



Science Arts & Métiers (SAM)

is an open access repository that collects the work of Arts et Métiers Institute of Technology researchers and makes it freely available over the web where possible.

This is an author-deposited version published in: <https://sam.ensam.eu>
Handle ID: <http://hdl.handle.net/10985/25702>



This document is available under CC BY-NC license

To cite this version :

Hongguang LIU, Yessine AYED, H el ene BIREMBAUX, FREDERIC ROSSI, Gerard POULACHON
- Impacts of flank wear and cooling strategies on evolutions of built-up edges, diffusion wear and cutting forces in Ti6Al4V machining - Tribology International - Vol. 171, p.107537 - 2022

Any correspondence concerning this service should be sent to the repository

Administrator : scienceouverte@ensam.eu



Impacts of flank wear and cooling strategies on evolutions of built-up edges, diffusion wear and cutting forces in Ti6Al4V machining

Hongguang Liu^{a,*}, Yessine Ayed^b, H el ene Birembaux^a, Fr ed eric Rossi^a, G erard Poulachon^a

^a Arts et M etiers Institute of Technology, LaBoMaP, Universit e Bourgogne Franche-Comt e, HESAM Universit e, Rue Porte de Paris, Cluny 71250, France

^b Arts et M etiers Institute of Technology, LAMPA, HESAM Universit e, 2 Boulevard du Ronceray, Angers 49035, France

Keywords:

Tool wear

Cryogenic machining

Cooling strategies

Ti6Al4V

A B S T R A C T

Titanium alloys are widely used in aerospace industries due to their excellent physical and mechanical performances, however, their poor machinability always induce fast tool wear. To better understand the interaction between progressive tool wear and cooling strategies in machining of titanium alloy Ti6Al4V, an in-depth analysis towards evolutions of built-up edges (BUEs), diffusion wear and cutting forces was carried out through experimental work. Design of experiments was used towards analyzing pertinent effects involved in machining Ti6Al4V. Uncoated carbide inserts were artificially treated with different initial flank wear (VB) in order to decouple the effects involved in progressive wear condition from rake and flank faces. Dry cutting, flood cutting with emulsion and cryogenic cutting with liquid nitrogen (LN₂) were used as different cooling strategies. The results show that initial VB presents significant contributions to BUEs formation, diffusion wear and cutting forces fluctuation, especially under aggressive cutting conditions. Cryogenic assistance significantly eliminates these issues compared to dry and flood conditions.

1. Introduction

Tool wear is a permanent concern in industries as it can significantly increase the costs and decrease quality and efficiency of production in manufacturing. In machining of difficult-to-cut materials like Ti6Al4V, heat accumulation is generally severe due to its low thermal conductivity [1]. Among different wear modes, crater wear and flank wear are reported as dominant conditions that can be quantitatively characterized [2], where VB value induced by flank wear is always used as the criterion for the end of tool-life as it can be conveniently obtained during machining [3]. Meanwhile, due to the interaction between flank face and machined surface, the impact of VB values is also a key factor from the perspective of surface integrity [4,5].

High temperature induced by materials deformation and fracture during machining is one of the main contributions to tool wear evolution. Deng et al. [6] investigated diffusion wear in dry cutting of Ti6Al4V and pointed out that the penetration depth of elements at tool-chip interface is dependent on temperature, and higher temperature will accelerate this procedure and speed up tool wear as a result. Bushlya et al. [7] showed that oxidation wear always appears with higher temperatures, which results in more intensive cratering in rake face. These

related tool wear procedures always show critical impacts on cutting performance and surface qualities. Moreover, tool wear is a progressive interaction between work material and cutting tool, where the cutting process can be changed with appearance of tool wear. Toubhans et al. [8] presented a method to predict cutting forces with consideration of built-up edges (BUEs), their method shows that the formation of BUEs may increase the fluctuation of cutting forces and decrease the cutting stability, and finally has a negative impact on surface integrity.

Flank wear is the dominant criterion applied for determination of tool life, which can also decrease surface quality. Therefore, understanding its impacts on cutting processes is very important. To precisely focus on its effects, several studies were performed in terms of pertinent topics through introducing initial flank wear prior to cutting operations. Liang and Liu. [9] carried out experimental tests concerning the influences of flank wear on surface integrity in dry cutting of Ti6Al4V. Their results show that higher VB values can induce more severe plastic deformation and less compressive stress into machined surfaces. Lin et al. [10] pointed out that the tool-work interaction can be changed due to the effects of flank wear. They developed a numerical model to characterize this process, which explained the location of occurrence of sticking on the chip through the thermal softening phenomenon. Karpat

* Corresponding author.

E-mail address: hongguang.liu@ensam.eu (H. Liu).

and Ozel. [11] investigated the influences of flank wear on heat partitions of tool-work interaction, showing that higher VB values can induce higher temperature within the area of flank wear, which will finally affect the surface integrity.

To avoid the decrease of surface quality induced by the increase of tool wear, coolants are always used during machining, which can also help to increase production efficiency by improving tool-life [12]. The effects of coolants are mainly divided into two portions, which are lubrication and cooling, respectively. Among different cooling strategies, emulsion is one of the most widely used coolants in industries due to its good performance and convenience, which shows decent performances in both lubrication and cooling [13]. Minimum quantity lubrication (MQL) is also a widely used method, which shows excellent performance in lubricating, however, its effects on cooling are mean [14], especially at higher cutting speeds with higher temperatures. Meanwhile, according to Rech et al. [15], the influences of friction coefficients on heat partition for tool-work interface are limited, which cannot provide a significant improvement in tool wear conditions for difficult-to-cut materials. As a result, better cooling strategies are more essential than lubricating methods in machining of those materials. In this case, cryogenic machining with supply of liquid nitrogen (LN₂) or liquid carbon dioxide (LCO₂) is becoming popular recently due to its excellent performance in cooling [16–18]. The forced convection process provides an extremely high heat convection coefficient between the cryogenic coolants and work materials, and the huge temperature gap also introduces a high heat flux, which decreases cutting temperatures rapidly [19]. Venugopal et al. [20] pointed out that the evolutions of flank wear and crater wear are both lower under cryogenic conditions compared to dry and wet cutting conditions, and tool-life can be well improved from this perspective. Kaynak et al. [21] compared tool wear evolution in cutting NiTi shape memory alloys under dry, minimum quantity lubrication (MQL) and cryogenic conditions, which shows that progressive wear always appear in dry and MQL conditions, while it is significantly improved when cryogenic coolants are applied, even if the cutting speed is high. Bermingham et al. [22] carried out some investigations on improvement of tool-life through application of different cooling strategies and showed that cryogenic coolant is an efficient method while the delivery system is a key factor influencing its cooling performance. Moreover, cryogenic cooling also characterizes a capability to improve surface integrity like surface roughness and subsurface hardness as reported by Rotella et al. [23], which also provides a good solution to restrain excessive deformation induced decrease of surface quality during machining [24,25]. Above all, cryogenic machining has shown good performances in both suppression of tool wear and improvement of surface quality. However, the details involved in specific aspect of progressive wear are still not clear, further investigations and more in-depth analysis are still required in terms of both fundamental research and process optimization towards industries.

In this study, impacts on evolutions of BUEs formation, diffusion wear and cutting forces fluctuation induced by initial flank wear and cooling strategies are investigated during machining of Ti6Al4V. Dry cutting, flood cutting with supply of emulsion and cryogenic cutting with supply of LN₂ are used as cooling approaches, respectively. To decouple the influences of wear conditions within rake face and flank face during the entire cutting progress, cutting tools are artificially treated with different initial VB values. Cutting conditions with mild parameters and aggressive parameters were adopted for comparison purpose. The results show that initial VB value has a great contribution to BUEs formation, especially with aggressive cutting parameters. Good cooling strategies can help to restrain the formation of BUEs, meanwhile, diffusion wear and cutting forces fluctuation can also be well controlled in this case, especially with the supply of LN₂.

Table 1
Experimental conditions.

No.	Abbreviation	Cutting speed (m/min)	Feed (mm/r)	Cooling	Flank wear (mm)
1	MD0	6	0.1	Dry	0
2	MD1	6	0.1	Dry	0.1
3	MD2	6	0.1	Dry	0.2
4	AD0	60	0.2	Dry	0
5	AD1	60	0.2	Dry	0.1
6	AD2	60	0.2	Dry	0.2
7	MF0	6	0.1	Flood	0
8	MF1	6	0.1	Flood	0.1
9	MF2	6	0.1	Flood	0.2
10	AF0	60	0.2	Flood	0
11	AF1	60	0.2	Flood	0.1
12	AF2	60	0.2	Flood	0.2
13	MC0	6	0.1	Cryogenic	0
14	MC1	6	0.1	Cryogenic	0.1
15	MC2	6	0.1	Cryogenic	0.2
16	AC0	60	0.2	Cryogenic	0
17	AC1	60	0.2	Cryogenic	0.1
18	AC2	60	0.2	Cryogenic	0.2

Notes: in the following text, related experimental conditions will be referred as abbreviations composed of three letters: 1st letter – **M** for Mild condition and **A** for Aggressive condition; 2nd letter – **D** for Dry condition, **F** for Flood condition and **C** for Cryogenic condition; 3rd letter – **0** for VB= 0, **1** for VB= 0.1 mm and **2** for VB= 0.2 mm. For example, aggressive parameters with dry cutting condition and VB= 0.2 mm will be described as AD2.

2. Design of experiments (DoE)

2.1. Experimental set-up and parameters

During machining process, the evolution of tool wear condition will be influenced by multiple factors, in this study, the main concerns are focused on different cooling strategies and initial flank wear (VB values). Three different cooling strategies were used in this research, which are dry cutting condition, flood cutting condition with supply of emulsion (model: B-Cool 755) and cryogenic cutting condition with supply of liquid nitrogen (LN₂), respectively. While for initial flank wear, three VB values were artificially prepared for cutting tools, which are VB= 0 mm, VB= 0.1 mm and VB= 0.2 mm, respectively. Moreover, although cutting parameter is not the main concern in this research, it is still a key factor influencing the performance of tool wear and cooling condition. As a result, to separate its effects, two differentiated conditions of mild and aggressive were used, respectively, which were chosen in terms of hitting the lower and upper limits of parameters applied in industries. Detailed parameters are as shown in Table 1.

In this study, a full factorial type was applied in terms of DoE, as a result, 18 different experimental conditions were used, and each case was repeated 3 times to confirm the repeatability of data, so 54 experiments were performed in total. Orthogonal cutting was realized by turning process on a CNC lathe (model: Leadwell LTC25iL) with uncoated carbide inserts (model: ARNO 122002-AK20). The rake angle and clearance angle are both 5° when inserts are installed on the tool holder (model: ARNO SXCCN 2525 M12-B). The tool holder was mounted on a dynamometer (model: Kistler 9129A) in order to measure cutting forces. In this study, for cryogenic condition, LN₂ was supplied through a specially designed nozzle fixed in front of rake face with diameter 2.5 mm to maintain a continuous projection towards tool-chip interface, and a phase separator was used in order to make sure that only liquid phases were applied on the work material. For flood cutting condition, emulsion was driven for both rake face and flank face to obtain the best cooling performance. While for dry cutting condition, as there are no disturbances induced by coolants, it is eligible for application of high-speed camera to capture chip flow with respect to different flank wear. However, the limited space in lathe makes an limitation for these devices, as a result, a specifically designed set-up on a 5-axis milling

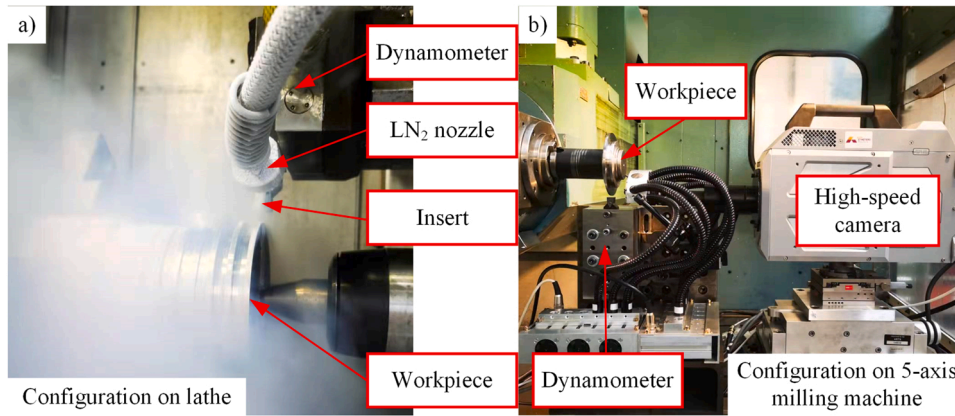


Fig. 1. Configurations of experimental set-up, a) set-up for cutting forces measurement with respect to flank wear and different cooling strategies on lathe; b) set-up for high-speed imaging of chip formation under dry condition on 5-axis milling machine.

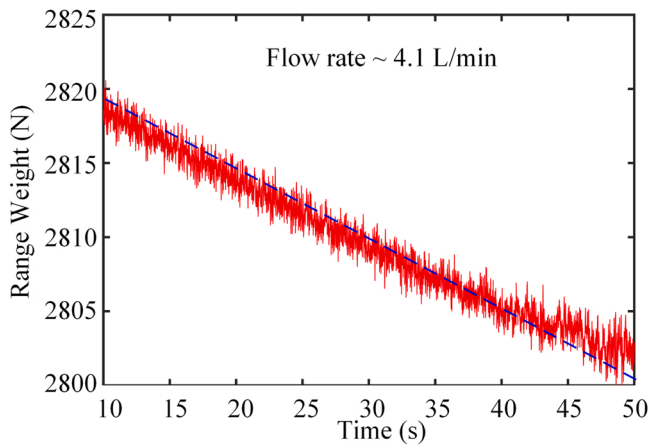


Fig. 2. Flow rate of LN₂ monitored through the force sensor.

machine (model: GAMBIN 120CR) was applied to repeat these cases in order to obtain high-speed images, as shown in Fig. 1b). This set-up transfers milling to turning through fixing cutting tool on the worktable and rotating the work material by spindle. Prior to be transferred to this set-up, the measured cutting forces between two devices have been verified to make sure that the dynamics of machine tool do not influence imaging of chip formation. Experimental set-ups can be described as shown in Fig. 1. Moreover, a constant time period of 10 s is applied for all the cases in order to reach a stable thermomechanical condition during orthogonal cutting, and each case was repeated 3 times to confirm the repeatability of data.

Moreover, for cryogenic machining, the internal pressure of LN₂ bottle was set to 12.5 bars, all the related set-ups were used to insure a

high flow rate in order to guarantee that the coolants driven into the cooling area were liquids to maintain the best cooling performance [26]. Meanwhile, a phase separator was also applied to separate and get rid of gas phase before it comes into the cooling area. The flow rate was monitored through the change of weight of LN₂ bottle with the help of a force sensor. The value of flow rate is measured as about 4.1 L/min, as shown in Fig. 2. The change of flow rate was due to the consumption of LN₂ with respect to time.

2.2. Treatment of cutting tools

To investigate the evolution of flank wear under different initial VB values, the inserts are prepared through grinding in order to artificially create desired VB values in advance, which are VB = 0, VB = 0.1 and VB = 0.2, respectively. Moreover, to maintain a unique shape of cutting edge, the inserts were then treated through a honing machine (model: OTEC DF-4) to prepare the cutting edge in order to obtain a unique edge radius of 10 μm, which is also beneficial in terms of treating flank surfaces with the same condition. Then the initial flank wear conditions and edge radius are measured through two different optical microscopes (models: Keyence VHX and Alicona), which can be described as shown in Fig. 3. Here it should be noticed that, the artificial flank wear shows a uniform band, while during actual machining it cannot evolve as uniform as artificial characterization. This method is mainly applied in terms of decoupling the effects of tool wear in rake face and flank face, and understanding the impacts induced by flank wear.

3. Evolution of BUEs

3.1. Impact of initial flank wear

Tool wear always occurs in rake face and flank face of cutting tools,

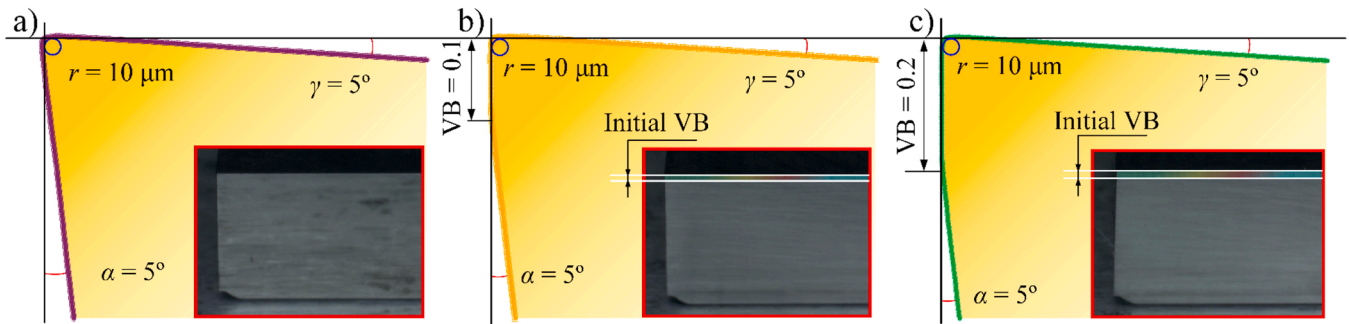


Fig. 3. Characterization of insert shapes with different initial flank wear conditions through Alicona, a) initial VB = 0, b) initial VB = 0.1 and c) initial VB = 0.2.

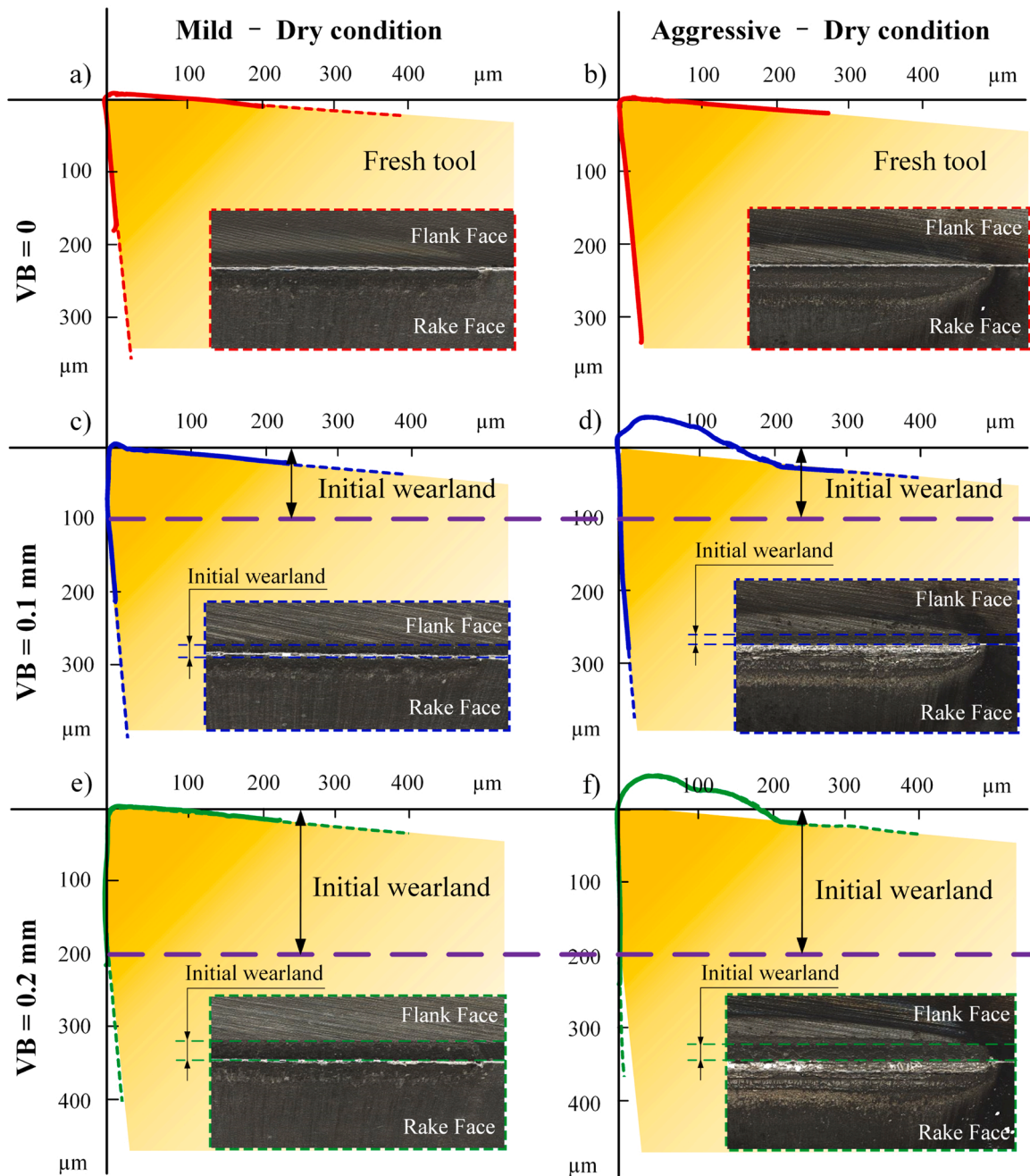


Fig. 4. Characterization of inserts section profile through Alicona under different cutting conditions, a) MD0, b) AD0, c) MD1, d) AD1, e) MD2 and f) AD2.

where the wear in rake face is due to the tool-chip interaction, which generally leads to the formation of built-up layers (BULs), BUEs, craters, etc. While for the wear in flank face, it is always induced by tool-work interaction and will normally characterizes as the formation of a wearland (VB). In general, for a fresh cutter, tool wear of both sides will occur simultaneously during the cutting process, however, their influences on each other are not clear. As a result, to isolate the influences of flank wear, fresh cutters were ground artificially with different initial VB values as presented in Fig. 3. When implementing initial flank wear, both tool wear and cutting performances are significantly influenced, especially for aggressive conditions. As Ti6Al4V is a typically difficult-to-cut material due to its low thermal conductivity and high elasticity, initial VB values introduce a severe thermal mechanical loading on the wearlands, and related thermal effects significantly speed up the interaction within tool-chip interface and the diffusion of titanium, which

finally leads to the formation of BUEs, as shown in Fig. 4.

For mild conditions, although no obvious BUEs were obtained, BULs still formed, which shows a parabolic distribution in rake face due to the different contact condition of the boarder. While for aggressive condition, besides formation of BULs, BUEs are also formed when initial VB value exists, and the high temperature induced by aggressive cutting parameters also introduce carbonization at the corner, as shown in Fig. 5b).

Meanwhile, the formation of BUEs under aggressive conditions only appear when initial VB values are introduced, which induces a gap in BULs and changes the contact process of tool-chip interface, as a result, the thickness of the whole BUL is changed, which separates the unique BUL into primary and secondary portions. These characteristics are all performed as titanium elements adhered on the rake face, as shown in Fig. 6.

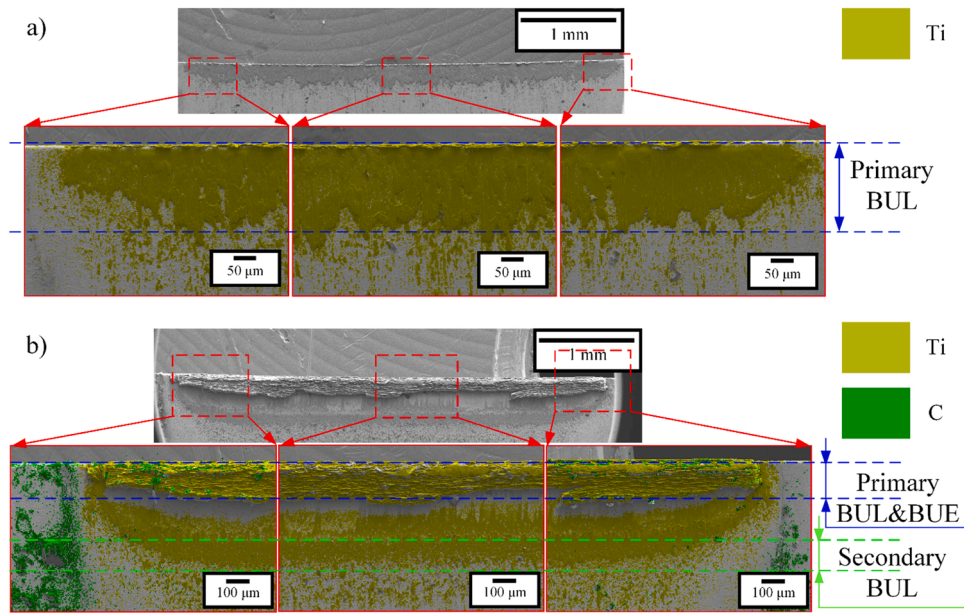


Fig. 5. Evolutions of BULs and BUEs in terms of different cutting parameters under dry condition, a) MD1 and b) AD1.

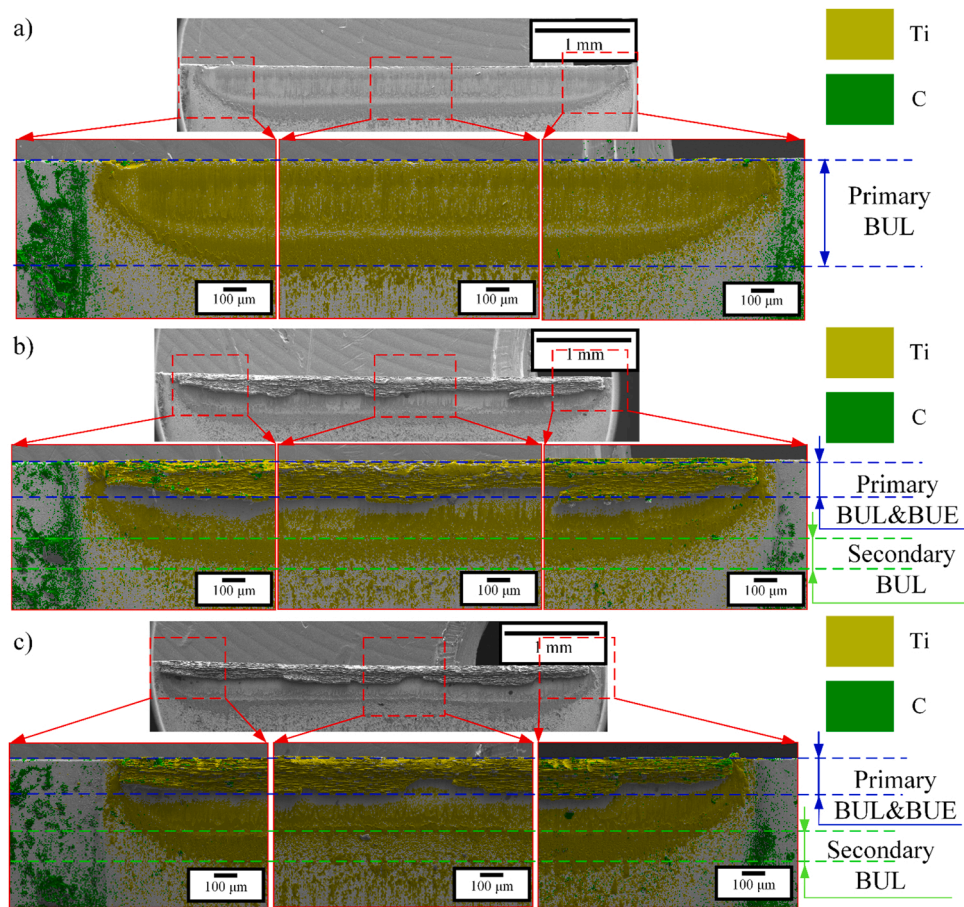


Fig. 6. Evolution of BULs and BUEs in terms of initial VB value under aggressive and dry conditions, a) AD0, b) AD1 and c) AD2.

Adhesions of titanium alloys on wearlands of flank surface can be found due to the enhancement of thermal effects induced by initial flank wear, this phenomenon also leads to higher friction in local area, which is reported as a major concern in terms of BUE formation by Atlati et al. [27]. Moreover, a burning pattern is observed with some oxidation and

carbonization in this case, as oxidation was reported to be a common phenomenon in dry cutting [7]. Pertinent phenomena have also been discussed in Section 3.2. However, the influences of initial VB values are not significant with respect to adhesion of Ti elements, as no additional adhesions outside the wearlands were observed. Moreover, these effects

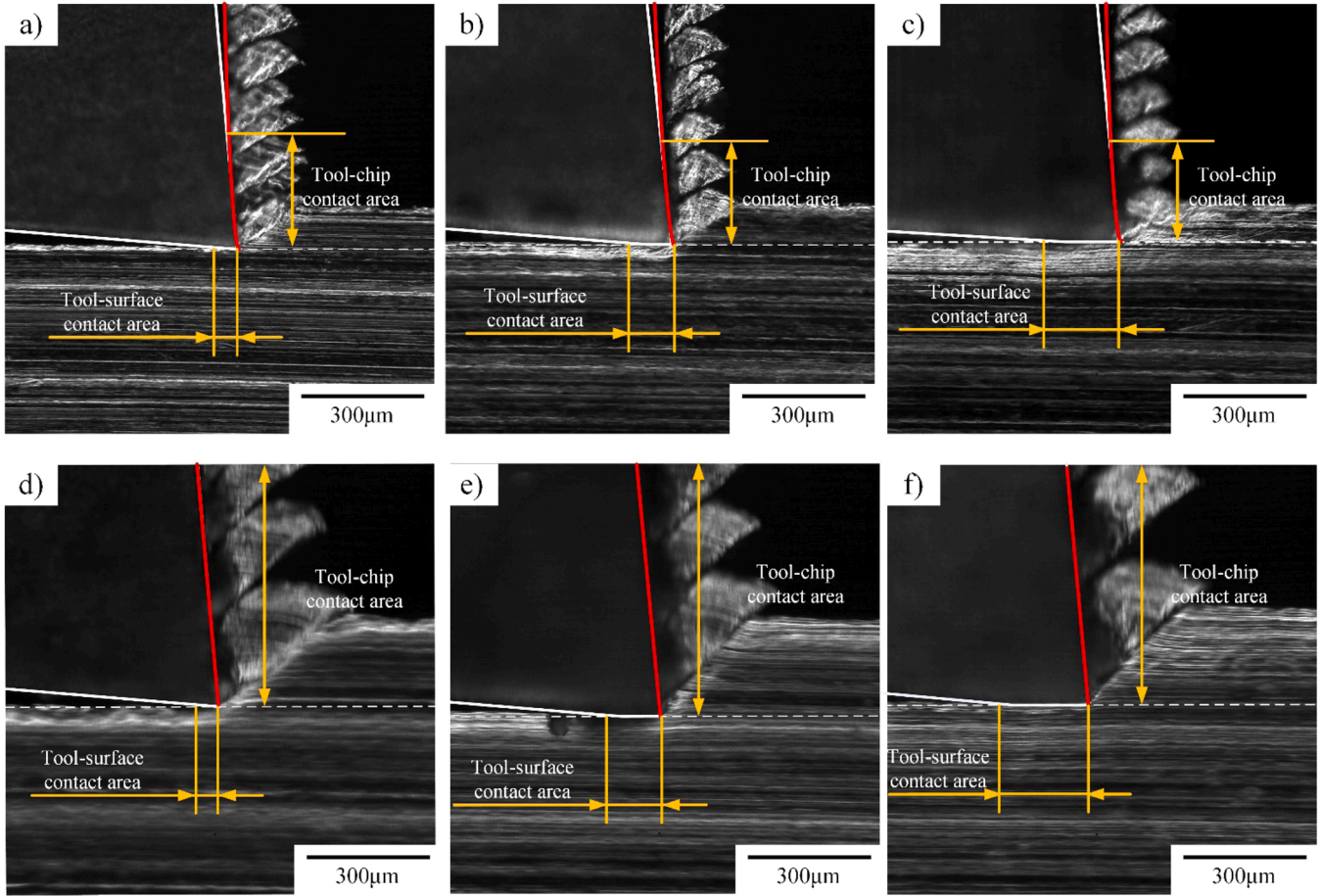


Fig. 7. Tool-work contact condition during chip formation with different parameters, a) MD0, b) MD1, c) MD2, d) AD0, e) AD1 and f) AD2.

of BUEs formation in terms of initial VB values are highly dependent on tool-chip interaction, where its length is directly influenced by uncut chip thickness, as shown in Fig. 7.

In this figure, due to the limitation of resolution, the change of tool-chip contact length with BUEs formation cannot be characterized quantitatively and precisely through high-speed camera. However, it can still be found that for aggressive conditions, the higher cutting speeds and feeds increase the contact length for both tool-chip interface and tool-surface interface, which induces more thermomechanical loadings. Meanwhile, due to the existence of initial flank wear, friction induced by tool-work interaction is also more severe, which provides additional heating source. This phenomenon makes more heat produced and heat dissipation difficult within cutting area, and finally speeds up the formations of BUEs.

3.2. Impact of cooling strategies

To eliminate thermal effects and slow down tool wear evolution, application of coolants is a common choice. However, for different cooling strategies, cooling performances and related influences on wear evolution are very different as well. Flood cutting condition with supply of emulsion is the most commonly used method in industries due to its flexibility and convenience. Cryogenic cutting with supply of LN₂ is becoming more and more popular recently due to its excellent performance in cooling. In this section, these two cooling strategies are used to characterize its impacts on BUEs evolution.

Under dry cutting conditions, dominant phenomena are induced by burning due to extremely high temperature, which are carbonization on rake face and oxidation on flank face, respectively, where a clear burning pattern can be observed through optical microscope. And this

phenomenon is the most severe when initial VB values are introduced. Meanwhile, with carbonization patterns observed under dry condition through optical microscope, a high intensity of carbon elements can be detected through Energy-dispersive X-ray spectroscopy (EDS) analysis, while this phenomenon is significantly improved with appearance of a clean rake face when coolants are applied. On the other hand, adhesion of materials and related formation of BUEs with initial VB are not changed even if under flood cutting condition. However, once cryogenic coolants are added, BUEs decrease immediately, as shown in Fig. 8.

Compared with carbonization within rake face, oxidation is more obvious within flank face, as a higher intensity of oxide can be detected through EDS with a similar pattern observed by optical microscope, while carbon elements are difficult to be detected. Meanwhile, oxidation always shows a parabolic pattern regardless of cutting parameters under dry condition, as shown in Fig. 9.

This phenomenon under dry condition shown in Fig. 9 can be attributed to thermal contact induced temperature distribution at the tool-work interface, as the width of cutting edge is larger than that of work material. And heat transfer makes temperature lower at corner while higher at center, as presented by Hamm et al. [28], which characterizes a perfect fit with the pattern obtained in this study. Moreover, the formation of oxidation pattern is also closely related to the contact with air, as the pattern is perfectly suppressed to the edge of tool-work interaction area when coolants are applied, which can be presented through optical microscopy as shown in Fig. 10.

These phenomena regarding to carbonization and oxidation are mainly induced by high temperature and contact with air, which can be well prevented through application of emulsion. However, formation of BUEs is still severe when initial VB exists even if emulsion is used. While when switched to cryogenic assistance with supply of LN₂, a significant

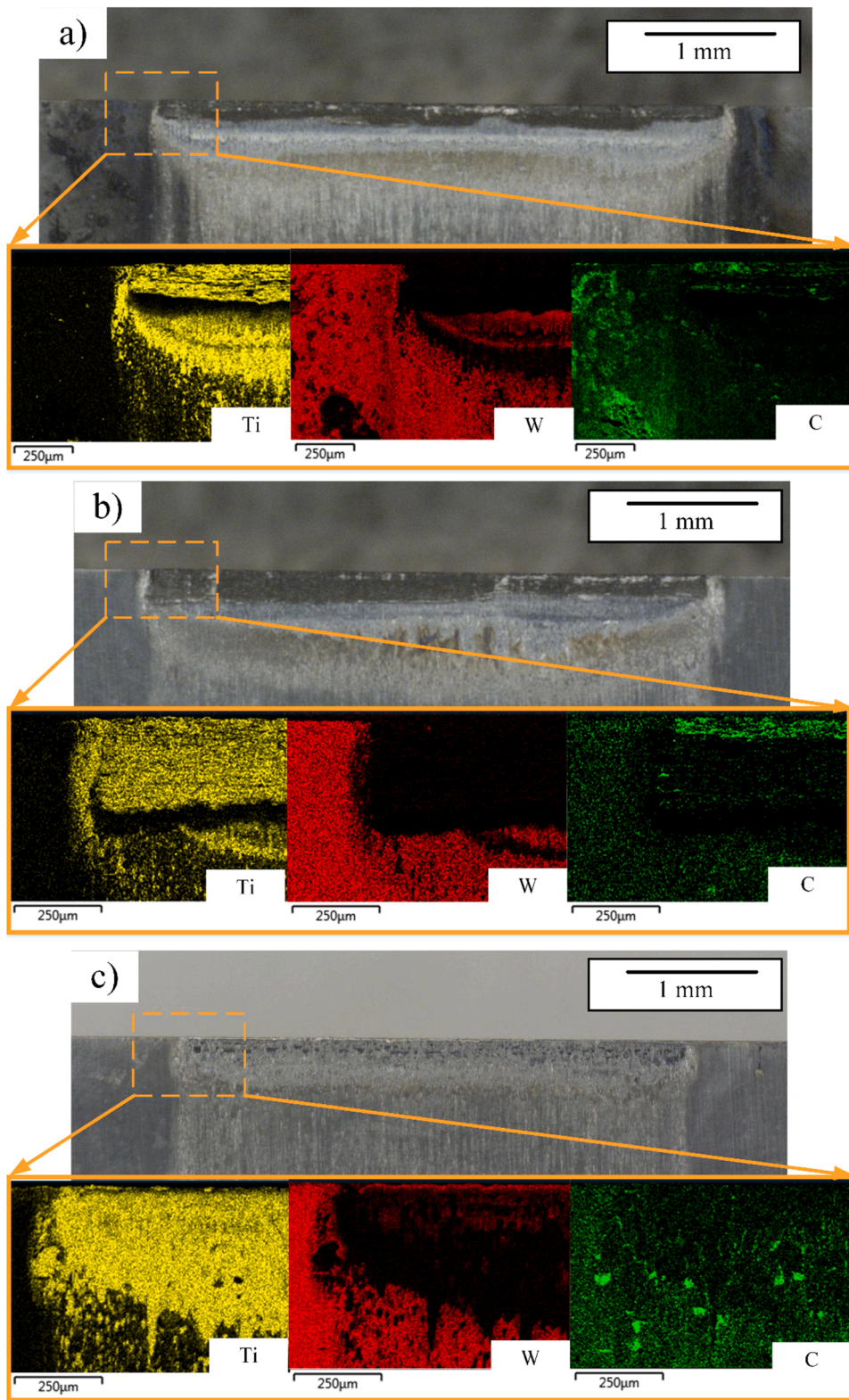


Fig. 8. Optical microscopy and EDS analysis of tool wear on rake face under different cooling conditions, a) AD2, b) AF2, c) AC2.

promotion was observed, where a clean rake face was obtained with almost no BUEs formed. The section profiles of inserts under different cutting conditions can be well characterized through Alicona, as shown in Fig. 11.

As a result, the formation of BUEs is mainly attributed to thermal effects, where heat accumulation is induced by severe friction between

flank face and work material, especially when a preliminary flank wear (VB) exists. This phenomenon is particularly prominent under aggressive conditions, as large amounts of heat can be accumulated within a very short time period in this case. Although emulsion is also an effective coolant, it cannot remove heats rapidly enough under this condition, as a result, formation of BUEs cannot be prevented. While for cryogenic

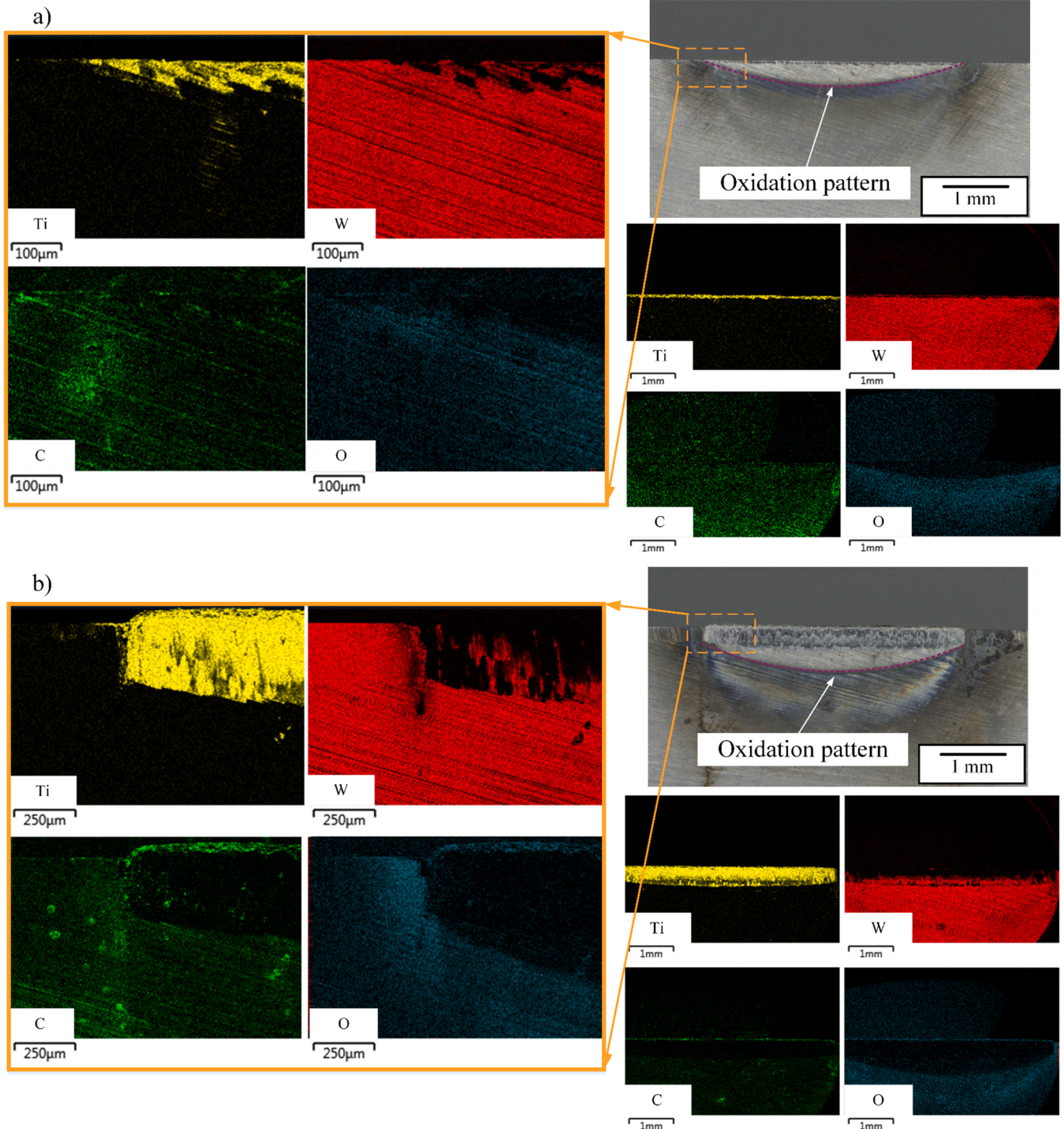


Fig. 9. Optical microscopy and EDS analysis of tool wear characteristics on flank surface under dry condition with different initial VB values, a) AD0 and b) AD2.

coolants, the cooling performance is much better than normal coolants, which eliminates formation of BUEs perfectly. However, micro-chipping becomes more common under this condition due to the high stress generation [29,30] and brittleness of cutting tool induced by low temperature, especially with sharp tools. For inserts with initial VB values, adhesion of materials will cover the cutting edge, even for micro-chipping areas, which can work as a protection of cutting edge to prevent further chipping behaviors. This behavior is more clear with higher initial VB value, as material adhesion becomes more severe with increase of initial VB even if BUEs are not formed as for dry and flood conditions, as shown in Fig. 12.

Although micro-chipping becomes more common with cryogenic assistance, tool-life was reported to be prominently improved in previous studies [5,26,31], as thermally activated mechanisms are always the dominant factors in tool wear of Ti6Al4V machining. Meanwhile, conditions of tool-work interaction within flank face are also changed when initial VB value exists, where a smaller interaction area between cutting tool and machined surfaces is characterized by cryogenic machining through less area of adhesion by titanium elements, as shown in Fig. 13.

Here the contact area with respect to initial wearland is reduced with application of cooling strategies, especially for cryogenic condition, as cryogenic coolants with extremely low temperature shows an excellent

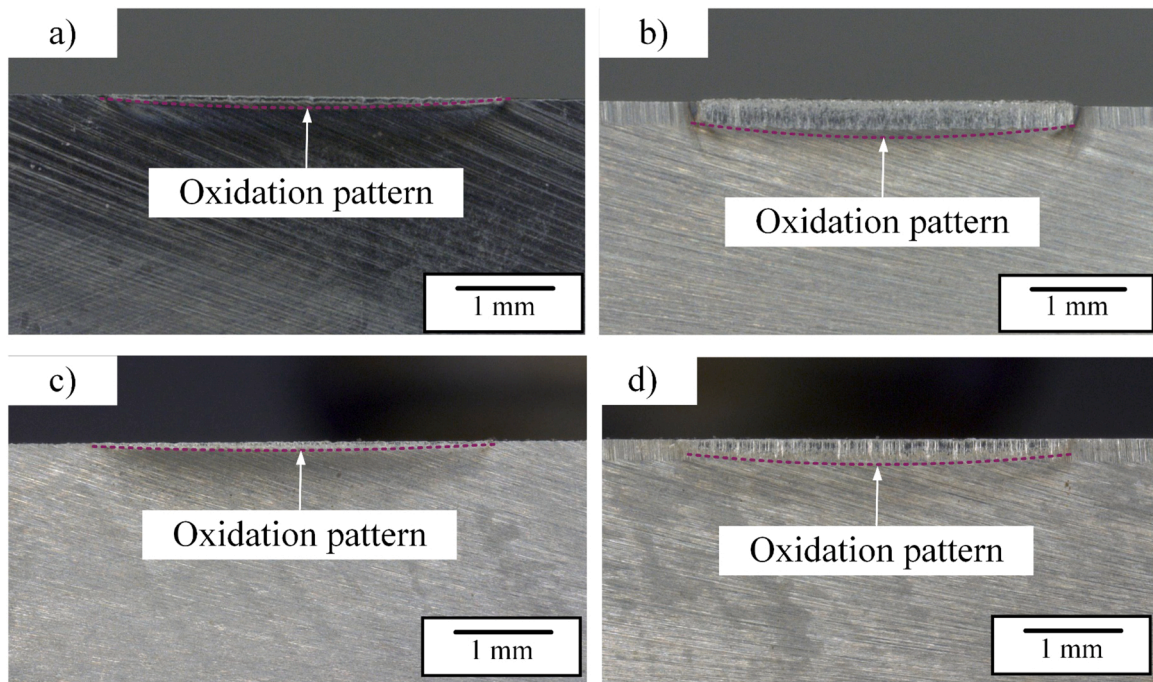


Fig. 10. Optical microscopy of oxidation pattern on flank face with supply of coolants, a) AF0, b) AF2, c) AC0 and d) AC2.

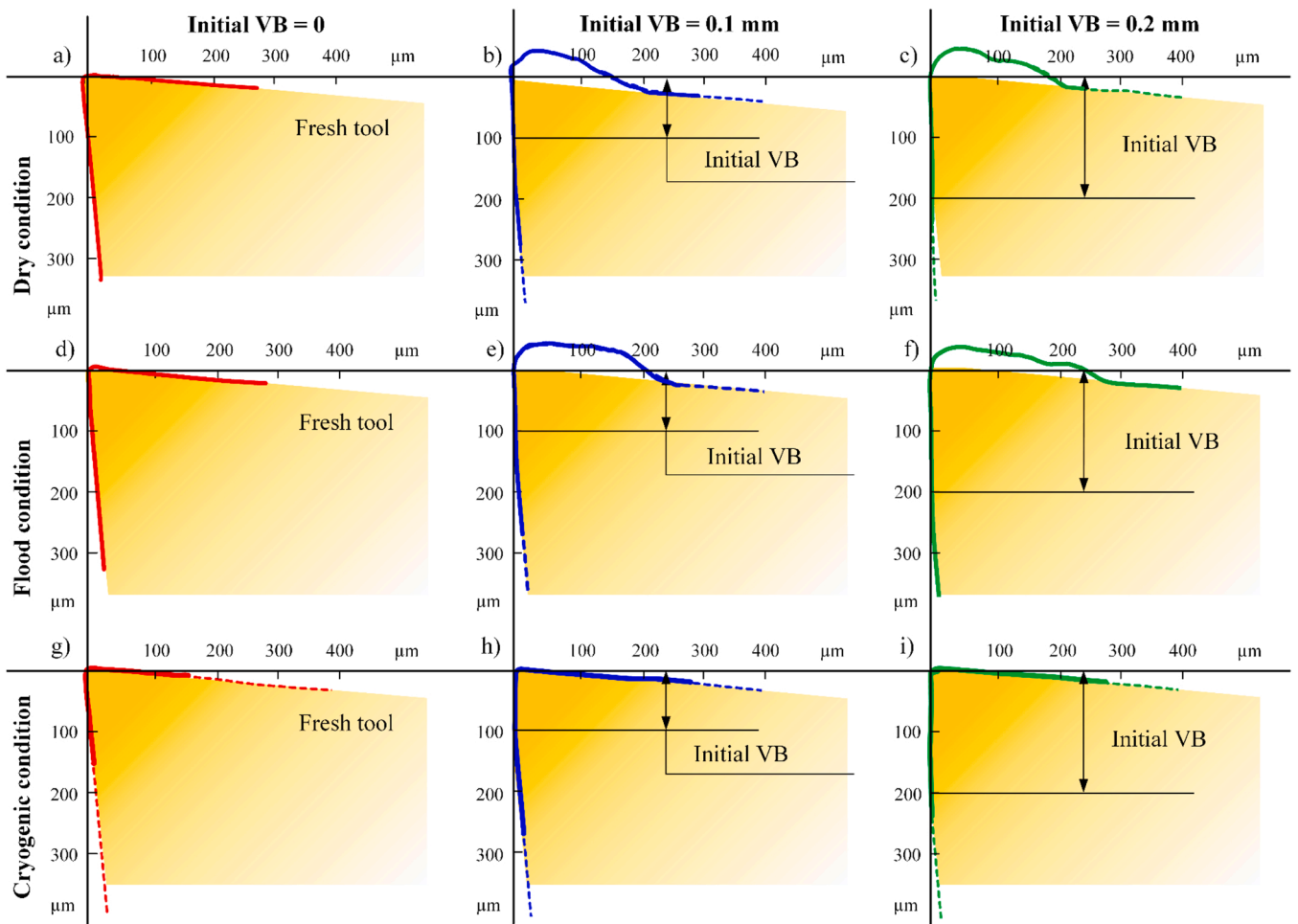


Fig. 11. Characteristics of BUEs formation under different cutting conditions, a) AD0, b) AD1, c) AD2, d) AF0, e) AF1, f) AF2, g) AC0, h) AC1 and i) AC2.

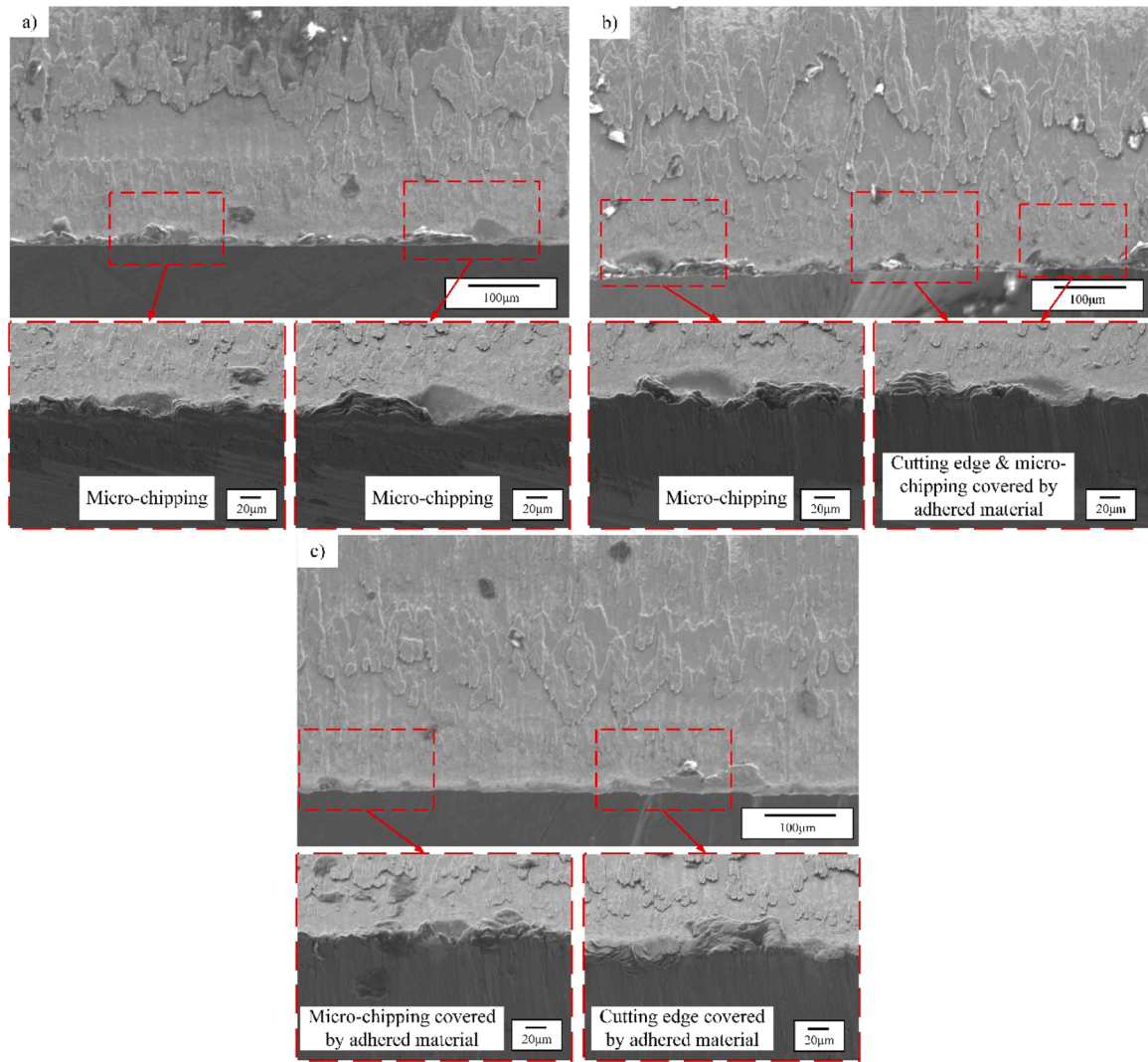


Fig. 12. Tool wear characteristics from the view of rake face under cryogenic conditions, a) AC0, b) AC1 and c) AC2.

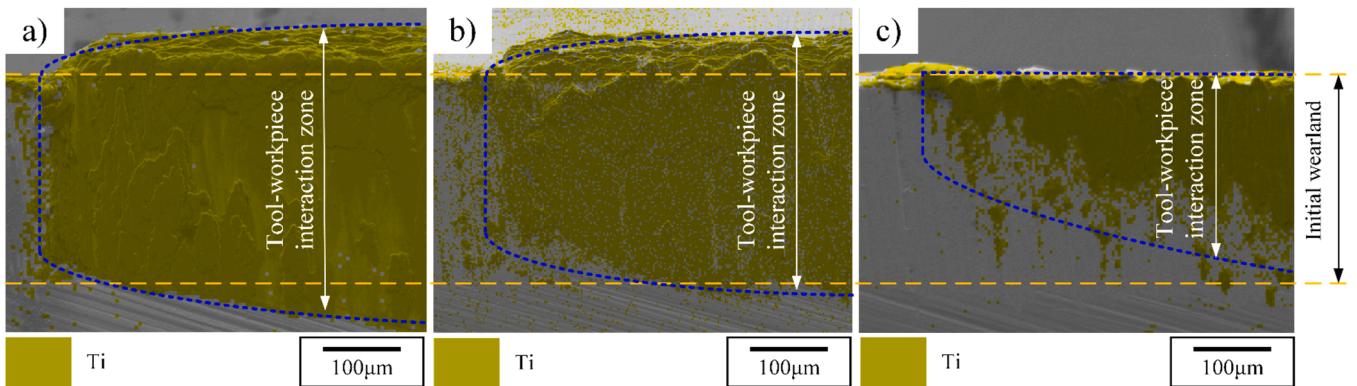


Fig. 13. Tool-work interaction from the view of flank face with different cutting conditions, a) AD0, b) AF0 and c) AC0.

performance in restricting thermal expansion [24,25]. Moreover, formation of BUEs will induce inverse condition and increase this area, which makes the contact condition of flood cutting similar with dry cutting, and it is also improved by cryogenic cutting.

4. Evolution of diffusion wear

Diffusion wear is a dominant mechanism in tool wear evolution of titanium machining, especially for uncoated inserts. This phenomenon is also reported to be prominently contributed by high temperatures and pressures [6,32–34], which can significantly decrease the strength at the interface. Moreover, adhesion always appears together with diffusion,

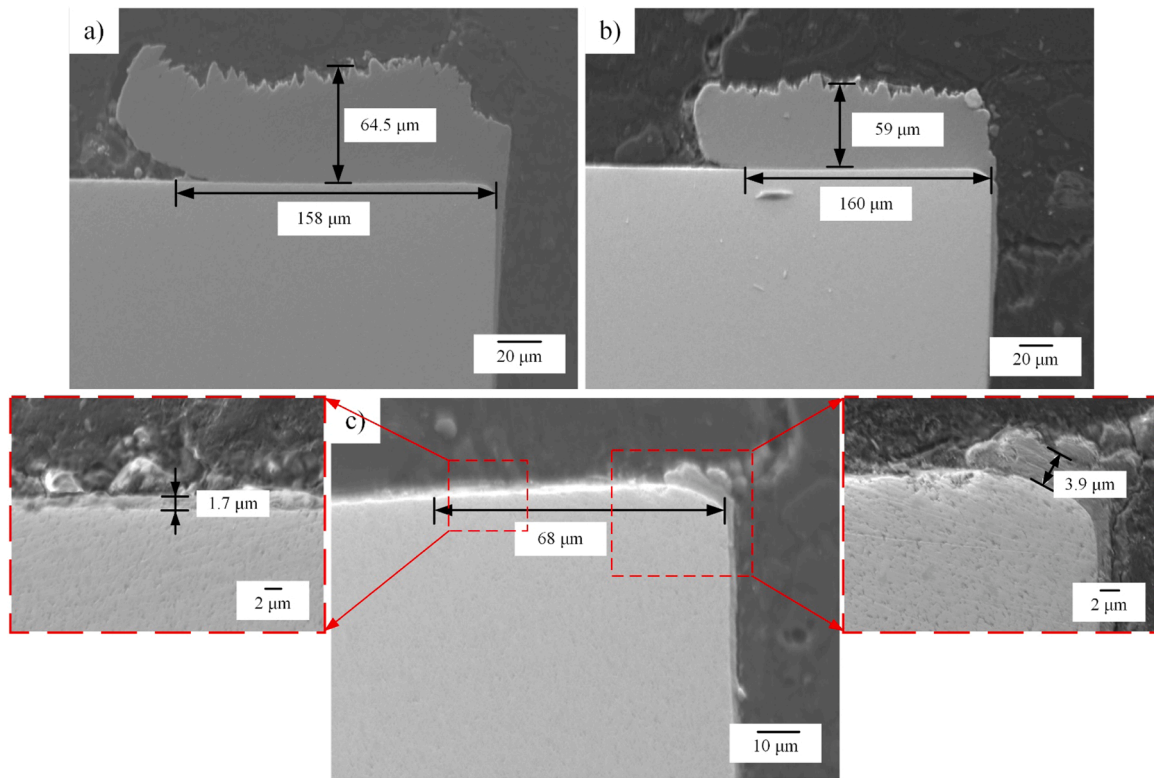


Fig. 14. Sectional view of cutting tools under different cooling conditions, a) AD1, b) AF1 and c) AC1.

and a comprehensive wear condition with adhesion-diffusion-abrasiveness will be introduced as a result, which can lead to multiple wear modes including micro-chipping, cratering, etc. [35]. Thus, the failure of cutting tools will be speeded up under this condition, which should be well prevented. As high temperature is a main contributor towards diffusion wear, cryogenic assistance is believed to be effective in terms of preventing pertinent behavior, therefore, a comparison of diffusion wear condition under different cooling strategies was carried out in this study, with specific cases of conditions AD1, AF1 and AC1.

To access the diffusion profile, the inserts are sectioned by wire electrical discharge machining (WEDM), which are then mounted and polished in order to obtain a perfect surface towards EDS analysis by SEM. From the sectional view, it can be distinguished that both the thickness of adhered Ti6Al4V layer and the length of adhered zone are significantly decreased when cryogenic coolants are applied. For the thickness of adhered layer, the value is around 60 μm for both dry and flood conditions, while it is suppressed to about 2 μm under cryogenic condition. And for the length of adhered area, it is around 160 μm for dry and flood conditions, while only 68 μm for cryogenic condition, as shown in Fig. 14. Apparent decrease of the contact length may be due to the high projection pressure provided by LN_2 , which changes the tool-chip contact condition. For flood condition, although there is also an impact from emulsion, the internal pressure is not as high as that from LN_2 , so the length of contact is not apparently influenced. The thick layers of work material adhered on the rake face under dry and flood conditions work as BUE and have a significant impact on cutting performances, which can enhance cutting forces fluctuation as reported by Toubhans et al. [8]. While for cryogenic condition, only a thin BUL forms at rake face with a tiny BUE at tool tip.

Then the intensities of different elements across Ti6Al4V/WC-Co interface were evaluated through EDS profile. Due to the different atomic properties and crystal structures of titanium and tungsten, there is a limitation of EDS resolution, which is also heavily dependent on acceleration voltage [36]. As a result, to obtain a better resolution, a

minimum acceleration voltage of 5 keV was applied in this case, which characterizes detecting area diameter of about 0.2 μm for titanium and about 0.055 μm for tungsten [37]. At this scale, a diffusion distance across the interface can be distinguished. Moreover, according to previous researches [38–40], a protective layer composed of TiC is easily formed at rake face during machining process, especially with a longer cutting time, so the distribution of carbon is also extracted. However, no clear TiC particles are observed as proposed by Graves et al. [40], which may be due to the short cutting time applied in this research, as TiC was reported with 900 s cutting time in their case, while only 10 s in this case. And to make the data more precise, a quantification of element composition was also measured along the profile to work as a supplementary. At rake face, the interaction between work material and cutting tool is the most profound due to the high pressure and severe friction induced high temperature. As a result, cooling strategies show a prominent effect within this area, as shown in Fig. 15. For dry condition, the intensity of titanium varies from 1.74 μm to 2.39 μm , while tungsten varies from 1.63 μm to 2.36 μm , where the intersection point appears at 1.88 μm . Subtracting the detecting area diameter, the estimated value for minimum diffusion distance is about 0.31 μm in this case. The same strategy is also applied for flood and cryogenic conditions, and the estimated values are about 0.32 μm and 0.17 μm , respectively. According to the estimation, cryogenic assistance shows some advances in terms of eliminating diffusion, while the amount is limited. Moreover, no apparent peaks of carbon are observed within titanium area prior to the intersection point, so the short cutting time in this study is not enough for the formation of TiC.

At flank face, cryogenic coolants are not directly delivered into this area, so that the diffusion distances are similar regardless of cooling conditions, as shown in Fig. 16, with all the values about 0.05 μm following the strategy as illustrated previously. As a result, it can be concluded that almost no diffusion occurs in flank face, regardless of cooling strategies.

Thus, cryogenic cooling with LN_2 shows a good performance in terms of suppressing BUEs and pertinent diffusion, especially at rake face,

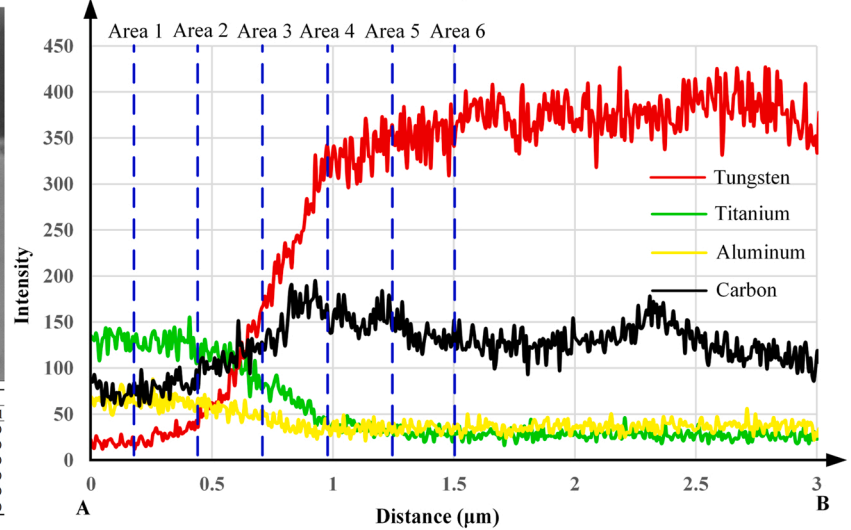
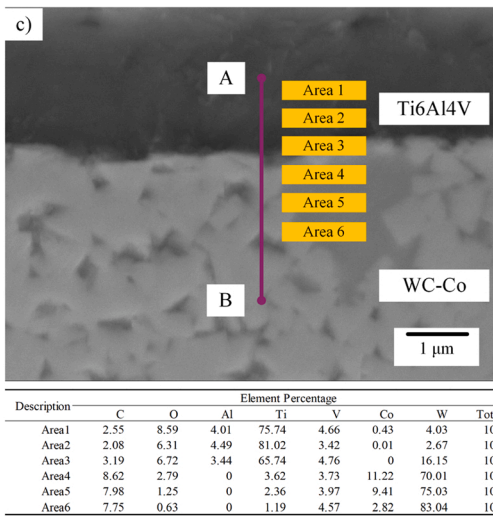
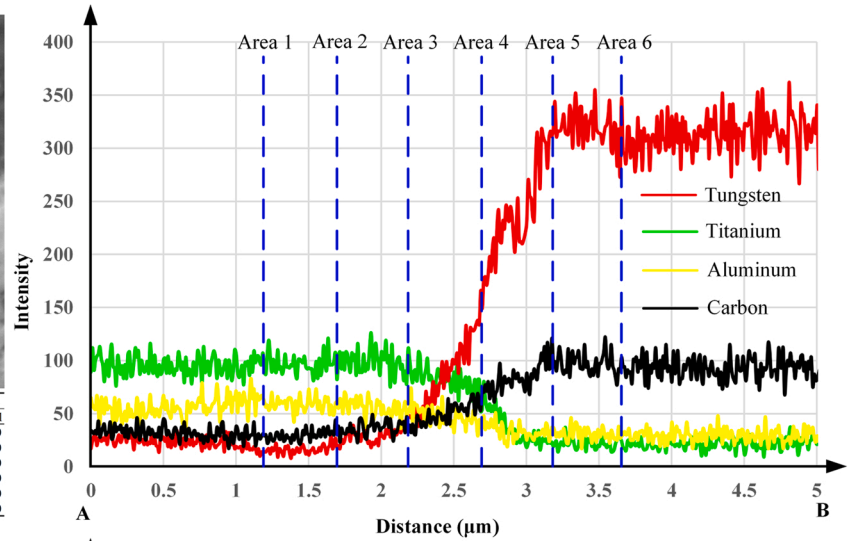
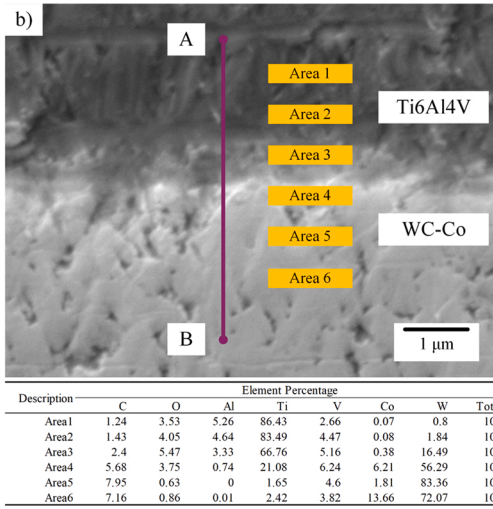
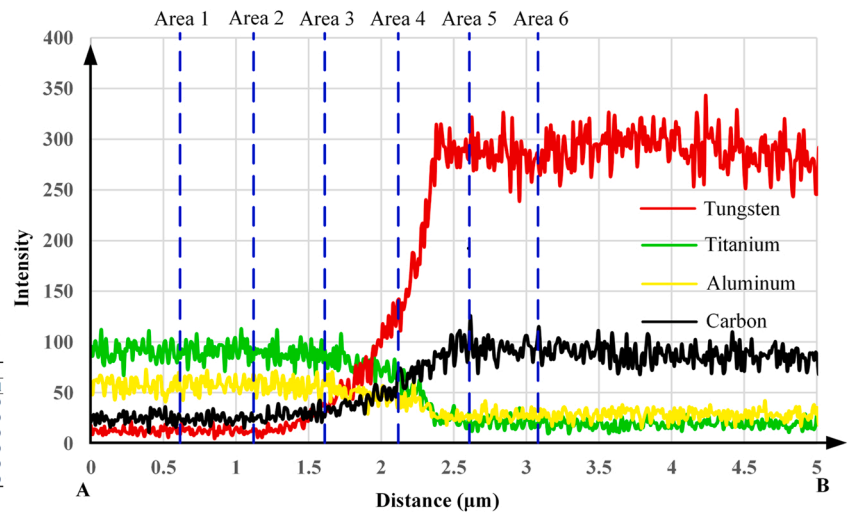
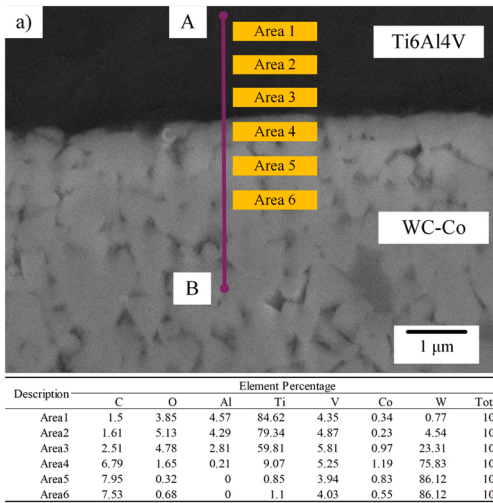
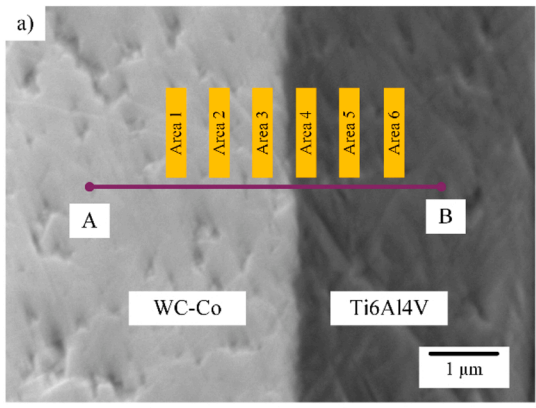


Fig. 15. Diffusion distance at cutting tool rake face under different cooling conditions, a) AD1, b) AF1 and c) AC1.

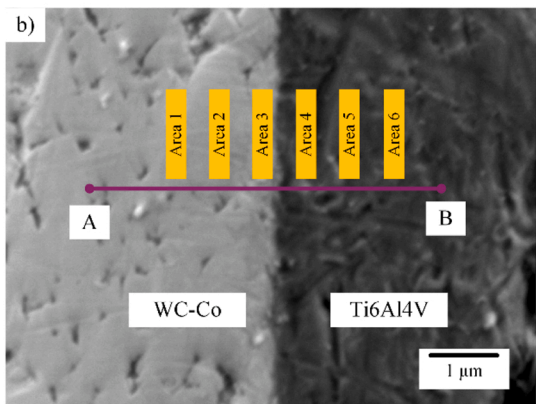
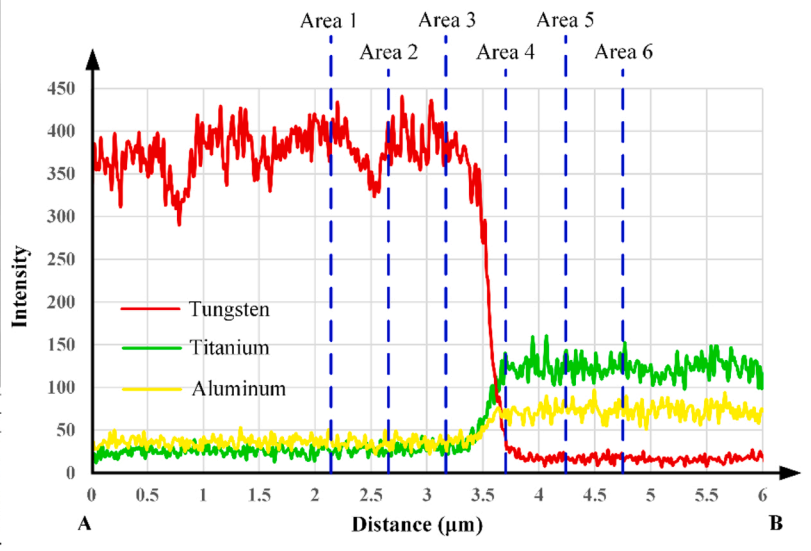
where the cryogenic coolants have a direct contact with the interface of work material and cutting tool. Also there may be a relationship between formation of BUEs and diffusion, while it cannot be clearly characterized in this study.

5. Evolution of cutting forces

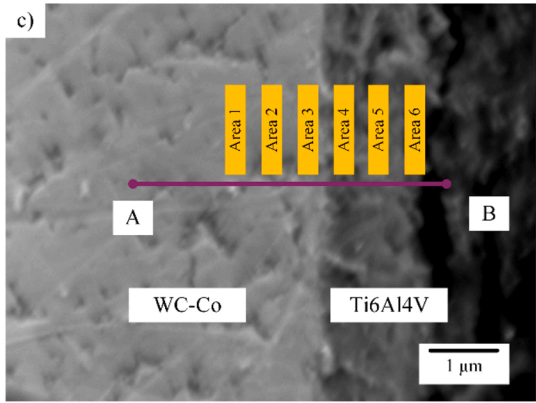
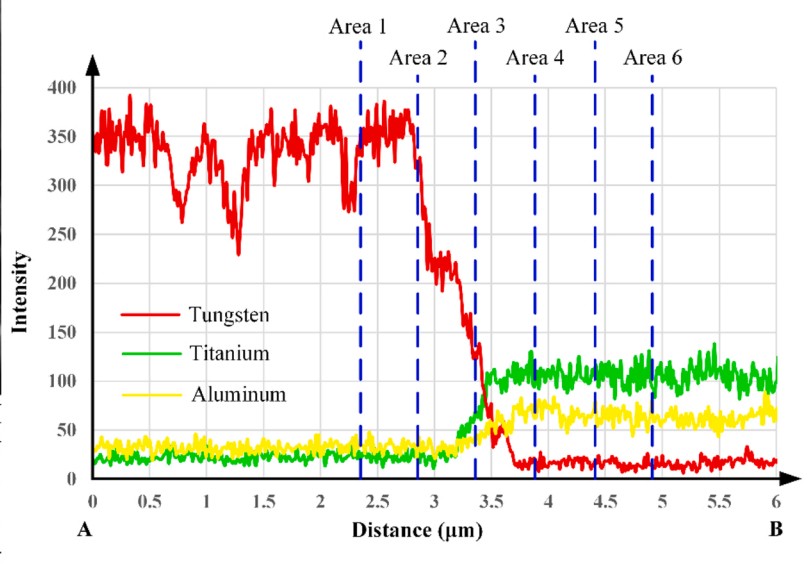
Cutting force is a very sensitive parameter with respect to the evolution of tool wear, especially the relationship between thrust forces and flank wear, as an additional contact is induced by the wearland, which



Description	Element Percentage						Total
	O	Al	Ti	V	Co	W	
Area1	0.31	0	0.09	3.88	9.9	85.81	100
Area2	0.59	0	1.66	4.07	3.95	89.73	100
Area3	1.1	0.08	4.02	5.34	3.48	85.97	100
Area4	5.07	4.67	86.28	3.24	0	0.74	100
Area5	5.45	4.68	87.1	2	0	0.78	100
Area6	4.95	4.63	85.36	3.77	0	1.29	100



Description	Element Percentage						Total
	O	Al	Ti	V	Co	W	
Area1	0.42	0	0.92	4.81	0.39	93.46	100
Area2	1.47	0.03	2.47	5.4	2.23	88.39	100
Area3	3.56	0.69	18.46	5.81	0.78	70.7	100
Area4	6.71	4.71	80.17	5.28	0.35	2.78	100
Area5	3.93	4.95	85.53	4.3	0	1.29	100
Area6	4.68	5.11	84.49	3.84	0.26	1.61	100



Description	Element Percentage						Total
	O	Al	Ti	V	Co	W	
Area1	0.99	0	3.04	4	1.33	90.63	100
Area2	0.88	0	0.99	4.45	1.4	92.27	100
Area3	5.93	0.18	11.16	2.55	0.88	79.31	100
Area4	14.44	3.67	73.19	1.42	1.51	5.77	100
Area5	12.36	3.55	78.46	0	1.02	4.61	100
Area6	11.92	3.89	77.61	2.31	0.99	3.28	100

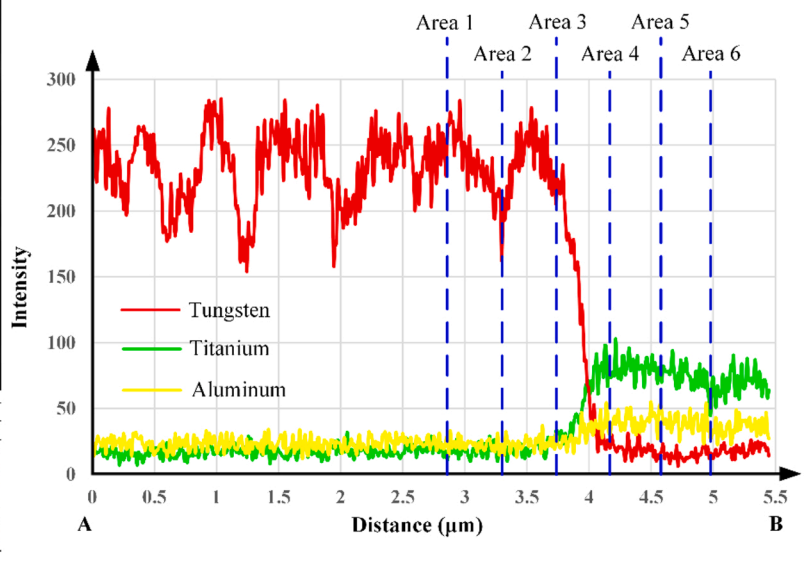


Fig. 16. Diffusion distance at cutting tool flank face under different cooling conditions, a) AD1, b) AF1 and c) AC1.

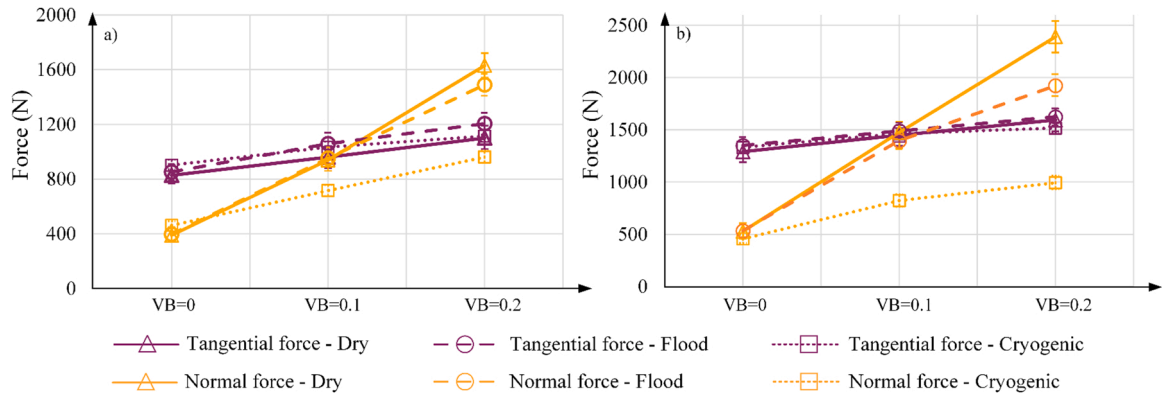


Fig. 17. Evolution of cutting forces under different cutting conditions, a) mild and b) aggressive.

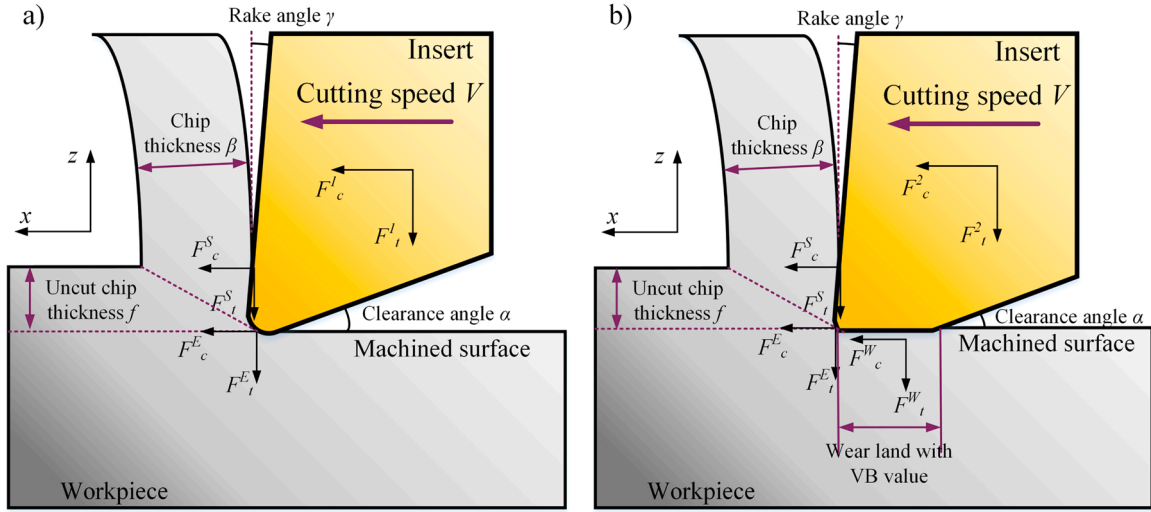


Fig. 18. Schematic of cutting forces decomposition [44] for a) fresh tool and b) worn tool.

causes a severe interaction between the cutting tool and work material, as shown in Fig. 17.

With the increase of VB value, the tangential force is slightly increased, while the thrust force is significantly changed with a much higher increasing rate regardless of cooling conditions, which can be even higher than tangential cutting force when VB reaches 0.2. Some previous study also showed a linear increase of cutting forces with respect to the increase of VB [41,42]. This phenomenon can be attributed to the normal pressure applied on the wearland as reported by Wang et al. [43]. It characterizes that additional forces are loaded when wearlands exist, while when cryogenic coolants are applied, interactions between flank face and work material can be well restricted as spring-back of the material is suppressed at low temperature, as presented in our previous study [25]. Moreover, Lin and Pan [44] presented a method to decompose cutting forces under this condition, which can also be used to explain this phenomenon in more details, as shown in Fig. 18.

And the relationship of cutting forces can be expressed as:

$$F_c^W = F_c^2 - F_c^l \quad (1)$$

$$F_t^W = F_t^2 - F_t^l \quad (2)$$

$$F_c^l = F_c^s + F_c^E \quad (3)$$

$$F_t^l = F_t^s + F_t^E \quad (4)$$

where F^l is the total force with fresh tool, F^2 the total force with worn tool, F_c denotes the tangential force and F_t the normal force, F^s presents the shear force applied on tool-chip interface, F^E the edge force applied on cutting edge and F^W the wear force applied on wearland.

From Fig. 17 and Fig. 18, cooling strategies have shown prominent contributions to the decrease of wear forces by limiting tool-work interaction at lower temperatures. It significantly decrease the value of F_t^W . The amplitude of the decrease is highly dependent on cooling performances, where cryogenic performs much better than other coolants, its decent cooling ability removes a large amount of heats in a very short time period, so a prominent decrease is obtained in terms of thrust forces in the wearland. As a result, according to Eq.(4), the values of final thrust forces are reduced as well. As the reductions of forces are more prominent under aggressive conditions, further analysis in the form of percentage is carried out compared to the results under dry conditions. When initial VB is 0.1 mm, the reductions of wear forces are 9% by flood condition and 61% by cryogenic condition, and the reductions of final thrust forces are 5.3% for flood and 44% for cryogenic, respectively. When initial VB is 0.2 mm, reductions of wear forces turn to be 25% for flood and 71% for cryogenic, while the reductions of final thrust forces are 19.5% for flood and 58.4% for cryogenic, respectively.

Moreover, under aggressive conditions, cutting forces fluctuation is easily activated due to the more severe interaction between cutting tool and work material compared to mild conditions, and implementation of cooling strategies also shows positive effects on it. As chatter is also easily excited by flank wear as reported in previous study [45], to avoid

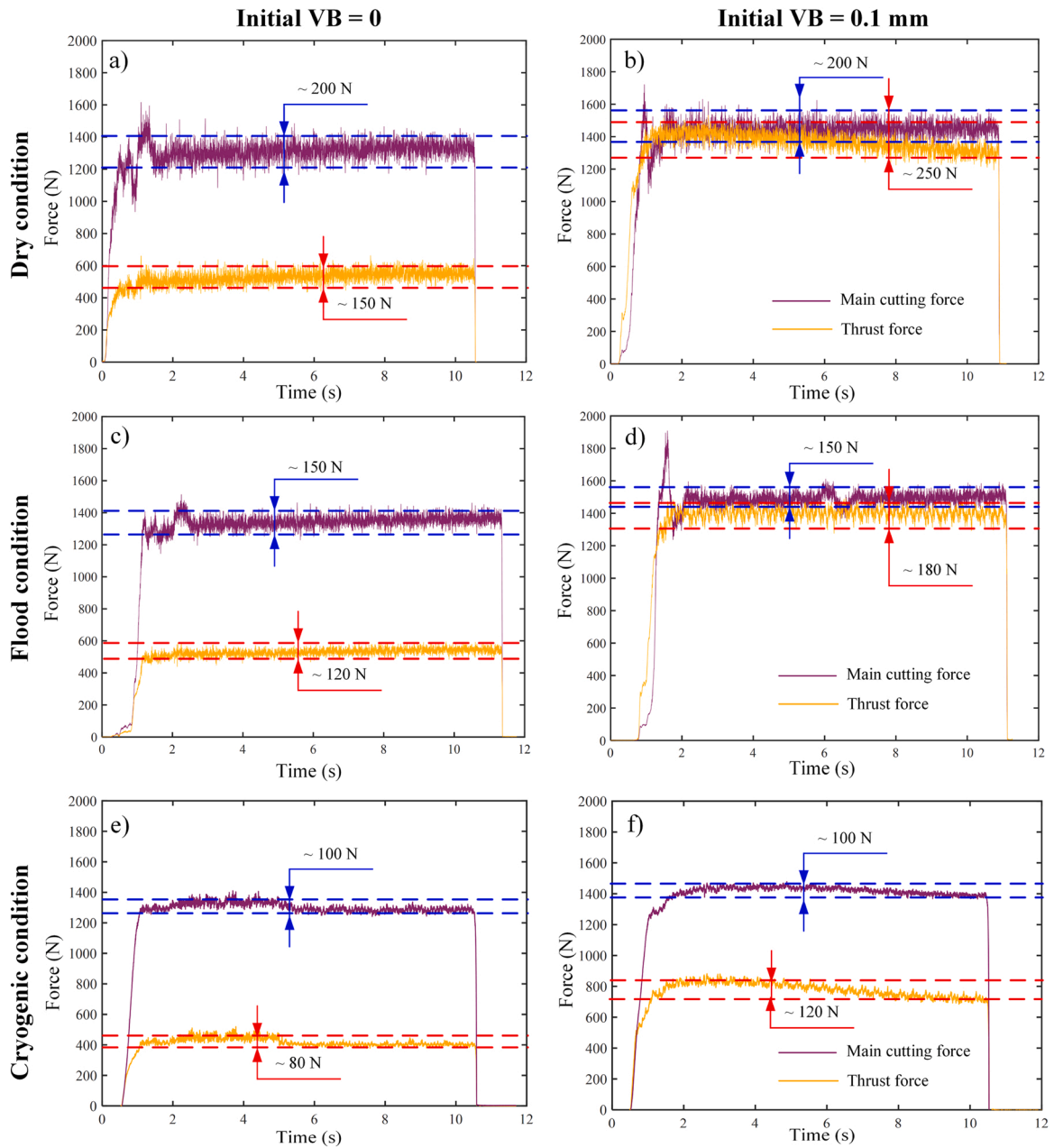


Fig. 19. Cutting forces evolution under different cutting conditions with aggressive parameters, a) AD0, b) AD1, c) AF0, d) AF1, e) AC0 and f) AC1.

its influences, cutting forces evolution with fresh tools and lower VB values are used for comparison, where the conditions are more stable, as shown in Fig. 19.

The results clearly show that supply of coolants has a significant influence on the suppression of cutting forces fluctuation. Fig. 19 a), c) and e) present a vertical comparison to characterize the impact of cooling strategies. For dry cutting condition shown in Fig. 19 a), the fluctuations of tangential force and normal force are about 200 N and 150 N, respectively, which are improved about 25% to 150 N and 120 N through flood cutting condition with the help of emulsion as shown in Fig. 19 c). Furthermore, when cryogenic cutting condition with LN₂ is applied, this improvement is enhanced about 50% to 100 N and 80 N for main cutting force and thrust force from Fig. 19 e), respectively. Moreover, the horizontal comparisons between Fig. 19 a) and b), c) and d), and e) and f) also present the influence induced by flank wear. For dry and flood cutting conditions, cutting forces fluctuation is increased with the increase of VB, while for cryogenic condition, almost nothing is

changed even if VB value exists. This phenomenon can be explained according to the results from Toubhans et al. [8]. They showed that higher cutting forces fluctuation can be activated with appearance of BUEs, while formation of BUEs is well restrained through application of LN₂ as shown in Fig. 11. As a result, the cutting forces remain stable with implementation of VB, while for dry and flood conditions, the fluctuation becomes more severe as materials are sticky to the cutting tools and BUEs form as a result. Therefore, cooling strategies, especially cryogenic cooling, have shown a perfect performance in restraining cutting forces fluctuation and improving cutting stability from both vertical and horizontal perspectives.

6. Discussions

In this study, evolutions of BUE formation, diffusion wear and cutting forces are investigated with respect to the impacts from different initial flank wear and cooling strategies. The results show that the

existence of initial flank wear significantly increases thermal issues during machining process, where BUEs can form rapidly. However, supply of cryogenic coolants reduce large amounts of heats produced by tool-chip interaction, where the formation of BUEs is perfectly controlled. Meanwhile, with higher thickness of BUEs and more titanium adhered on the rake face, higher cutting forces fluctuation is obtained with higher distance of diffusion, which can accelerate tool wear and may also induce poor surface quality.

Here we used a constant cutting time of 10 s for all the cases in order to obtain a thermomechanical stable condition. Normally, in terms of orthogonal cutting, the major concern is to investigate the mechanisms involved in cutting processes, so a relatively short cutting time is always applied. While the real cutting time is much longer in industries when referring to tool life, especially in terms of turning, milling, etc. Investigations concerning these aspects have been performed in some previous studies [22,26,41]. This study mainly aims at revealing the impacts coming from flank wear and different cooling strategies on BUEs formation, diffusion wear and cutting forces variation, also the inner mechanisms involved in pertinent processes. However, as cooling is a time-dependent process, it should be notified that some differences may be even highlighted with a longer cutting time when LN₂ is delivered, which can be considered from the following perspectives:

- 1) Tool wear in machining Ti6Al4V is significantly attributed to thermal issues, and fast dissipation of heat is introduced by delivery of LN₂, which can significantly slow down the evolution of tool wear;
- 2) Under the same wear condition, the excellent cooling performance provided by LN₂ prominently prevents the formation of BUEs, which retards the further evolution of progressive tool wear;
- 3) Diffusion is a thermally activated and time-dependent procedure, while its evolution can be restricted to some extent with the help of LN₂, which can be more profound with longer cutting time.

7. Conclusions

To summarize, the results show that initial flank wear can bring negative effects to the performances of tool wear and cutting conditions, while it can be well controlled and suppressed through good cooling strategies, especially with cryogenic assistance. The conclusions can be drawn as follows:

- The existence of initial flank wear enhances the interaction between flank face and work material, which induces severe friction and pertinent thermal effects, and increases the formation of BUEs and BULs.
- Limited improvement is obtained by supply of emulsion in terms of restraining BUEs formation with aggressive cutting parameters and initial flank wear, while it is significantly improved by supply of cryogenic coolant LN₂.
- Supply of cryogenic coolants is beneficial towards eliminating diffusion wear, where the diffusion distance within rake face is decreased from 0.32 μm to 0.17 μm at aggressive conditions within a certain cutting time of 10 s. Although the amount is tiny, it can slow down crater wear and elongate tool life.
- Thrust force is more sensitive to existence of initial flank wear than main cutting force, as it is comprised of edge force and wear force, and evolution of wear forces is closely related to the size of wearlands.
- Cutting forces fluctuation under aggressive conditions can be well controlled by applying proper cooling strategies, and cryogenic assistance shows a prominent improvement towards dry and flood conditions, where the improvement can be more than 50% towards dry condition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to acknowledge Institute Carnot ARTS for providing the complete fundings for this research. The authors would also like to acknowledge Dr. Bertrand Marcon from LaBoMaP for his kind assistance in preparation of experiments and Denis Lagadrillère for his kind help in SEM-EDS tests.

References

- [1] Rahman M, Wang Z-G, Wong Y-S. A review on high-speed machining of titanium alloys. *JSME Int J Ser C* 2006;49:11–20. <https://doi.org/10.1299/jsmec.49.11>.
- [2] Hartung PD, Kramer BM, von Turkovich BF. Tool wear in titanium machining. *CIRP Ann* 1982;31:75–80. [https://doi.org/10.1016/S0007-8506\(07\)63272-7](https://doi.org/10.1016/S0007-8506(07)63272-7).
- [3] Arrazola P-J, Garay A, Iriarte L-M, Armendia M, Marya S, Le Maître F. Machinability of titanium alloys (Ti6Al4V and Ti555.3). *J Mater Process Technol* 2009;209:2223–30. <https://doi.org/10.1016/j.jmatprotec.2008.06.020>.
- [4] Akhavan Niaki F, Mears L. A comprehensive study on the effects of tool wear on surface roughness, dimensional integrity and residual stress in turning IN718 hard-to-machine alloy. *J Manuf Process* 2017;30:268–80. <https://doi.org/10.1016/j.jmapro.2017.09.016>.
- [5] Agrawal C, Wadhwa J, Pitroda A, Pruncu CI, Sarikaya M, Khanna N. Comprehensive analysis of tool wear, tool life, surface roughness, costing and carbon emissions in turning Ti–6Al–4V titanium alloy: cryogenic versus wet machining. *Tribol Int* 2021;153:106597. <https://doi.org/10.1016/j.triboint.2020.106597>.
- [6] Jianxin D, Yousheng L, Wenlong S. Diffusion wear in dry cutting of Ti–6Al–4V with WC/Co carbide tools. *Wear* 2008;265:1776–83. <https://doi.org/10.1016/j.wear.2008.04.024>.
- [7] Bushlya V, Lenrick F, Ståhl J-E, Ma'Saoubi R. Influence of oxygen on the tool wear in machining. *CIRP Ann* 2018;67:79–82. <https://doi.org/10.1016/j.cirp.2018.03.011>.
- [8] Toubhans B, Fromentin G, Viprey F, Karaoui H, Dorlin T. Machinability of inconel 718 during turning: cutting force model considering tool wear, influence on surface integrity. *J Mater Process Technol* 2020;285:116809. <https://doi.org/10.1016/j.jmatprotec.2020.116809>.
- [9] Liang X, Liu Z. Experimental investigations on effects of tool flank wear on surface integrity during orthogonal dry cutting of Ti-6Al-4V. *Int J Adv Manuf Technol* 2017;93:1617–26. <https://doi.org/10.1007/s00170-017-0654-x>.
- [10] Lin ZC, Pan WC, Lo SP. A study of orthogonal cutting with tool flank wear and sticking behavior on the chip—tool interface. *J Mater Process Technol* 1995;52:524–38.
- [11] Karpat Y, Özel T. Predictive analytical and thermal modeling of orthogonal cutting process—part II: effect of tool flank wear on tool forces, stresses, and temperature distributions. *J Manuf Sci Eng* 2006;128:445–53. <https://doi.org/10.1115/1.2162591>.
- [12] Khanna N, Agrawal C, Dogra M, Pruncu CI. Evaluation of tool wear, energy consumption, and surface roughness during turning of inconel 718 using sustainable machining technique. *J Mater Res Technol* 2020;9:5794–804. <https://doi.org/10.1016/j.jmrt.2020.03.104>.
- [13] Al Sofyani S, Marinescu ID. Analytical modeling of the thermal aspects of metalworking fluids in the milling process. *Int J Adv Manuf Technol* 2017;92:3953–66. <https://doi.org/10.1007/s00170-017-0429-4>.
- [14] Faverjon P, Rech J, Valiorgue F, Orset M. Optimization of a drilling sequence under MQL to minimize the thermal distortion of a complex aluminum part. *Prod Eng Res Dev* 2015;9:505–15. <https://doi.org/10.1007/s11740-015-0614-y>.
- [15] Rech J, Arrazola PJ, Claudin C, Courbon C, Pusavec F, Kopac J. Characterisation of friction and heat partition coefficients at the tool-work material interface in cutting. *CIRP Ann* 2013;62:79–82. <https://doi.org/10.1016/j.cirp.2013.03.099>.
- [16] Yildiz Y, Nalbant M. A review of cryogenic cooling in machining processes. *Int J Mach Tools Manuf* 2008;48:947–64. <https://doi.org/10.1016/j.jmactools.2008.01.008>.
- [17] Jawahir IS, Attia H, Biermann D, Duflou J, Klocke F, Meyer D, et al. Cryogenic manufacturing processes. *CIRP Ann* 2016;65:713–36. <https://doi.org/10.1016/j.cirp.2016.06.007>.
- [18] Hong SY, Ding Y. Cooling approaches and cutting temperatures in cryogenic machining of Ti-6Al-4V. *Int J Mach Tools Manuf* 2001;41:1417–37. [https://doi.org/10.1016/S0890-6955\(01\)00026-8](https://doi.org/10.1016/S0890-6955(01)00026-8).
- [19] Lequien P, Poulachon G, Outeiro JC, Rech J. Hybrid experimental/modelling methodology for identifying the convective heat transfer coefficient in cryogenic assisted machining. *Appl Therm Eng* 2018;128:500–7. <https://doi.org/10.1016/j.applthermaleng.2017.09.054>.
- [20] Venugopal KA, Paul S, Chattopadhyay AB. Tool wear in cryogenic turning of Ti-6Al-4V alloy. *Cryogenics* 2007;47:12–8. <https://doi.org/10.1016/j.cryogenics.2006.08.011>.

- [21] Kaynak Y, Karaca HE, Noebe RD, Jawahir IS. Tool-wear analysis in cryogenic machining of NiTi shape memory alloys: a comparison of tool-wear performance with dry and MQL machining. *Wear* 2013;306:51–63. <https://doi.org/10.1016/j.wear.2013.05.011>.
- [22] Bermingham MJ, Palanisamy S, Kent D, Dargusch MS. A comparison of cryogenic and high pressure emulsion cooling technologies on tool life and chip morphology in Ti-6Al-4V cutting. *J Mater Process Technol* 2012;212:752–65. <https://doi.org/10.1016/j.jmatprotec.2011.10.027>.
- [23] Rotella G, Dillon OW, Umbrello D, Settineri L, Jawahir IS. The effects of cooling conditions on surface integrity in machining of Ti6Al4V alloy. *Int J Adv Manuf Technol* 2014;71:47–55. <https://doi.org/10.1007/s00170-013-5477-9>.
- [24] Merzouki J, Poulachon G, Rossi F, Ayed Y, Abrivard G. Effect of cryogenic assistance on hole shrinkage during Ti6Al4V drilling. *Int J Adv Manuf Technol* 2020;108:2675–86. <https://doi.org/10.1007/s00170-020-05381-z>.
- [25] Liu H, Birembaux H, Ayed Y, Rossi F, Poulachon G. A hybrid modelling approach for characterizing hole shrinkage mechanisms in drilling Ti6Al4V under dry and cryogenic conditions. *Int J Adv Manuf Technol* 2021. <https://doi.org/10.1007/s00170-021-08229-2>.
- [26] Ayed Y, Germain G, Melsio AP, Kowalewski P, Locufier D. Impact of supply conditions of liquid nitrogen on tool wear and surface integrity when machining the Ti-6Al-4V titanium alloy. *Int J Adv Manuf Technol* 2017;93:1199–206. <https://doi.org/10.1007/s00170-017-0604-7>.
- [27] Atlati S, Haddag B, Nouari M, Moufki A. Effect of the local friction and contact nature on the built-up edge formation process in machining ductile metals. *Tribol Int* 2015;90:217–27. <https://doi.org/10.1016/j.triboint.2015.04.024>.
- [28] Hamm I, Poulachon G, Rossi F, Biremaux H. Innovative experimental measurements of cutting temperature and thermal partition during Ti-6Al-4V orthogonal cutting. *Procedia CIRP* 2021;102:281–6. <https://doi.org/10.1016/j.procir.2021.09.048>.
- [29] Shah P, Khanna N, Chetan. Comprehensive machining analysis to establish cryogenic LN₂ and LCO₂ as sustainable cooling and lubrication techniques. *Tribol Int* 2020;148:106314. <https://doi.org/10.1016/j.triboint.2020.106314>.
- [30] Bordin A, Bruschi S, Ghiotti A, Bariani PF. Analysis of tool wear in cryogenic machining of additive manufactured Ti6Al4V alloy. *Wear* 2015;328–329:89–99. <https://doi.org/10.1016/j.wear.2015.01.030>.
- [31] Hong SY, Markus I, Jeong W. New cooling approach and tool life improvement in cryogenic machining of titanium alloy Ti-6Al-4V. *Int J Mach Tools Manuf* 2001;41:2245–60. [https://doi.org/10.1016/S0890-6955\(01\)00041-4](https://doi.org/10.1016/S0890-6955(01)00041-4).
- [32] Bejjani R, Salame C, Olsson M. An experimental and finite element approach for a better understanding of Ti-6Al-4V behavior when machining under cryogenic environment. *Materials* 2021;14:2796. <https://doi.org/10.3390/ma14112796>.
- [33] Bermingham MJ, Palanisamy S, Dargusch MS. Understanding the tool wear mechanism during thermally assisted machining Ti-6Al-4V. *Int J Mach Tools Manuf* 2012;62:76–87. <https://doi.org/10.1016/j.ijmactools.2012.07.001>.
- [34] Ramirez C, Idhil Ismail A, Gendarme C, Dehmas M, Aebly-Gautier E, Poulachon G, et al. Understanding the diffusion wear mechanisms of WC-10%Co carbide tools during dry machining of titanium alloys. *Wear* 2017;390–391:61–70. <https://doi.org/10.1016/j.wear.2017.07.003>.
- [35] Liang X, Liu Z. Tool wear behaviors and corresponding machined surface topography during high-speed machining of Ti-6Al-4V with fine grain tools. *Tribol Int* 2018;121:321–32. <https://doi.org/10.1016/j.triboint.2018.01.057>.
- [36] Marks S. . 2020. Extreme Tips & Tricks – Things to Remember During Extreme Operation - Nanoanalysis. Oxford Instruments 2020. (<https://nano.oxinst.com/library/blog/extreme-tips-and-tricks>).
- [37] JEOL Ltd. 2021. (<https://www.jeol.co.jp/en/>).
- [38] Hatt O, Crawforth P, Jackson M. On the mechanism of tool crater wear during titanium alloy machining. *Wear* 2017;374–375:15–20. <https://doi.org/10.1016/j.wear.2016.12.036>.
- [39] Hatt O, Lomas Z, Thomas M, Jackson M. The effect of titanium alloy chemistry on machining induced tool crater wear characteristics. *Wear* 2018;408–409:200–7. <https://doi.org/10.1016/j.wear.2018.05.020>.
- [40] Graves A, Norgren S, Wan W, Singh S, Kritikos M, Xiao C, et al. On the mechanism of crater wear in a high strength metastable β titanium alloy. *Wear* 2021;484–485:203998. <https://doi.org/10.1016/j.wear.2021.203998>.
- [41] Ayed Y, Germain G. High-pressure water-jet-assisted machining of Ti555-3 titanium alloy: investigation of tool wear mechanisms. *Int J Adv Manuf Technol* 2018;96:845–56. <https://doi.org/10.1007/s00170-018-1661-2>.
- [42] Ayed Y. . 2013. Approches expérimentales et numériques de l'usinage assisté jet d'eau haute pression: étude des mécanismes d'usure et contribution à la modélisation multi-physiques de la coupe. Ecole nationale supérieure d'arts et métiers-ENSAM, 2013.
- [43] Wang J, Huang CZ, Song WG. The effect of tool flank wear on the orthogonal cutting process and its practical implications. *J Mater Process Technol* 2003;142:338–46. [https://doi.org/10.1016/S0924-0136\(03\)00604-6](https://doi.org/10.1016/S0924-0136(03)00604-6).
- [44] Lin Z-C, Pan W-C. A thermoelastic-plastic large deformation model for orthogonal cutting with tool flank wear—part I: computational procedures. *Int J Mech Sci* 1993;35:829–40. [https://doi.org/10.1016/0020-7403\(93\)90042-S](https://doi.org/10.1016/0020-7403(93)90042-S).
- [45] Chiou RY, Liang SY. Chatter stability of a slender cutting tool in turning with tool wear effect. *Int J Mach Tools Manuf* 1998;38:315–27. [https://doi.org/10.1016/S0890-6955\(97\)00079-5](https://doi.org/10.1016/S0890-6955(97)00079-5).