribute to the literature highlighting the tool wear behavior of a commercially important material by a systematic approach under sustainable machining conditions. Therefore, this study deals with the machinability of this alloy for the first time from the perspective of tool wear. Such an approach will create new opportunities for prominent sectors to decrease the cutting tool costs which prefer titanium alloys as the base material. In this direction, singular and hybrid lubri-cooling approaches namely, MQL, cryogenic and cryo-MQL were adopted to the turning operation for measuring their capabilities in reducing/eliminating the tool wear and promoting mechanism when

Table 1

Pioneered work in the area of hybrid cooling/lubrication system.

Authors, year and reference	Workpiece and cutting tool material	Cooling condition details	Investigations
Bagherzadeh et al., 2021, [26]	Ti6Al4V and uncoated carbide inserts	MQL, CO ₂ , LN ₂ , CO ₂ +MQL, LN ₂ +MQL	Cutting forces, tool wear, cutting temperature, surface roughness
Khan et al., 2021[27]	Ti6Al4V and uncoated carbide inserts	Flood and cryo+MQL	Surface quality, Power and energy consumption, Carbon emissions, Cost
Ross et al., 2021 [28]	Nimonic-80A and PVD-TiAlN coated inserts	Flood, MQL, CO ₂ , CO ₂ +MQL	Tool wear, cutting temperature, surface roughness
Chen at al., 2022[29]	Ti6Al4V and uncoated carbide inserts	Dry, MQL, LN ₂ , Hybrid (LN ₂ and MQL)	Cutting forces, chip morphology, surface integrity
Sterle et al., 2020[30]	Inconel 718 and TiAlN coated carbide	Dry, emulsion, LCO ₂ , LCO ₂ +MQL (oil), LCO ₂ +MQL (MoS ₂)	Surface cleanliness, Surface roughness, surface topography, microstructure of machined surface
Grguras et al., 2021[31]	Ti6Al4V and AlCrTiN coating drill	Dry, LCO ₂ +MQL	Cutting forces and chip morphology
Gajrani (2020) [32]	Ti6Al4V and uncoated carbide inserts	Dry, MQL, Hybrid (LN ₂ and MQL)	Cutting forces, surface roughness, microhardness, tool surface morphology, contact length

compared to dry cutting. The research provides insights into the behavior of wear mechanisms and tool life for better turning quality under sustainable machining environments.

2. Materials and methods

2.1. Workpiece, cutting tool and machine tool details

In this paper, the turning operation was conducted on titanium grade (9) alloy i.e., (Ti-3Al-2.5V). The alloy has dimensions of 150 mm length and 35 mm diameter and the first layer of 1 mm was removed to avoid the oxidation effect. This alloy has potential in various modern sectors such as biomedical, aerospace and sports etc. This alloy is also considered under the category of hard to machine material owing to the presence of highly reactive chemical compounds. The chemical composition of workpiece material is tabulated in Table 2.

Further, the cutting tool used to machine the Ti-3Al-2.5V alloy in this work was uncoated carbide and rhombic shape. This tool is mostly utilized for hard to machine materials like titanium and its alloys. The tool has an ISO designation of CNMG 120408 having nose radius of 0.8 mm, respectively. Next, the machine tool used to perform the turning test was CNC turning center having Siemens control system with 6KW motor.

2.2. Cooling condition details

The present work focused on the influence of lubricating and refrigerating conditions on the tool wear progressions while machining Ti-3Al-2.5V alloy. The four types of cooling mediums were used and the details are given below and also the mechanism of these cooling conditions are shown in Fig. 1:

Table 2

wt% of chemical elements present in Ti-3Al-2.5V alloy [33].

Al	V	Fe	O	C	N	H	Ti
3.2	2.5	0.25	0.12	0.05	0.02	0.012	Balance

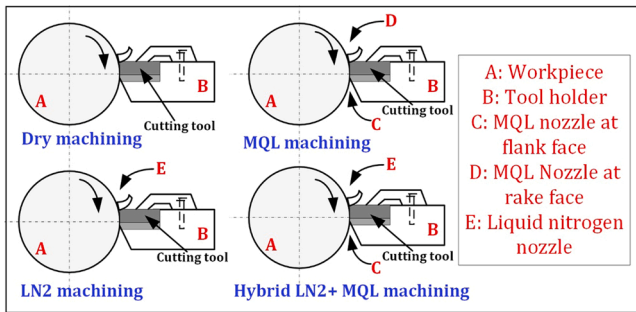


Fig. 1. Cooling conditions and its mechanism used in this work.

Dry machining: The machining carried out without using any fluid is called dry machining. In general, it's the most sustainable machining method because no cutting fluid is used during machining. However, the dry machining is not preferred for difficult to machine material like titanium and its alloys due to the presence of high cutting temperature at tool-chip interface.

MQL machining: This is also called the minimum quantity lubrication and in this cooling condition, the minute amount of particles mixed with compressed air has been used at cutting zone. The coolant is helpful in providing the lubrication effect whereas the compressed air is used to lower down the cutting temperature. In this work, dual nozzle MQL system with 45 mm distance from the cutting zone was used and the position of nozzles were on rake and flank surface. The compressed air pressure was kept fixed of 6 bar along with the cutting fluid flow rate of 0.0008 l/min.

Liquid nitrogen (LN₂): This is also called the cryogenic cooling in which the liquid nitrogen has been used at cutting zone. This low

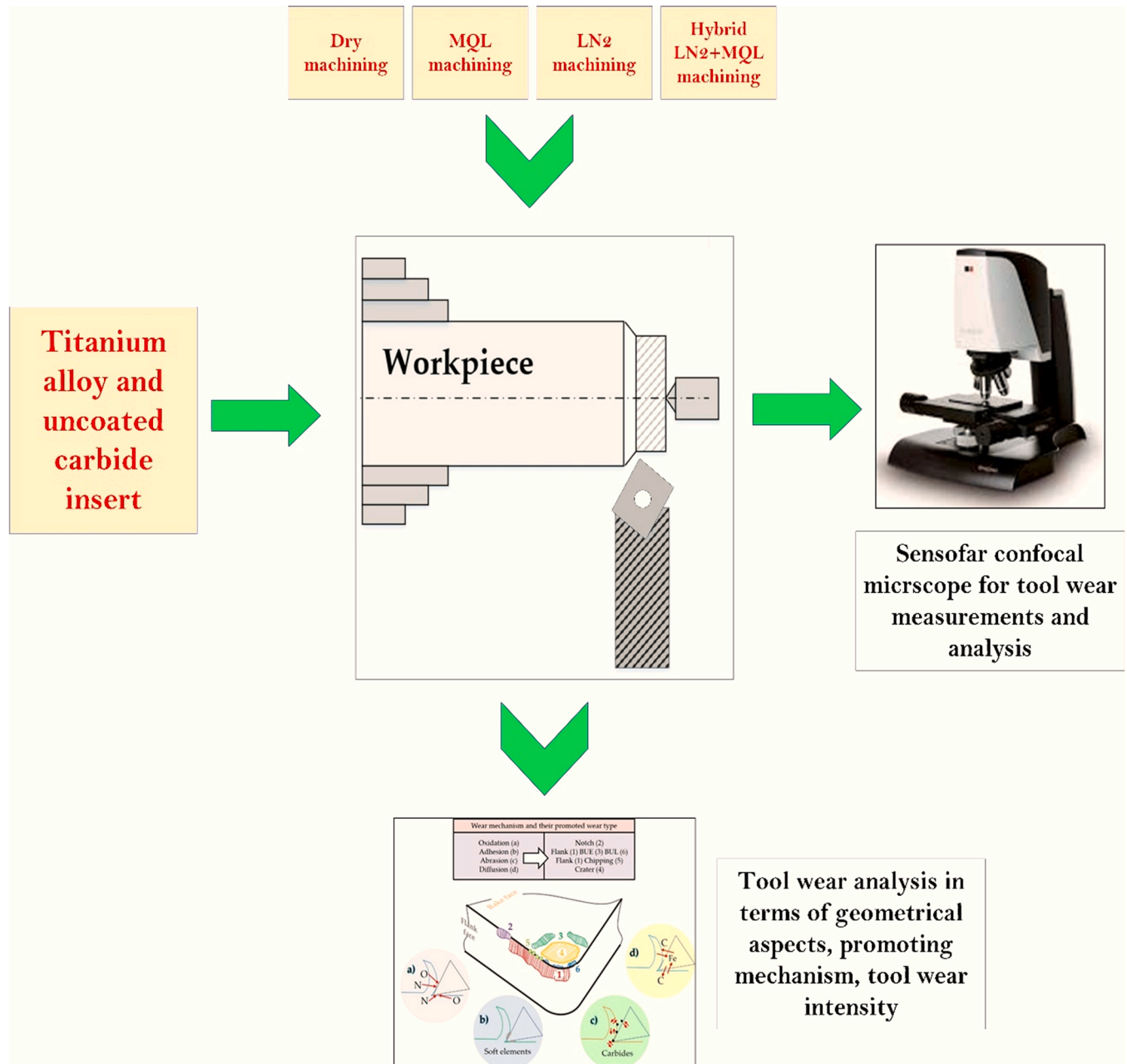


Fig. 2. Experimental study adopted in this work.

temperature gas reduces the cutting temperature upto great extent without affecting the environment. The single nozzle is used with flow rate of 0.35 l/min and 4 bar pressure.

Hybrid LN₂+MQL: This is the latest technology in the context of sustainable machining. The effect of oiling and cooling is greatly noticed with hybrid cooling system. In this method, one nozzle of MQL and one nozzle of liquid nitrogen is positioned at cutting zone and with this combined effect, the good results by means of low cutting temperature and friction has been noticed at cutting zone.

2.3. Measurement of tool wear

The current work concerns the tool wear measurement details after machining Ti-3Al-2.5V alloy under sustainable cooling conditions. The machining parameters used to calculate the tool wear were 150 m/min cutting speed, 0.20 mm/rev feed and 0.5 mm depth of cut, respectively. These machining parameters are selected based on the tool manufacturer recommendation and trial experiments. The ISO standard of ISO 3685 standard (1993) and flank wear ($VB_{max} \geq 0.3$ mm) criteria was followed to measure the tool wear values. Further, the Sensofar Confocal Microscope having Senso View software and Mountains map software was used to analyze the tool wear results. In the end, the scanning electron microscope (SEM) with EDX mapping was utilized to research the promoting mechanism of tool wear. The complete experimental setup and measurement procedure is demonstrated in Fig. 2.

3. Results and discussions

3.1. Geometrical features of tool wear

During chip removal, cutting tools are exposed to a very high level of friction. Severe stress and temperature gradients on the tool surface further complicate the problem [34]. Tool wear is a progressive failure phenomenon with the main wear type, which develops depending on the machining parameters, workpiece and tool material, cutting environment, and tool tip geometry and coating [35]. The most prevalent and critical types of wear in turning process for a single-point cutting insert are nose, flank, notch, and crater wear [36]. However, it is possible to state that especially flank wear, crater wear and corner (nose) wear are the most decisive actors of tool life [37]. As shown in Fig. 3, one or more of the wear mechanisms are responsible for the formation of each wear type.

The damages on the clearance and chip surfaces of the fresh cutting tools that cut the Grade/9 titanium alloy are shown in Fig. 4. The friction

between the fresh surface and the tool's clearance surface induces wear on the flank face with the effect of the adhesive and/or abrasive wear mechanisms that increase in parallel with the increase in temperature during machining [39]. In the machining of titanium alloys, it was emphasized in many previous researches that flank wear is the predominant wear type [40,41]. Also, in practice, it is important in determining tool life (T) that the most practical magnitude is flank wear (VB) or maximum flank wear (VB_{max}). A standard measure of tool life for carbide tools according to ISO 3685 [42] is the time corresponding to $VB = 0.3$ or $VB_{max} = 0.6$ mm. However, in machining superalloys such as titanium alloys, observing VB alone is not sufficient for predicting tool life.

As seen in Fig. 4, another dominant wear type in machining Grade/9 titanium alloys is crater wear. Crater wear, which develops on the rake face owing to combination of diffusion and adhesion as the chip passes over the rake surface, is commonly connected with the elevated temperatures produced at the chip-tool interface while cutting titanium alloys [43]. A wear value close to VB (refer to Fig. 5) or even higher can be observed on the rake surface. Crater wear causes weakening of the tool edge and subsequent breakage of the cutting tool, while VB causes higher cutting forces and poor tolerances [44]. In addition, Abbas et al. [45] reported that crater wear (KB) is more sensitive to cutting length than flank wear and that typical tool wear when machining Ti6Al4V alloy is crater wear.

Fig. 5 illustrates the size changes (wear amount in terms of VB and KB) of the tools on both the flank and rake faces. Accordingly, as seen in Fig. 5(a) excessive flank wear observed in dry turning indicates the end of the tool's life according to the ISO standard mentioned above. Excessive heat is created because to high tool-chip-workpiece friction in a dry cutting environment where adequate heat evacuation is not possible, resulting in an increase in tool temperature. The tool material softens as the tool temperature rises, resulting in severe workpiece adhesion and increased wear. There was a tremendous reduction in flank wear with the penetration of cooling/lubricating means into the cutting medium. Even thanks to these lubrication/cooling tools, the flank wear value of the cutting tool remained within the favorable tool life limits i.e., $VB < 0.3$ mm. The atomized cutting oil and compressed air delivered with the MQL penetrate the cutting zone interfaces as an aerosol promoting both the boundary lubrication and cooling action. In this way, friction, temperature and contact length can be reduced [46]. On the other hand, LN₂ reduces the temperature tremendously, reducing adhesion and contact length. Also, the minimum wear achieved in hybrid cooling is attributed to the longer time the oil droplets stay in the environment without evaporation, with the effect of cryogenic cooling [47]. A similar trend to flank wear results was also observed in crater wear as provided in Fig. 5(b). High-temperature formation in the secondary cutting zone (chip surface) can induce fast crater wear by diffusion when machining titanium alloys at medium/elevated cutting speeds using carbide cutting inserts [48]. The advanced and hybrid refrigerating and oiling methods utilized in this study have gradually contributed to the limiting of this type of wear. In hybrid cooling/lubrication experiments, cryogenic cooling of the cutting tool and a stable lubrication service to the contact surfaces are considered to significantly reduce crater dissolution-diffusion wear. When tool wear is evaluated from a tribological point of view, the reduction in flank wear value compared to dry machining is 89.4 %, 92.3 % and 94.2 % owing to MQL, LN₂, MQL and hybrid LN₂-MQL cutting strategies. In terms of crater wear, the improvement was 87.7 %, 90.4 % and 90.8 % thanks to MQL, LN₂, MQL and hybrid LN₂-MQL.

3.2. Tool wear analysis under dry conditions

It was emphasized in previous studies [49,50] that the elevated cutting temperature concentrated near the cutting edge, as well as the higher chemical activity of titanium with the tool material, are the primary leads to tool wear when machining titanium alloys. For

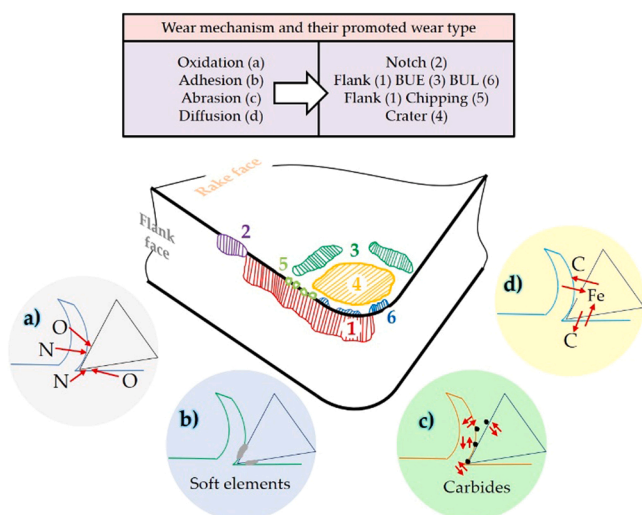


Fig. 3. Wear mechanism and their promoted wear type modified by [38].

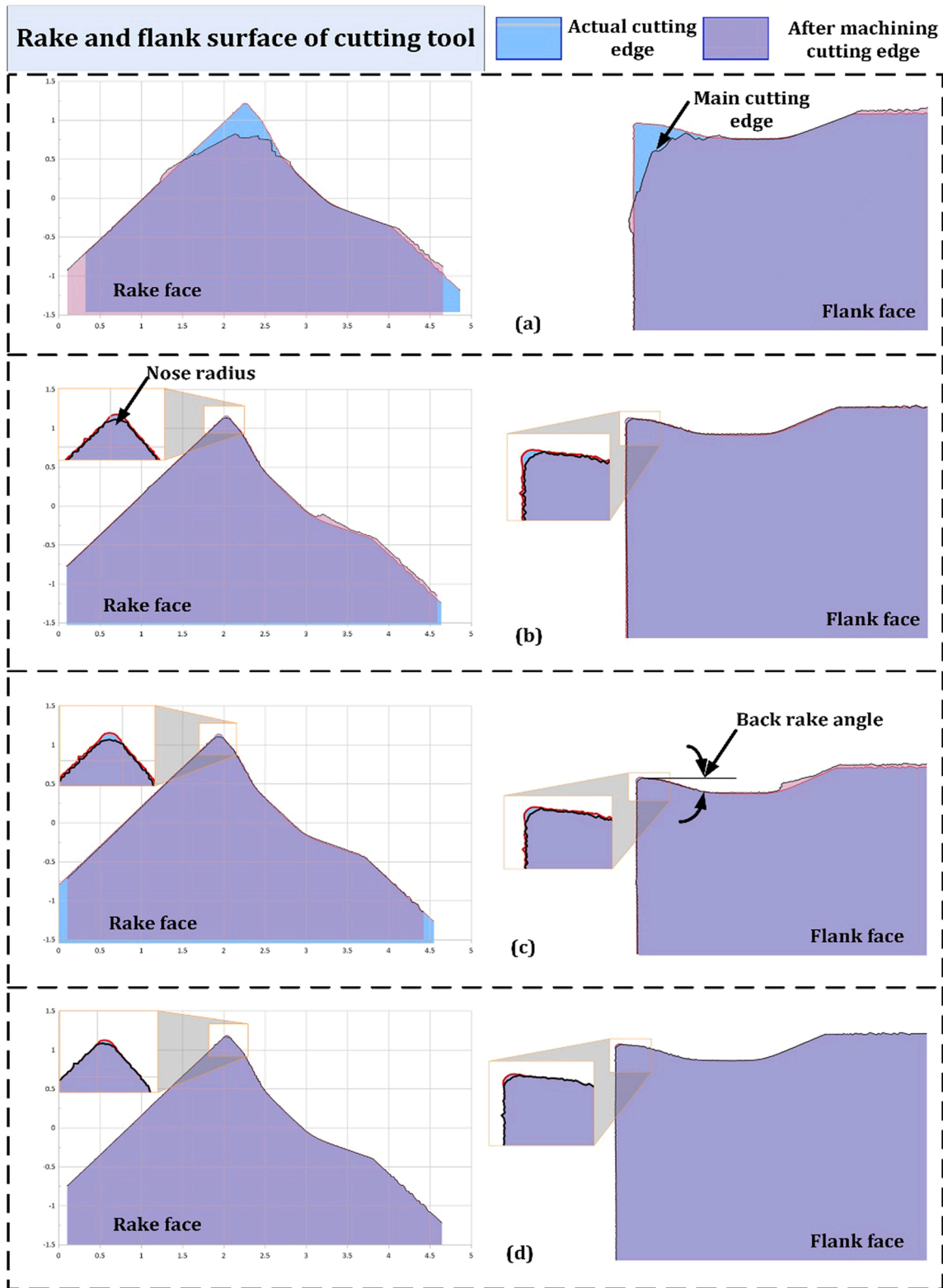


Fig. 4. Tool profile views from rake and flank face under sustainable cooling strategies (a) Dry (b) MQL (c) LN_2 (d) Hybrid LN_2 and MQL.

machining superalloys, WC/Co carbide tools have shown to be one of the most cost-effective tool materials [51]. It can be said that a cutting process in which uncoated tools are employed without cutting fluid is a desirable process in terms of health and environmental aspects [52]. However, when cutting titanium alloys using WC/Co tools, the degradation of the cutting insert geometry due to possible wear mechanisms is

a serious problem. This event can lead to more destructive results, especially in dry machining environment. From Fig. 6, the final condition of the cutting insert in the turning of the titanium grade 9 alloy using an uncoated carbide tool under dry cutting is given with SEM and EDX analysis images. Accordingly, the BUE form detected on the tool from the SEM analysis has emerged as a result of the adhesion wear

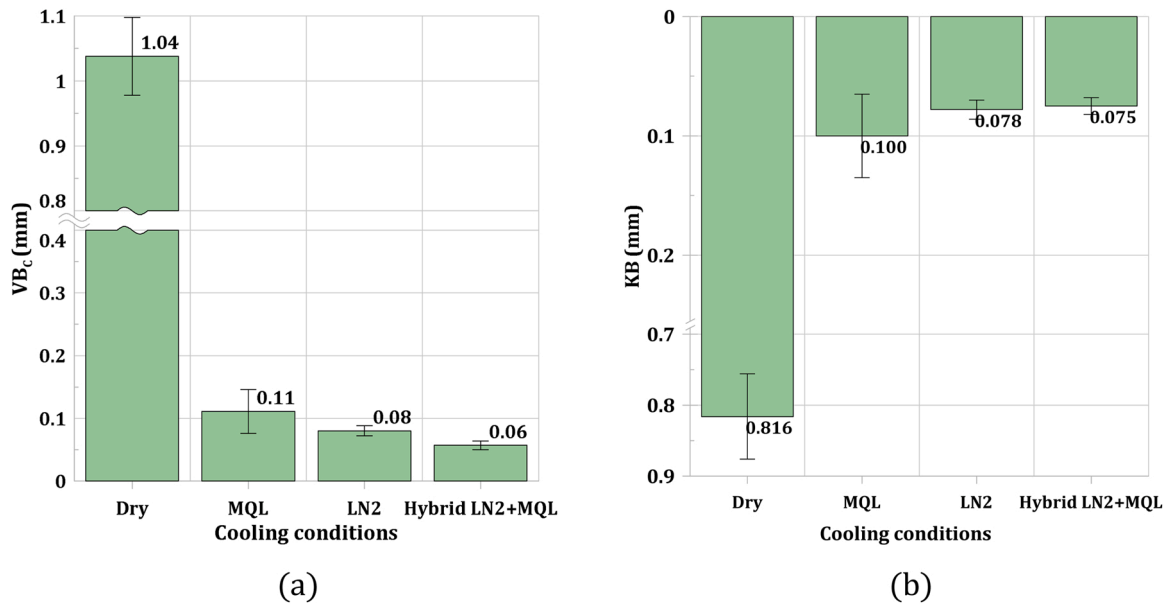


Fig. 5. Geometrical wear aspects of cutting tools.

mechanism. When machining titanium alloys, temperatures in the cutting region over 400 °C change the contact at the tool-chip interface from sliding to sticky [49,53]. As seen in Fig. 6, the rough wear surface allowed for easy cold welding of the peak contact region at the tool-chip interface, resulting in chip buildup on the worn surface. When the binding strength between the tool and chip contact is less than the shear stress, the adhered material in the form of unstable peels off, causing tool wear. When the adhesive force is high enough, however, the sticky substance on the cutting edge continues to grow, forming BUE [54]. When the EDS analysis is examined, the existence of Ti, Al and V elements can be seen on the uncoated carbide tool. Since these elements are not in the tool material composition, it is obvious that they come from the workpiece material. There may be more than one reason for this situation. So, the chemical approximation between the tool and the workpiece is one of them. Also, because it is a thermally triggered process, the low thermal conductivity of the workpiece material causes a extreme temperatures around the machining area, which subsequently activates the diffusion mechanism. The diffusion coefficient is a key metric in determining the diffusion process, especially in machining titanium alloys, the diffusion coefficient is critical at temperatures above 600 degrees [53]. In summary, when machining titanium alloys with WC/Co carbide tools, several types of tool failure i.e., abrasive, adhesive, and diffusion wear can be observed. In this study, the major mechanisms among the identified tool wear mechanisms were determined to be diffusion and adhesive wear. Chemical proximity and temperature are the main actors of the diffusion wear mechanism. Diffusion of titanium elements such as Ti, Al, and V to a WC/Co carbide tool creates a change in the tool substrate's composition, which can speed up tool wear [49].

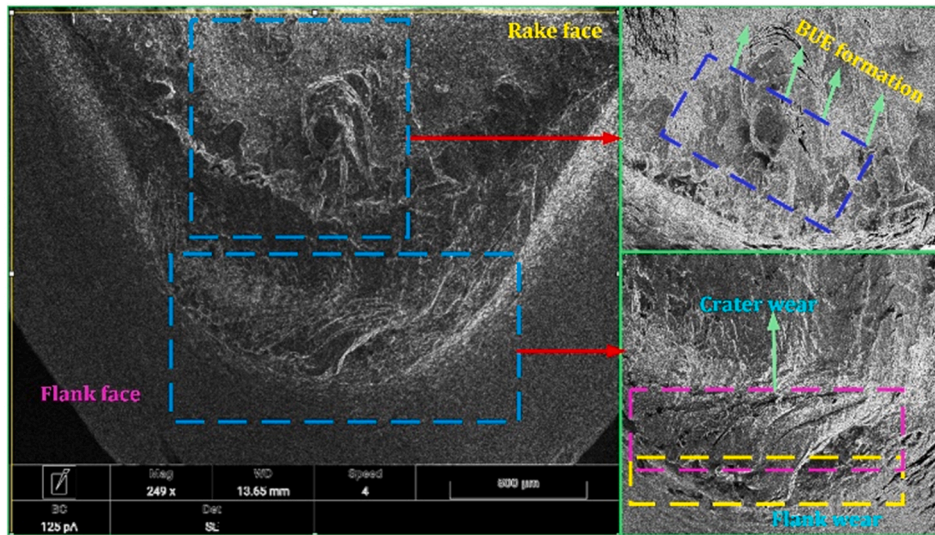
3.3. Tool wear analysis under MQL conditions

During machining of titanium alloys, premature tool failure is never desired as good and it reduces the cutting tool's planned lifespan. To avoid this situation, it is believed that uncoated carbide inserts are the favorable tools for cutting titanium alloys because, in addition to their low economic cost, it has good thermal conductivity, high toughness and the ability to keep hardness at elevated temperatures [55]. In cutting these materials, the application of cutting fluid is considered essential because of the inclination of the work material to adhere to the insert, high friction in the tool-work interface area, and less heat discharge with

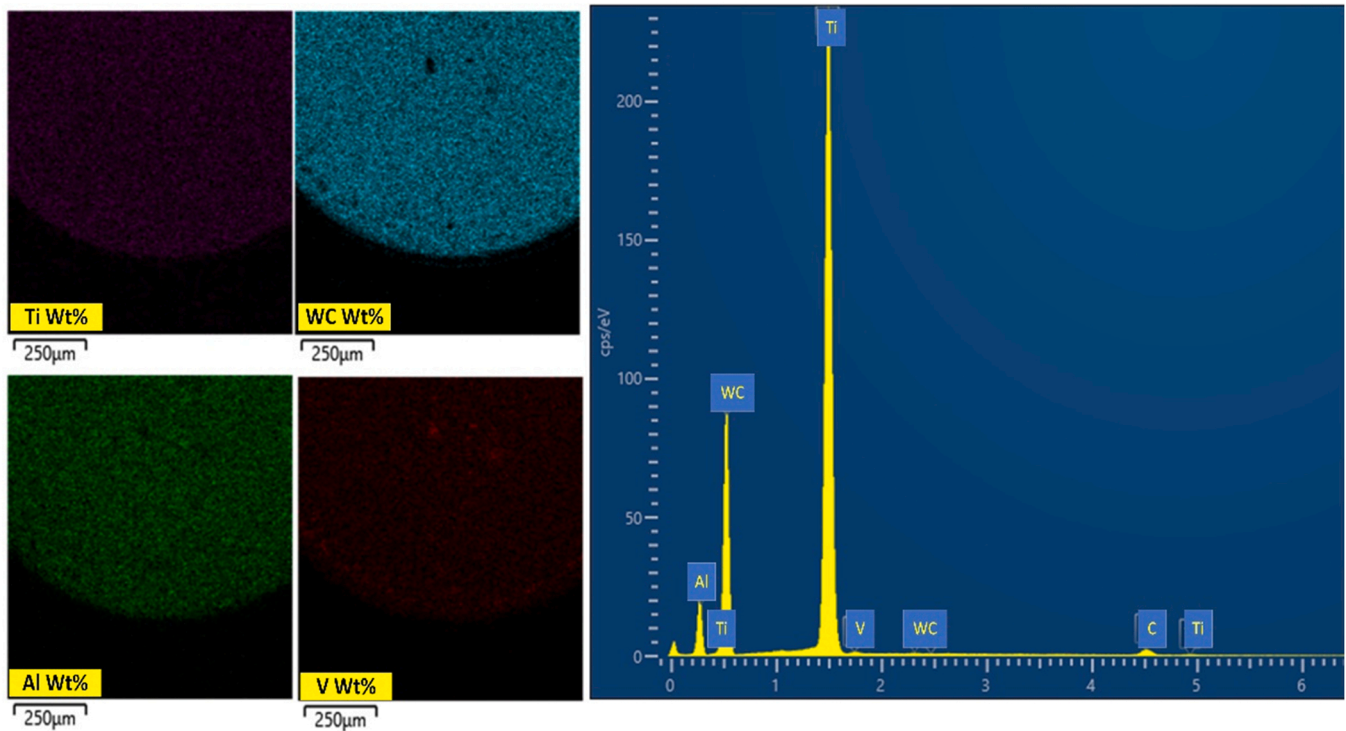
the chip owing to the alloy's low thermal conductivity, and the necessity of removing the chip from the cutting area. As explained in Section 3.1, when the sizes of both crater wear and flank wear that occurred during the machining of the alloy in different environments were compared, it was seen that dry cutting was not suitable. The MQL used in this study is an environmentally friendly cutting approach that consumes the optimum amount of cutting fluid blended with compressed air sent into the cutting zone [56]. In this application, a very small amount of lubrication, together with compressed air, is transferred to the machining region by capillary action, either drop by drop or mist [57]. In this way, both heat transfer is increased and friction is reduced. While there is consensus in the literature that MQL is an environmentally viable option, there are different opinions about its machining performance. For example, in some studies, while MQL has been reported to give very good results [58], it has been reported that it is insufficient especially in heavy machining conditions or in the machining of superalloys [59]. In present investigation, the microscopic evaluation of worn uncoated carbide tools under MQL cooling/lubrication condition while turning titanium grade 9 alloy is shown in Fig. 7. When looking comparatively to the dry environment, it is visible that fewer damaged areas on the tool. The SEM image shows portions of the chip and flank of the cutting tool revealing crater wear, flank wear, and chipping wear. Crater and flank wear is thought to be a complex phenomenon that occurs as a combination of abrasive, adhesion and diffusion wear. Although the effectiveness of adhesion and diffusion wear under MQL is not observed as clearly as that of dry cutting, the workpiece material determined from the EDS analysis still proves that these mechanisms exist. In addition, micro-chipping or micro-cracks are seen in Fig. 7. Chipping is a failure mode commonly observed in titanium machining [60]. Such a phenomenon may be due to the high stress occurring at the tool cutting edge and the rigidity of the machining process. Another possible reason is the BUE form and its unstable behavior caused by the adhesion wear mechanism. Unstable BUE periodically causes small pieces of tool material to be removed, resulting in chipping of the tool cutting edge [61].

3.4. Tool wear analysis under cryogenic cooling conditions

In recent years, one of the most effective social factors influencing the choice of machining medium has been employees' health and environmental concerns. As a result, academics have concentrated on alternate machining processes in order to make the process safer,



(a)

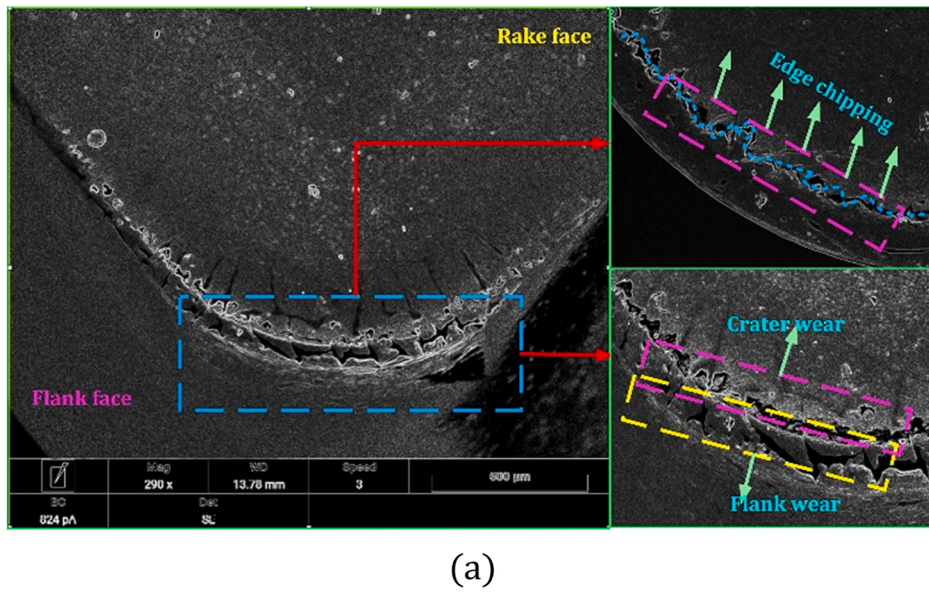


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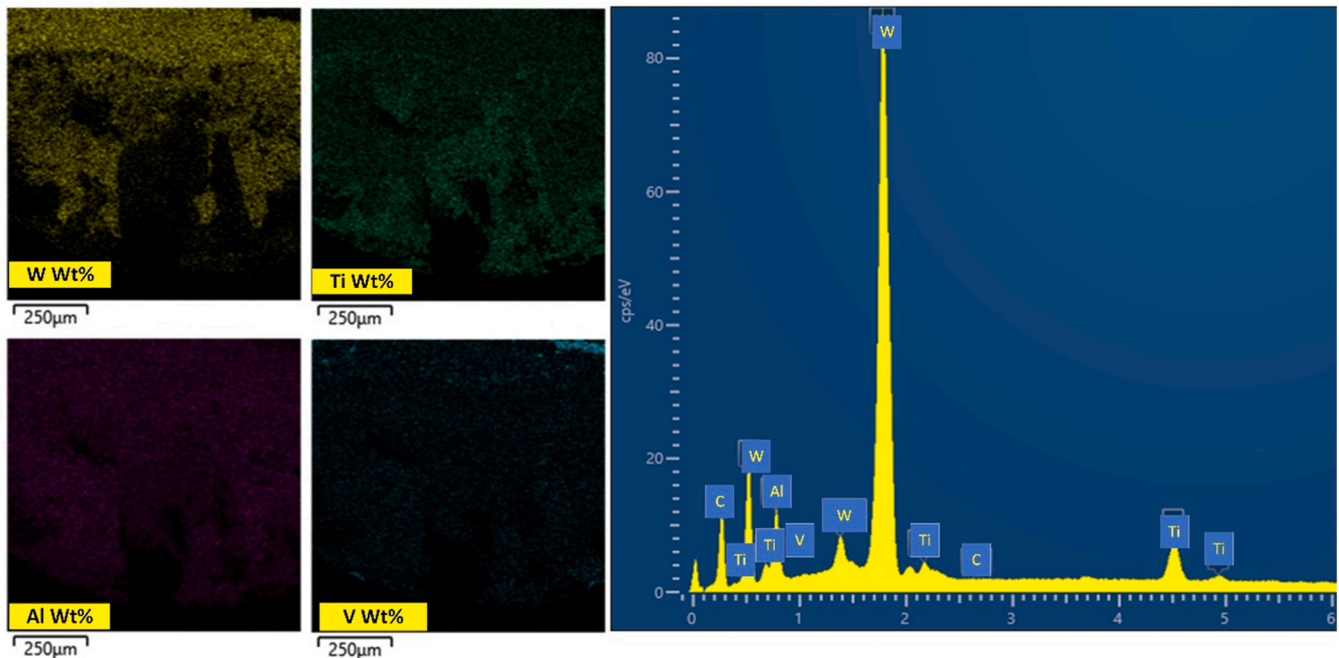
Fig. 6. In-depth analysis of cutting tools under dry conditions (a) SEM of cutting tools (b) Mapping and EDX of cutting tool.

healthier, and more environmentally friendly [62]. Cryogenic machining is the outcome of such an attempt as a long-term solution for cutting heat-resistant metals in the modern machining industry. [63]. Liquid nitrogen (LN_2) is commonly utilized as a coolant/lubricant in cryogenic cutting processes because it evaporates quickly into the atmosphere from the cutting zone [64]. Surfactants, defoamers, biocides, and chelating agents are not present in evaporating nitrogen vapors. Such method also prevents the possibility of process mist forming. Furthermore, LN_2 naturally evaporates in the environment, lowering disposal expenses. The effect of the preferred LN_2 cryogenic cooling method on cutting tool wear in the machining of titanium grade 9 alloy was analyzed in Fig. 8 with the help of SEM and EDS images.

Accordingly, the wear caused by abrasive and adhesion wear mechanisms also appeared under cryogenic cooling. Abrasive traces, workpiece material layer that appears to be plastered on the tool, and workpiece elements i.e., Ti, Al, and V detected from EDS analysis are the basis of this claim. Sartori et al. [65] have also reported that regardless of the cutting strategies employed in machining the titanium alloy, adhesion and abrasive are the most important wear mechanisms that occur at different magnitudes depending on the cutting conditions. It can be seen that the size of the damaged area of the tool is less compared to dry cutting. Bordin et al. [66] revealed a considerable decrease in material adhesion through cryogenic environment when cutting the titanium alloy Ti6Al4V. Compared to MQL, chipping was not observed



(a)



(b)

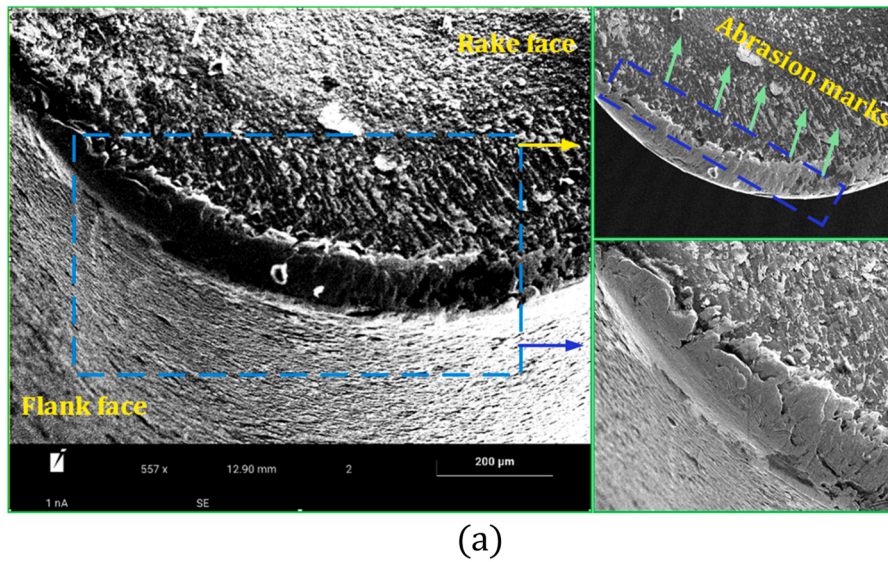
Fig. 7. In-depth analysis of cutting tools under MQL conditions (a) SEM of cutting tools (b) Mapping and EDX of cutting tool.

under LN_2 . The most essential aspect in reducing tool failure modes while cutting hard-to-machine materials is that cryogenic cooling allows for a significant drop in cutting temperature when compared to dry mode [67]. Also, Bermingham et al. [68] reported a reduction in both friction force and tool-chip contact length when turning under a cryogenic environment. Similarly, Hong et al. [67] stated that when a cryogenic liquid is delivered to the cutting zone, the hardness of the workpiece increases with cryogenic cooling, resulting in a decrease in the friction force and thus the coefficient of friction. It is well known that the temperature in the machining region can be significantly decreased by using LN_2 during the cryogenic cooling process. [69]. This is supposed to inhibit the establishment of a high-temperature environment that activates the affinity between the tool and the workpiece, causing adhesion and abrasive wear on the tool's chip surface rather than diffusion wear. Cryogenic fluids improve the chemical stability of the

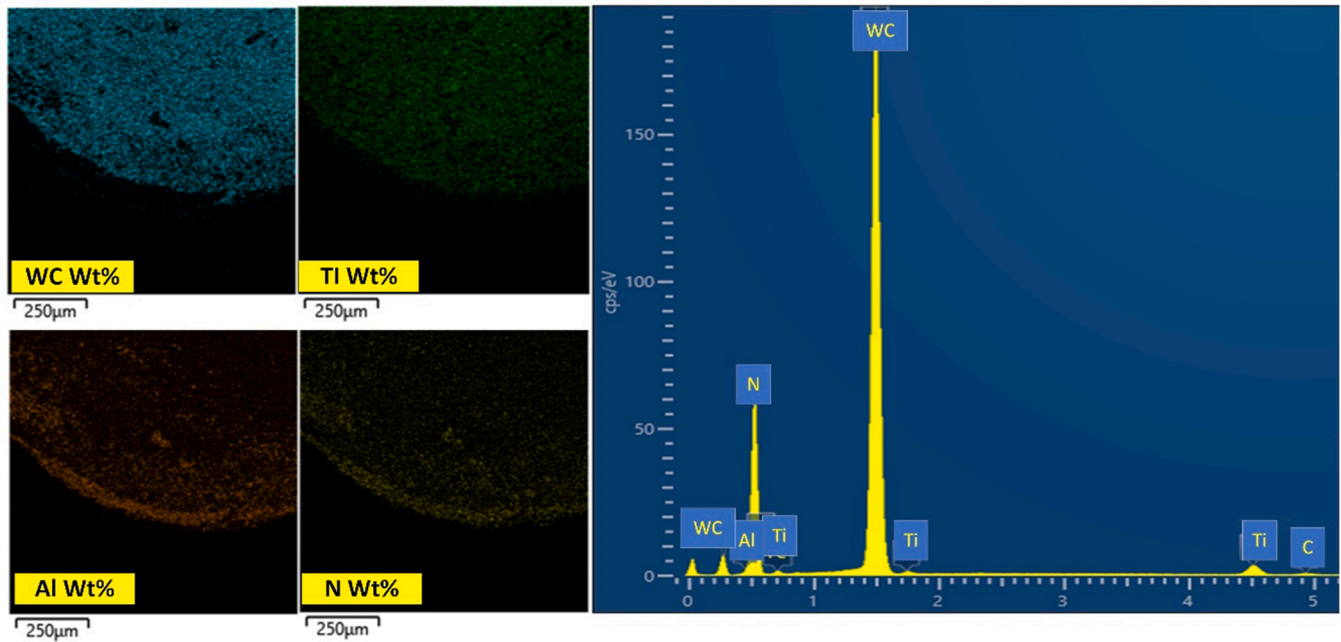
workpiece and the cutting tool, allowing for more tool usage time [70]. The combination of these factors reduces the possible effects of diffusion and adhesive wear mechanisms and thus less tool damage occurs while machining Ti alloy.

3.5. Tool wear analysis under hybrid cooling conditions

Cryogenic cooling and micro-lubrication applications are combined in hybrid cooling (HC). The procedure not only decreases cutting area temperature and preserves the oil film's efficient lubricating capacity, but it also demonstrates its unique benefits in enhancing product quality and cutting tool life [71]. In addition, because HC is pollution-free and ecologically benign, it adheres to the principle of sustainable machining. Considering these positive effects of HC, the Grade/9 titanium alloy was turned under HC and finally, the damages on the tool were examined



(a)



(b)

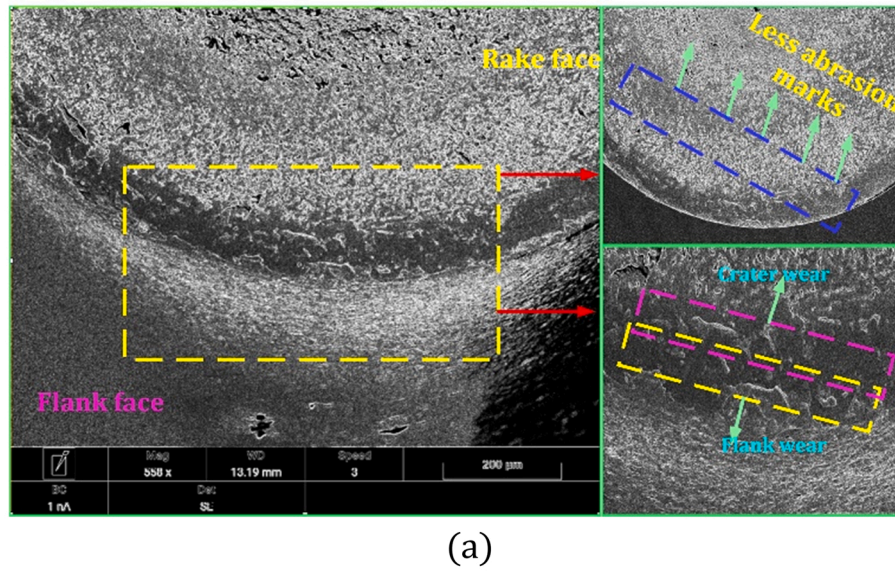
Fig. 8. In-depth analysis of cutting tools under LN₂ cooling conditions (a) SEM of cutting tools (b) Mapping and EDX of cutting tool.

with SEM and EDS images as illustrates in Fig. 9. Compared to the tools worn under other environments used in this study, a less damaged tool was obtained with HC-assisted turning at the end of the cutting time. It was also considered important that the HC method showed the effect of the tool on both the flank and rake surfaces. This can be explained by the cooperation between cryogenic liquid and MQL, which eliminates the shortcomings of each other at the time of cutting. That is, in the MQL method, the oil film formed between the tool and chip thanks to micro-lubrication has a key role in reducing friction. However, excessive increase in temperatures during cutting reduces the effectiveness of MQL. The low viscosity of the oil at high temperatures or the complete evaporation of the oil drops from the environment causes dry friction of the contact surfaces. Through HC, the decrease in the viscosity of the lubricating oil or its evaporation from the cutting zone is prevented by cryogenic cooling, and thus, the contact of the rubbing surfaces is relatively prevented by maintaining the oil film thickness. Moreover, the cryogenic fluid maintains the elevated absorption of the lubricating

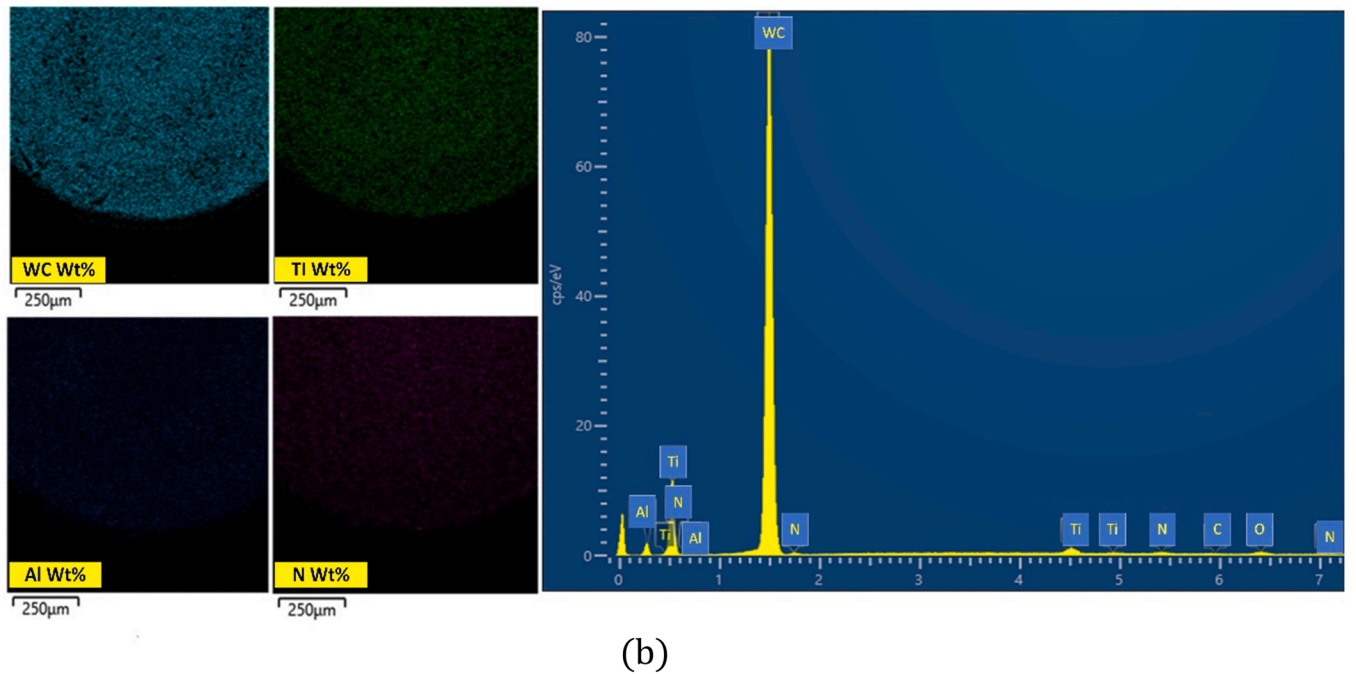
layer while also reducing the negative effects of oil film oxidation produced by excessive heat in the cutting area [71]. By preventing the temperature from overheating, the long-term effect of the lubricating film can effectively reduce the friction between the tool and the workpiece and limit the thermal effect of the temperature. In addition, the solid-to-liquid phase transition of the lubricating oil in the cutting zone also allows some heat to be absorbed in the cutting zone. This is the result of the HC's direct and/or indirect cooling/lubrication ability as shown representatively in Fig. 10. However, as can be seen from the EDS analysis in Fig. 9, the presence of workpiece elements on the tool is proof that the adhesion cannot be completely eliminated.

3.6. Overall comparison of tool wear values and key points discovered

The most common wear modes discovered during tool wear evaluation are adhesion, diffusion, and wear, each of which is impacted differently by the cutting environment. The mechanical and thermal



(a)



(b)

Fig. 9. In-depth analysis of cutting tools under hybrid CryoMQL cooling conditions (a) SEM of cutting tools (b) Mapping and EDX of cutting tool.

properties of the Ti alloy are responsible for each of the wear phenomena, either separately or in a combination of both. Hardness is the main cause of abrasive wear, while thermal conductivity is responsible for diffusion and adhesive wear mechanisms. The alloy's limited thermal conductivity allows more heat to travel to the tool, resulting in a high temperature on the tool. Thus, a suitable environment for adhesion and diffusion mechanisms is created between the workpiece material and the tool material [65]. However, as can be seen from the topography analysis for overall comparison in Fig. 11, the effect of cooling/lubrication strategies is clearly seen when the damage caused by these wear mechanisms to the tool is compared. When this comparison is concretely expressed on the basis of the tool rejection criterion ($VB \geq 0.3$ mm) of the ISO 3685 standard, the tool life is complete at the end of the cut length of 600, 750, 900 and 1050 mm in dry cutting, MQL, LN_2 and hybrid cooling, respectively, as depicted in Fig. 12 (a). The wear zones observed are clearly defined in Fig. 12(b). Both Fig. 12 (a) and (b) followed the same trend and the tool failure occurred quickly in the case of dry

machining. There is no stable zone in dry machining and the stability of tool is increased with the change in cooling conditions and the maximum life of tool is noticed under hybrid cooling conditions. The reason is already included in the previous sections.

In addition, the intensity of tool with respect to cutting length i.e., $(\Delta VB_{max}/\Delta L)$ is calculated in this work. The following Eqs. (1) to (4) are used to calculate the intensity of cutting tool:

$$(\Delta VB_{max}/\Delta L)_{Dry} = (0.6692345 * L^{(0.6692345-1)}) * 0.0042741 \quad (1)$$

$$(\Delta VB_{max}/\Delta L)_{MQL} = (0.6696601 * L^{(0.6696601-1)}) * 0.0036496 \quad (2)$$

$$(\Delta VB_{max}/\Delta L)_{LN_2} = (0.7222797 * L^{(0.7222797-1)}) * 0.0020343 \quad (3)$$

$$(\Delta VB_{max}/\Delta L)_{Hybrid} = (0.8403471 * L^{(0.8403471-1)}) * 0.0008004 \quad (4)$$

Where: L - Machining length and VB_{max} is tool flank wear, ΔVB_{max} - Increment in wear rate VB_{max} ; ΔL - Increment of Machining length.

Fig. 12(c) shows that how quickly wear changes as a function of the

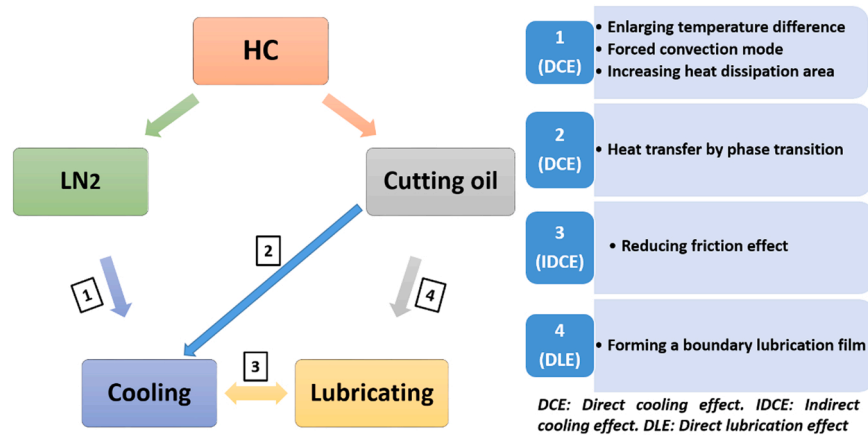


Fig. 10. Interaction between cooling/lubrication in the HC method and its possible effects. Reproduced from Ref. [72].

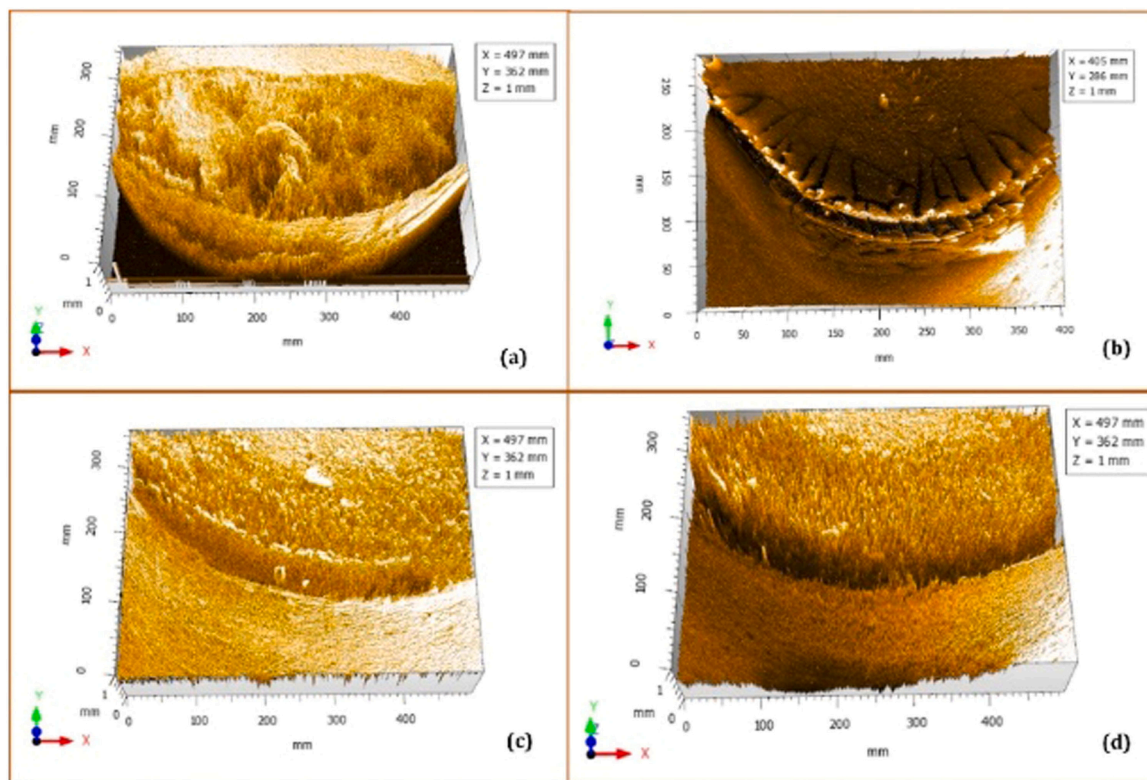


Fig. 11. Overall comparison of tools under various sustainable environment (a) Dry (b) MQL (c) LN₂ (d) Hybrid LN₂ and MQL.

machine length. It has been determined that the tool used under dry cutting is exposed to more intense wear at the beginning of the cutting process than in other cutting environments and according to Fig. 12(c), hybrid cooling follows the standard trend with good tool life values. This also demonstrates the importance of using cooling and lubrication at the first contact of the tool with the workpiece.

4. Conclusions

This experimental study put forward a comparison of tool wear mechanism under dry, cryogenic-LN₂, MQL, and hybrid LN₂-MQL cooling conditions in the turning of titanium alloy. The SEM and EDS analysis is carried out to analyze the tool wear under different cooling/lubrication environments. The following conclusions are drawn based on experiments:

- Comparison of tool flank wear under different cooling environments underscored minimum tool wear $VB = 0.06$ mm under hybrid LN₂-MQL, while maximum tool wear $VB = 1.04$ mm under dry conditions. Similarly, the minimum rake wear $KB = 0.075$ mm was measured under hybrid LN₂-MQL and a maximum of $KB = 0.816$ mm under dry conditions. In other words, the reduction in flank wear value compared to dry machining is 89.4 %, 92.3 % and 94.2 % owing to MQL, LN₂, MQL and hybrid LN₂-MQL cutting strategies. In terms of crater wear, the improvement was 87.7 %, 90.4 % and 90.8 % thanks to MQL, LN₂, MQL and hybrid LN₂-MQL.
- SEM of tool flank face showed predominant wear mechanisms were adhesion, diffusion, and wear, each of which is affected differently under cooling environments. Progressive wear was observed under hybrid LN₂-MQL, while accelerated tool wears under dry conditions.

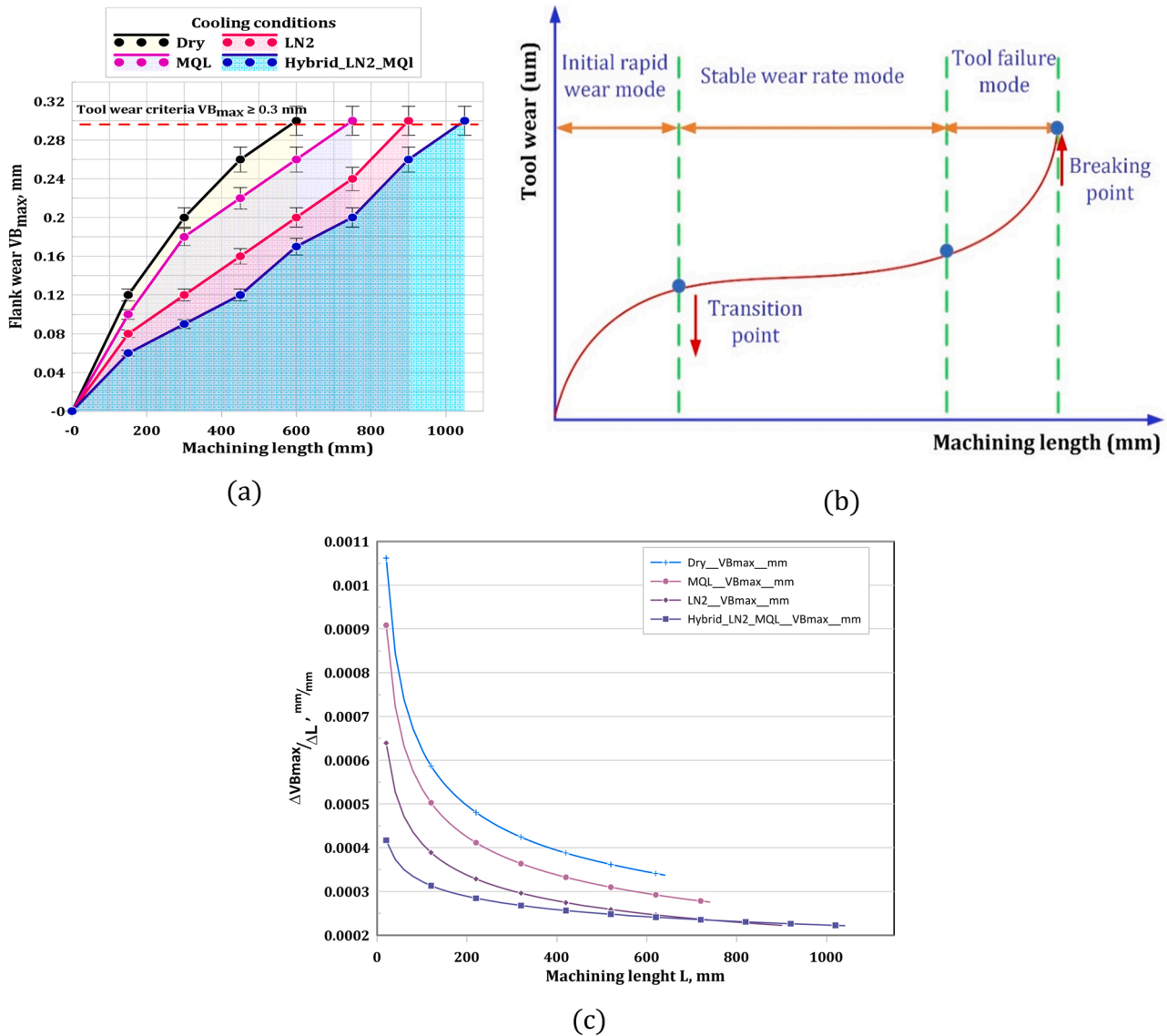


Fig. 12. (a) Flank wear vs machining length under different cutting strategies (b) General tool wear stages observed in machining and (c) Intensity of tool wear values with respect to machining length under different cooling conditions.

- EDS analysis showed that adhesion of chemical elements such as aluminum (Al), nitrogen (N), titanium (Ti), and tungsten carbide (WC) are dominant on worn flank edge under all environments, however deposition concentration under hybrid LN₂-MQL was far less than dry conditions.
- A comparison of tool life under cryogenic LN₂, MQL, and hybrid LN₂-MQL in terms of cutting length showed maximum tool life (1000 mm) under hybrid LN₂-MQL and minimum tool life (600 mm) under dry conditions. The results claim prove that the good lubrication as well as cooling effects promotes the tool life during machining of titanium alloys.
- As a future scope, the more detailed studies on other cooling conditions with different materials could be performed.

Statement of Originality

As the corresponding author, I, Munish Kumar Gupta, hereby confirm on behalf of all authors that:

(1) The paper has not been published previously, that it is not under consideration for publication elsewhere, and that if accepted it will not be published elsewhere in the same form, in English or in any other

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Declaration of Competing Interest

There is no conflict of interest to declare.

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