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Tool wear characteristics in rough turning of Inconel 718 with coated carbide tool under conventional and high-pressure coolant supplies

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Abstract
The machining of nickel-based superalloys is often challenging due to their excellent physical properties. High-temperature gradients are generated at the cutting zone, which accelerates the tool wear and impairs its performance. However, introducing high-pressure coolant (HPC) lubrication has been shown to improve both the tool life and surface integrity. In this investigation, attention has been mainly focused on the tool wear characteristics in the rough turning of Inconel 718. The longitudinal turning experiments have been conducted under conventional and HPC lubrication with two cutting speeds. Coated carbide inserts have been analyzed using several techniques including scanning electron microscopy, energy-dispersive X-ray spectroscopy, and 3D scanning. The experimental procedure has embraced the tool life, the tool wear, the generated forces, and the wear mechanisms. The examination of the worn tool surfaces demonstrates that although the depth of cut notching is more pronounced, it is possible to reduce the flank wear by using HPC lubrication. The results also highlight a marginal reduction in cutting and axial forces, a good chip fragmentation, and a significant improvement of the tool life. Furthermore, the investigations show that the wear mechanisms are strongly influenced using HPC under the various investigated cases.

Keywords Inconel 718 · Coated carbide tools · High-pressure coolant · Rough turning · Tool wear mechanisms

1 Introduction

When machining nickel-based alloys such as the well-established Inconel 718, the cutting edge is subjected to extreme thermomechanical loads. This generally leads to both the thermal softening of the tool material and the weakening of its hardness and bond strength [1]. In addition, thermally driven wear mechanisms such as diffusion or plastic deformation can be promoted, which in turn accelerates the tool failure and impairs the surface integrity of the final product [2]. Despite the considerable improvement and the recent advances in the field of cutting tool materials and coatings, it is still necessary to look for alternative solutions to upgrade the conventional process.

In this context, multiple emerging technologies with a great capability of improving the overall efficiency of the process have been developed. Among these technologies, high-pressure coolant (HPC) lubrication appears as a promising method to improve both the workpiece surface integrity and the tool performance. This technique has been found to be effective in cutting tool lubrication, controlling the temperature fields of the cutting tool and the workpiece, enhancing the chip fragmentation, and therefore reducing the tool wear [2, 3].

Although machining Inconel 718 under HPC lubrication has been immensely studied, the majority of experimental investigation have mainly been focused on the process development, while little attention has been paid to understand the relevant tool wear mechanisms [4]. The effect of HPC lubrication in turning Inconel 718 with coated carbide tools was

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reported by Ezugwu et al. [5, 6]. A tool life improvement by up to 350% and 740% was achieved for finish and rough conditions, respectively. The dominant observed tool failure mode was the nose wear. The experiments conducted by Colak et al. [7] indicated a clear tendency toward reducing the crater wear when turning the Inconel 718 nickel-based alloy under HPC lubrication. The authors suggested that abrasive and diffusion wear mechanisms might be the explanation for the crater wear formation under the investigated cooling pressure. Conflicting results were reported by Sharman et al. [8] where the HPC lubrication supply is found to provide no significant improvements regarding the tool life in the finish turning of Inconel 718. The authors reported that administering HPC on the tool rake face cannot prevent tool wear by attrition and the formation of built-up edge (BUE).

The present work aims to gain more fundamental understanding of the wear characteristics under the influence of HPC during the rough turning of Inconel 718. The pressurized coolant was applied directly at the rake face of the coated carbide tool. The tool wear and the relevant wear mechanisms were investigated using different analyses, including scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and 3D scanning.

2 Experimental setup

Cutting tests were performed on a LEADWELL LTC25iL lathe, equipped with a 30-KW Hammelmann high-pressure fluid delivery system. The fluid is filtered with a Hammelmann 1-60985 10-μm filtration system before entering the internal reservoir and also prior to entering the high-pressure pump. A round bar of Inconel 718 having 141-mm diameter and 360-mm length with an average hardness of 49.7 ± 1.3 HRC was used for the machining tests. The microhardness measurements were performed along 6.5-mm depth below the machined surface under a linear sequence. The as-received workpiece material has undergone a precipitation hardening heat treatment in order to precipitate the different phases and give optimum mechanical properties. The microstructure of the workpiece material consists of a 62-μm average grain size with clusters of carbide particles distributed randomly in blocky or script morphologies within the grains and along the grain boundaries, as shown in Fig. 1. Grain size and hardness analyses of Inconel 718 were carried out on samples taken close to the outer surface of the bar by using wire electrical discharge machining as illustrated in Fig. 2.

The cutting tool used for longitudinal turning experiments (axial direction) is a TiAlN/TiN–coated carbide insert SECO TS2500 grade. The CNMG 1204-08 M1 insert was mounted on a SECO PCLNR 2525M12 Jet-Stream tool holder, as depicted in Fig. 2. The turning experiments were conducted with two different cutting speeds (35 and 45 m/min) under conventional and HPC lubrication, while the feed rate and the depth of cut were kept constant and equal to f=0.1 mm/rev and a_p=1.5 mm, respectively. Each experiment was performed only once with multiple cutting passes. A fresh cutting edge was used for each experiment, and all data were collected during the cut. Two cooling strategies were investigated in this study. Under conventional lubrication, the cutting experiments were carried out by flooding the cutting tool and the workpiece. The coated carbide insert was fixed in the same tool holder. It is worth mentioning that the Jet-Stream was disassembled and the fluid has been applied through an external pipe, as illustrated in Fig. 2. The HPC was applied from an external two-nozzle adaptor having a 1.7-mm diameter at a pressure of 100 bar with an average flood rate of 15 l/min. The pressurized coolant was injected directly toward the gap between the tool rake face and the chip backside. Under both cooling strategies, an emulsion-based cutting fluid (5% concentration) was used. Table 1 summarizes the geometrical characteristics of the tool and the cutting conditions used in this research.

A piezoelectric dynamometer (Kistler 9129AA) was used to measure the cutting, feed, and radial forces. The tool wear evolution (average flank wear (VB) and average notch wear (VB_N)) were followed and observed every 30 s or 60 s using a binocular microscope. The measurements were repeated twice with two persons for each run, and the average value is considered for further analysis. The tests would be stopped once the average flank wear criterion, set to 0.3 mm, was reached. At the end of the tool wear tests, the carbide insert was examined using SEM for refined analyses. Furthermore, for a better understanding of the wear patterns encountered under the investigated cutting conditions, the analyses of material deposits at the tool rake face were carried out using the EDS technique. Finally, the surface topography of the tool rake face was scanned using a 3D profilometer.

3 Analysis and discussion

3.1 Tool wear tests at V_c= 35 m/min

In this section, the evolution of the tool wear from a new cutting edge to final wear stages is observed to characterize the wear mechanisms. Figure 3a illustrates the evolution of the flank wear versus machining time. Three wear stages can be observed. After a running phase, the curves show a stable evolution. A rapid brutal slope variation is then remarked when machining with conventional lubrication. These three stages of tool wear are generally observed when machining Inconel 718 [9, 10] . The tool flank wear progresses very quickly up to the rejection criteria within 9.5 min. On the other hand, although longer tool engagement is achieved under

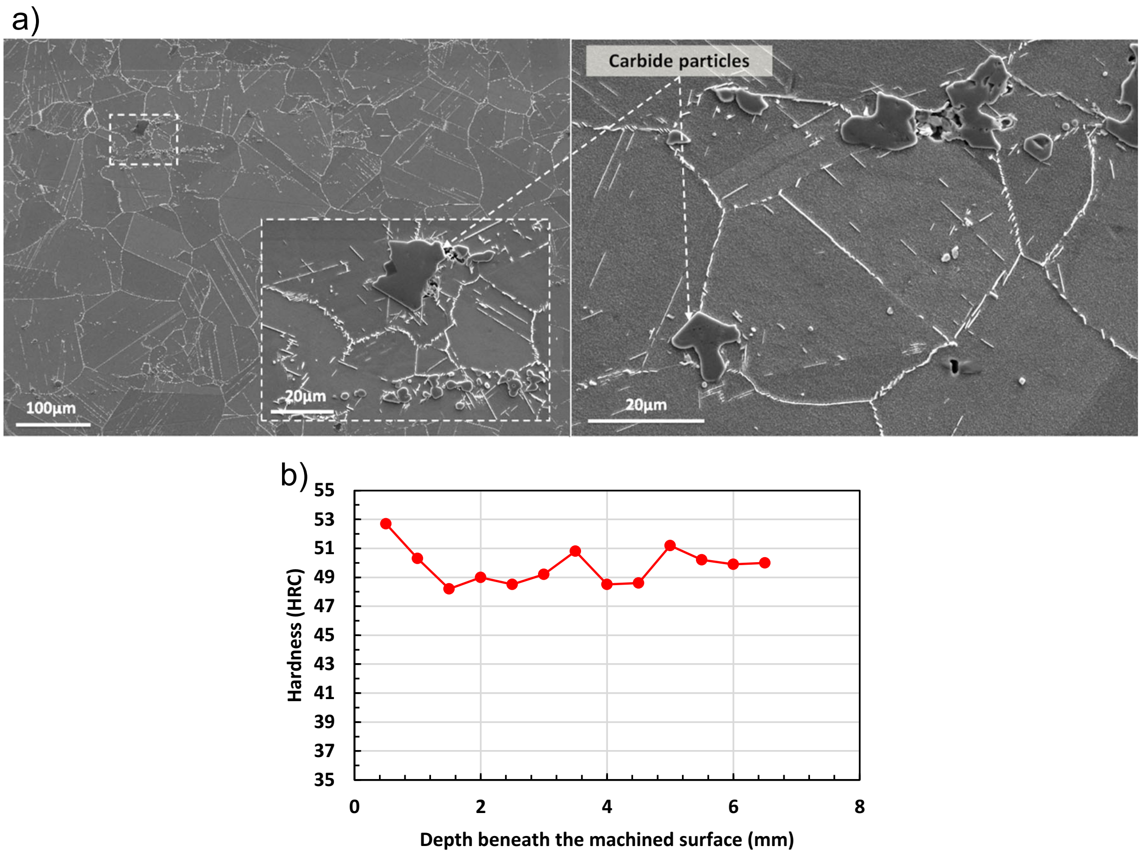


Fig. 1 **a** Microstructure of Inconel 718 workpiece used in this study. **b** Microhardness measurements

HPC lubrication, the flank wear rate rises steadily to reach 0.26 mm within 20 min of machining time.

Figure 3b depicts the steady growth of the notch wear rate under conventional and HPC lubrication. A higher value of notch wear is recorded for HPC lubrication. Similar results were reported by Klocke et al. [11] and Ezugwu et al. [12] who found that the notch wear developed under HPC lubrication was more pronounced when compared to conventional lubrication.

Notching at the depth of cut is a combined wear type that occurs in a random and unpredictable manner on both the relief and the rake face of the cutting tool. This type of wear is common when machining nickel-based alloys. With the progress of machining time, the notch wear joins the crater region, which can undermine the entire tool tip, making it very fragile and prone to catastrophic failure under the increase in the concentrated stress [5].

Figure 4a illustrates the evolution of the average value of cutting and the axial force (F_c, F_a) versus machining time. Under conventional lubrication, an exponential evolution of both force components can be observed. A similar evolution can be noticed in Fig. 3, where the tool flank face is found to evolve exponentially against machining time under the same coolant pressure. The application of HPC lubrication lowers the main forces relatively to the conventional lubrication. A clear tendency concerning the evolution of cutting and axial forces can be observed at the end of the machining test. In fact, it can be clearly seen that the cutting and the axial forces both present a lower, more stable, and smoother increasing trend under HPC lubrication than those under conventional lubrication. This could be related to the different wear rates recorded during machining with and without HPC lubrication.

To evaluate the effect of the coolant on the generated forces independent of the tool wear, the evolution of the average value of F_c and F_a versus flank wear is analyzed, as shown in Fig. 4b. An almost linear relationship between the two force components and the flank wear can be observed in both lubrication strategies. Interestingly, the cutting force F_c may not be modified by the HPC lubrication when compared to conventional lubrication. On the contrary, the difference between the measured axial forces under both cooling strategies is significant. Under the same flank wear, the HPC lubrication results in a substantial reduction in the axial force by nearly 62 N at VB= 0.09 mm and 220 N at VB= 0.24 mm. This suggests that F_a is more sensitive to the coolant pressure than F_c.

It is also well established that the application of HPC improves chip breakability. Indeed, long continuous spiral chips are formed with conventional lubrication, while smaller fragmented chips are produced under HPC lubrication, as illustrated in Fig. 5. This will result in a reduction in the tool-

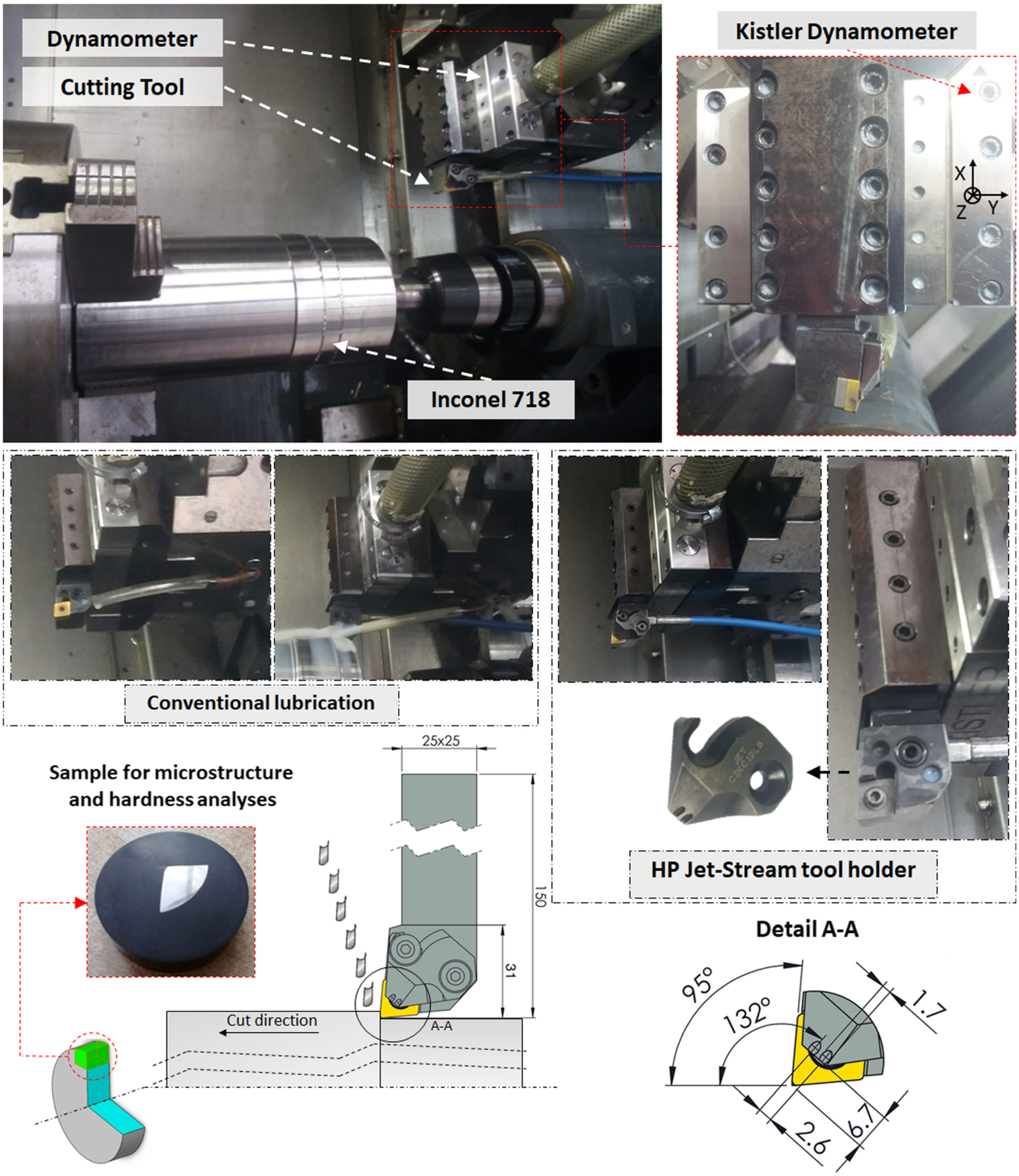


Fig. 2 Experimental setup [9]

Table 1 Lubrication and cutting conditions

Tool geometrical parameters	Cutting edge angle $\boldsymbol{k}_{\mathbf{r}}$ (deg)	95
	Nose radius r_ε (mm)	0.8
	Rake angle γ (°)	+6
	Clearance angle α (°)	+6
Cutting parameters	Cutting speed V_c (m/min)	35; 45
	Feed rate f (mm/rev)	0.1
	Depth of cut a_p (mm)	1.5
Lubrication	Cooling strategy	Conventional, HPC (100 bar)
	Fluid	An emulsion-based cutting fluid (5% concentration)

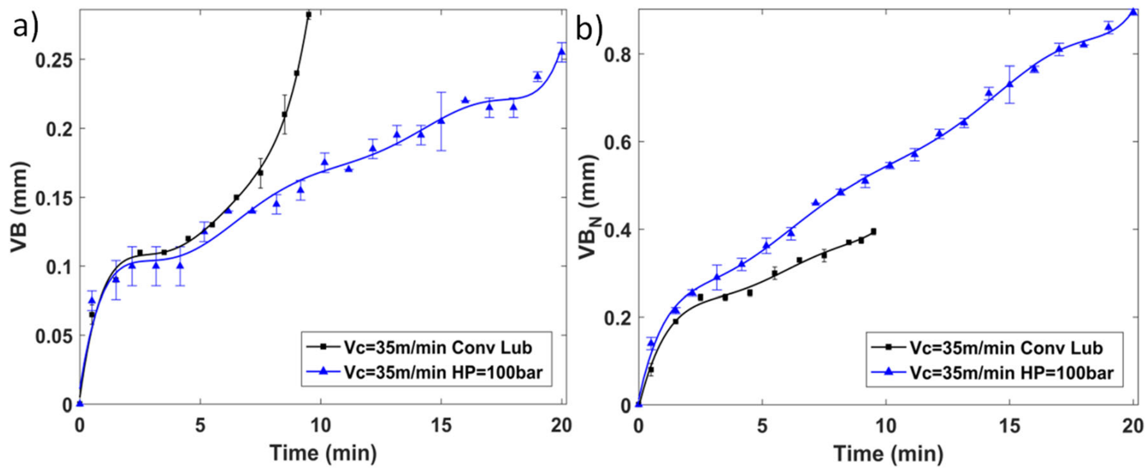


Fig. 3 Evolution of tool wear at cutting speed of 35m/min: **a** flank wear, **b** notch wear

chip interface, offering adequate cooling and lubrication, thus preventing the tool from excessive heating [6].

Figure 6 and Fig. 7 represent the SEM micrographs of the tool flank and rake faces at the end of the machining test conducted under conventional and HPC lubrication, respectively. The adhesion of the work material on both tool faces is visible. The flank wear region developed under conventional lubrication is unevenly distributed. However, under HPC lubrication, an even and almost indistinctive distribution is observed.

The least flank wear is observed under HPC lubrication, mainly due to the increase in the convective heat transfer coefficient. As highlighted in the investigation carried out by Ezagwu et al. [6], the high induced temperature in the tool interfaces is the major cause of tool wear acceleration. By administering the cutting fluid under high pressure into the wedge between the tool and the chip, the lubricant can penetrate deeper and get closer access to the tool tip. The cooling phenomenon at the tool flank face is also further improved.

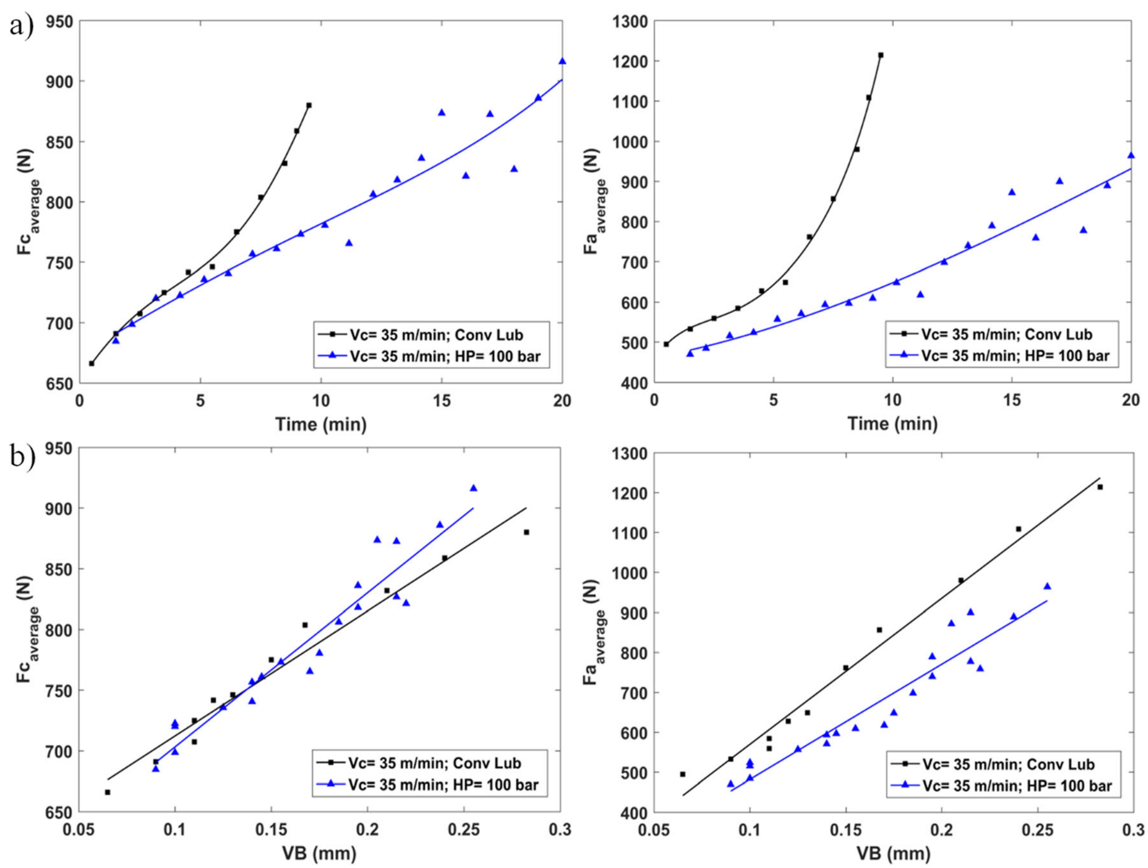
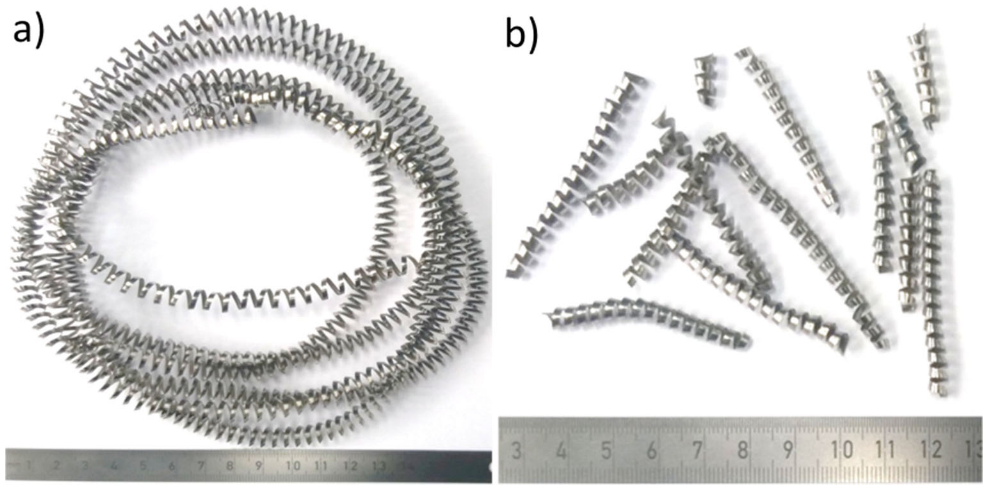


Fig. 4 Evolution of forces when machining at cutting speed of 35 m/min as a function of **a** machining time and **b** flank wear

Fig. 5 Chip morphologies at cutting speed of 35 m/min at end of machining test under **a** conventional lubrication and **b** HPC lubrication



Thus, the tool thermal loads are kept to a minimum, and thermally related wear mechanisms, including oxidation, diffusion, and chemical reaction, can be reduced. The carbide insert can perform within a secure temperature condition.

The occurrence of abrasion on the tool flank face can be also seen and can be attributed to the scrubbing action of the hard particles and impurities contained in the workpiece material matrix against the surface cutting tool [13]. Note that these scratches, along the direction of movement of the workpiece, are not developed in the entire flank face, probably because the BULs are continually formed and stacked up on the tool flank face creating a protecting layer. Thus, the scrubbing action of the hard inclusion and the carbide particles contained in the workpiece material matrix may be less pronounced. As mentioned in Zhu et al. [14], the scratches become clearer as the frequency of peeled off adherent layers becomes lower.

It can be noticed that besides flank wear, notching at the DOC line is significantly distinguished especially under HPC lubrication, Fig. 7(a). Under both experiments, the notch wear is predominantly extended across the flank face. In Fig. 7(b), the tool notch wear is provided at higher magnification. A close examination of the notch region reveals the presence of the work material. This indicates that adhesion plays a part in the wear mechanism. According to AbdulHadi et al. [15] and Xue et al. [16], adhesion between the tool and the chip would also cause notching. Indeed, since the adhering layer is never completely stable but periodically splits off from the contact zone by the chip flow, it takes small fragments from the tool material. In addition, since the notch region is directly exposed to the pressurized coolant, the adhering layer is forcefully plucked away by the pressurized water jet. A combination of the layer instability and the acceleration of the adhesive wear mechanism under the mechanical effect of the HPC can explain the formation of the distinguished notch wear.

As reviewed by Ezugwu et al. [17] and Akhtar et al. [18], different investigations were carried out to explain the mechanism behind notch formation, and a number of explanations were proposed including abrasion, work-hardened layer, and attrition wear. However, no consensus of opinion exists as to the cause of notching at the DOC line when machining nickel-based alloys, and it was often associated to a combination of many factors rather than a single wear mechanism.

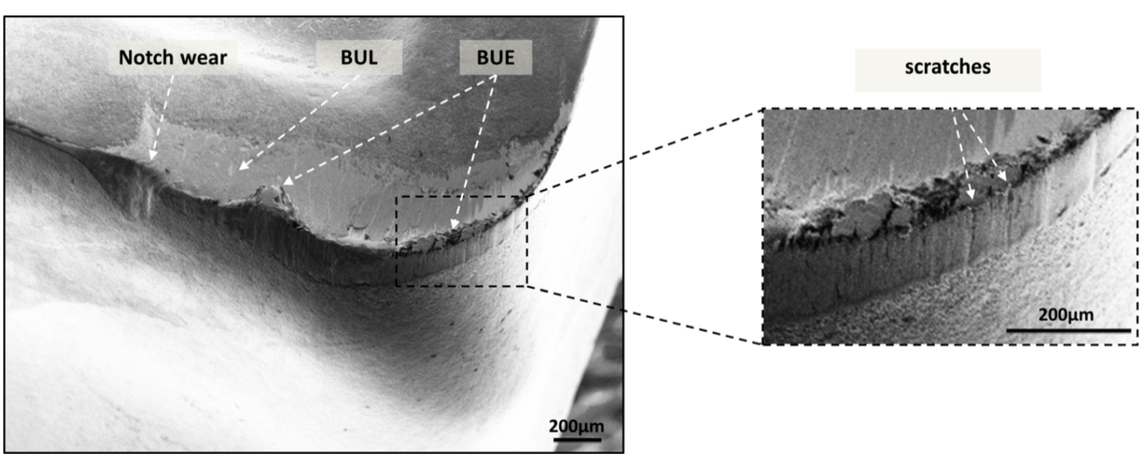


Fig. 6 SEM image of tool rake/flank faces at end of machining test at cutting speed of 35 m/min under conventional lubrication

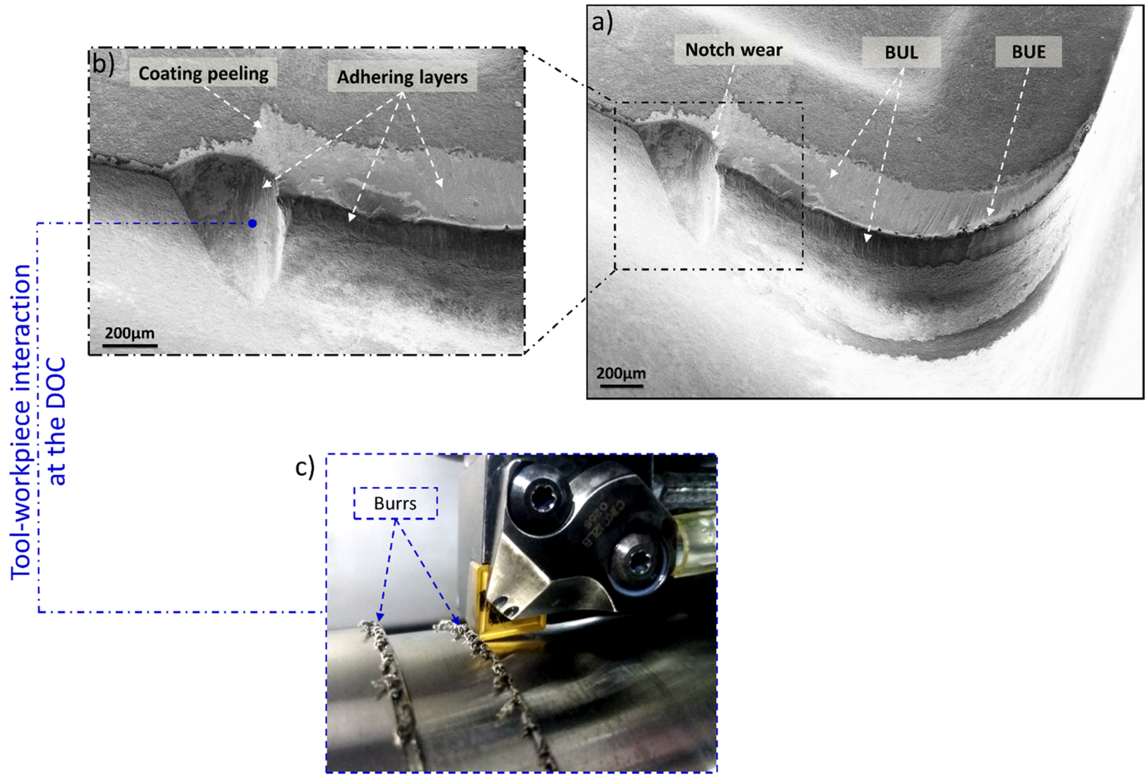


Fig. 7 (a) SEM image of tool rake/flank faces at end of machining test at cutting speed of 35 m/min under HPC lubrication, (b) enlarged view of notch wear region, and (c) formation of burrs on workpiece at end of machining test.

It is also worth pointing that the grain size variation along the workpiece bar radius can significantly affect notching at the DOC when machining the Ni alloy. This statement is in line with the experimental observation reported by Polvorosa et al. [19] when face turning Waspaloy with uncoated cemented carbide inserts and by Olovsjö et al. [20] when face turning wrought Alloy 718 with cemented carbide tools. However, the microstructure and hardness analyses conducted in this investigation reveal no significant grain size and hardness variation along the part of the workpiece bar for which the longitudinal turning tests were performed (close to the outer surface of the bar). Indeed, all cutting tests were performed with a similar outer diameter of the workpiece. Only a 9-mm reduction in the workpiece radius was observed at the end of the tests. Since the hardness keeps an almost near value and no microstructure gradient is observed within the part of the workpiece bar the tests were conducted, any potential influence connected to the grain size and hardness variation on the notch wear is expected to be neglected.

Furthermore, in the experimental tests reported in this investigation, it is noticed that the notch wear can be associated with the burr formation. As it can be seen in Fig. 7(c), long burrs tend to form at the front edges of the workpiece perimeter. At the highest formed burrs, significant notch wear is developed. This statement is supported by Olovsjö et al. [20], where the burr formation due to the strong lateral plastic flow of the material takes place where the notch wear is developed.

To examine the material deposit in the worn surfaces of the tool, the inserts are analyzed using the EDS. A typical series of micrographs, revealing details of the adhering layers on the tool rake face, are shown in Fig. 8 and Fig. 9.

As it can be seen in Fig. 8, the occurrence of a BUE at the cutting edge can be observed under conventional lubrication. The formation of the BUE at the tool edge is pronounced near the DOC region. Furthermore, the crater region is covered by nickel elements, indicating adhesion. At the end of the tool-chip contact zone, the amount of the deposit material is reduced because of the chip separation from the tool rake face. Additionally, coating begins to be plucked off from the crater region, probably due to the adhesion mechanism [21].

With the application of HPC lubrication, the EDS examination, depicted in Fig. 9b, shows a different pattern. Owing to the change in the coolant pressure, the amount of adhered material varies. The BUE around the cutting edge is less pronounced. The adhered material further restricts to the crater valley. It is also possible to observe the reduction in the maximum tool-chip contact length from 0.476 mm under conventional lubrication to 0.369 mm under HPC lubrication. Moreover, a smaller coating delamination and coating peeling in the crater region can be observed. At the DOC, the amount of flaked coating is more pronounced revealing the carbide element beneath the coating layer.

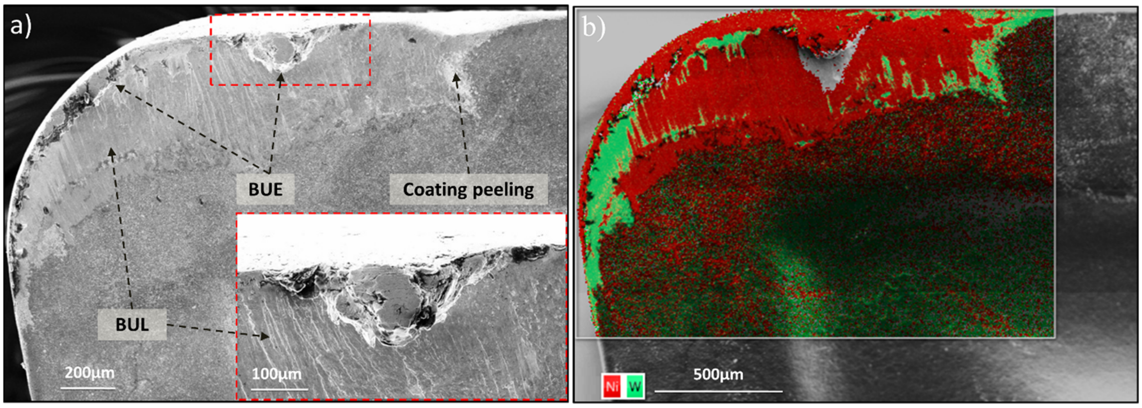


Fig. 8 Tool wear at end of machining test at cutting speed of 35m/min under conventional lubrication: **a** SEM micrographs, **b** EDS analysis

On the other hand, Fig. 10 reveals subsequent adherence at the cutting edge. Actually, the BUE formed under conventional lubrication is removed smoothly, while under HPC lubrication the BUE is removed with a small material fragment from the tool cutting edge. Note that these small breakages do not progress up to the collapse of the cutting edge, so it partially affects the carbide insert integrity. The examination of the tool rake and flank faces reveals that this cyclic process of adhesion and removal of the BUE at the cutting edge holds constant throughout the test. This can be referred to by BUE instability.

Cantero et al. [22] mentioned that tool chipping could be promoted by the BUE formation. Xavior et al. [23] also observed that the BUE at the tool cutting edge generally would result in tool chipping. In addition, the tool chipping can be also caused by an accelerated adhesive wear mechanism, especially under HPC lubrication. In fact, the mechanical effect of the high-pressure water jet tends to curl the chip to a greater extent and consequently reduces the tool-chip contact length and promotes chip breakability. As a result, the coolant gets more access to the tool tip and the BUE is directly exposed to the pressurized water jet. The deposit materials at the tool cutting edge are forcibly removed by the water jet leading to a tool chipping.

On the basis of this experimental result, it can be stated that, in the context of turning a nickel-based alloy under HPC lubrication, tool chipping can be caused by a combination of adhesion instability (BUE instability) and acceleration of the adhesion mechanism under the action of the high-pressure water jet.

3.2 Tool wear tests at V_c= 45 m/min

In order to have a better understanding of the cutting speed effect on tool wear mechanisms, similar tests have been performed at a cutting speed of 45 m/min. Figure 11a shows the evolution of the tool flank wear under both cooling conditions. The flank wear curves have a minor difference during the initial 2 min. As cutting proceeds, the flank wear gradually increases under HPC lubrication to 0.275 mm after 6.2 min of machining time, while a sharp rise can be observed under conventional lubrication. The tool gets quickly worn in less than 3.5 min.

An improvement in the tool life up to 76% is achieved owing to the use of HPC lubrication at a cutting speed of 45 m/min. Analyzing the results illustrated in Fig. 3a and Fig. 11a, it can be seen that the highest gain in the tool life is attained when machining at a cutting speed of 35 m/min under HPC

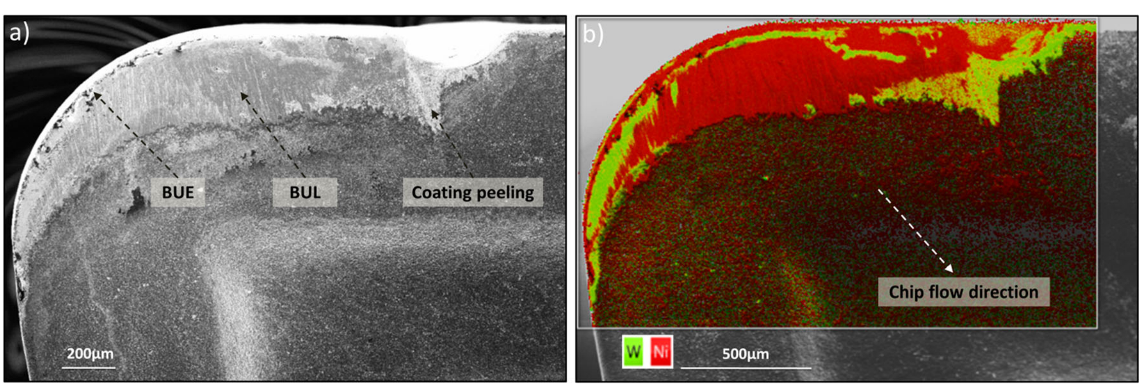


Fig. 9 Tool wear at end of machining test at cutting speed of 35m/min under HPC lubrication: **a** SEM micrograph, b EDS analysis

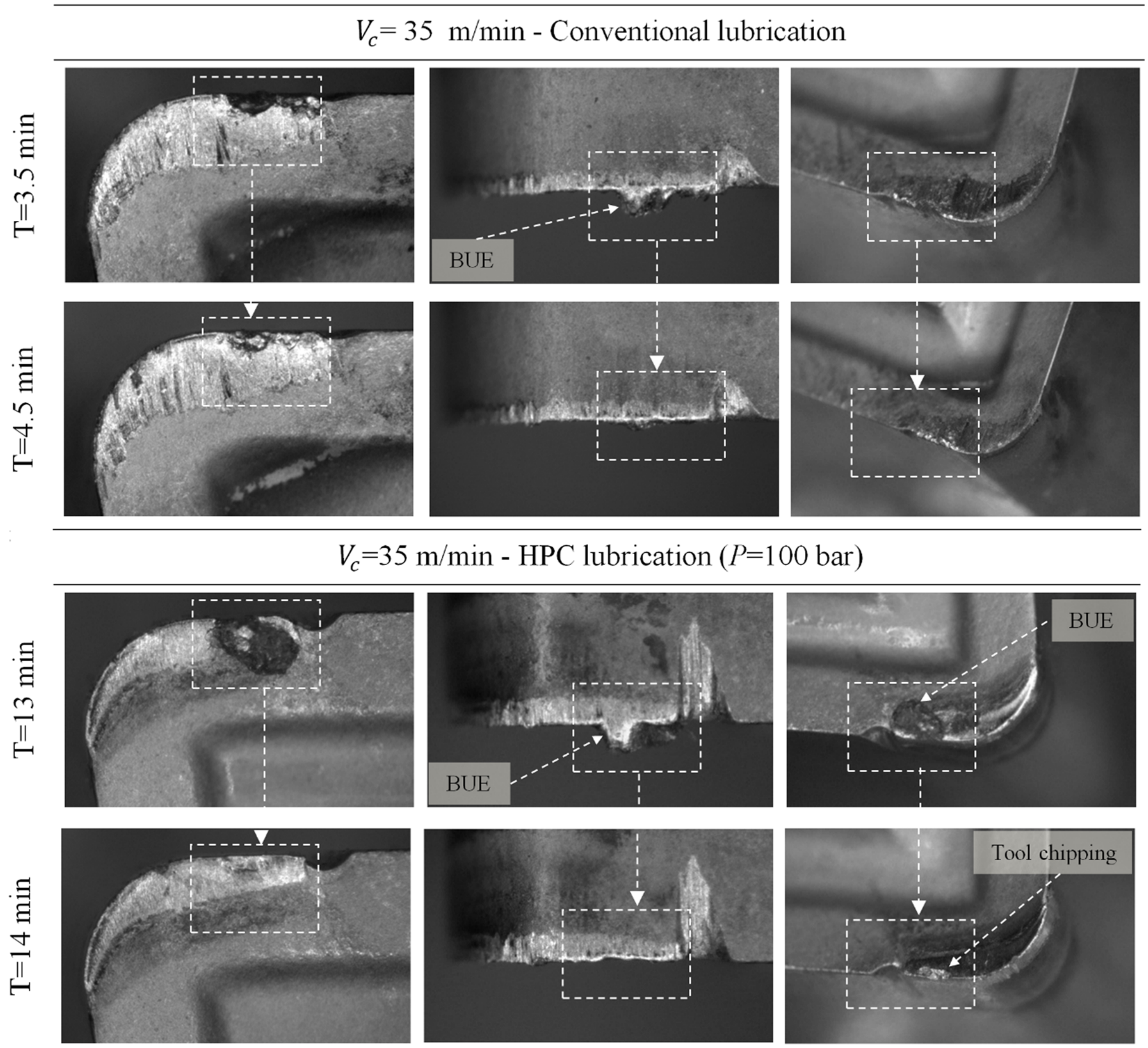


Fig. 10 Subsequent adherence of BUE at tool cutting edge

lubrication, where a 110% improvement in the tool life is recorded. Despite using the HPC lubrication, the tool life decreases with the increase in the cutting speed. Probably because a higher speed enhances heat generation, higher

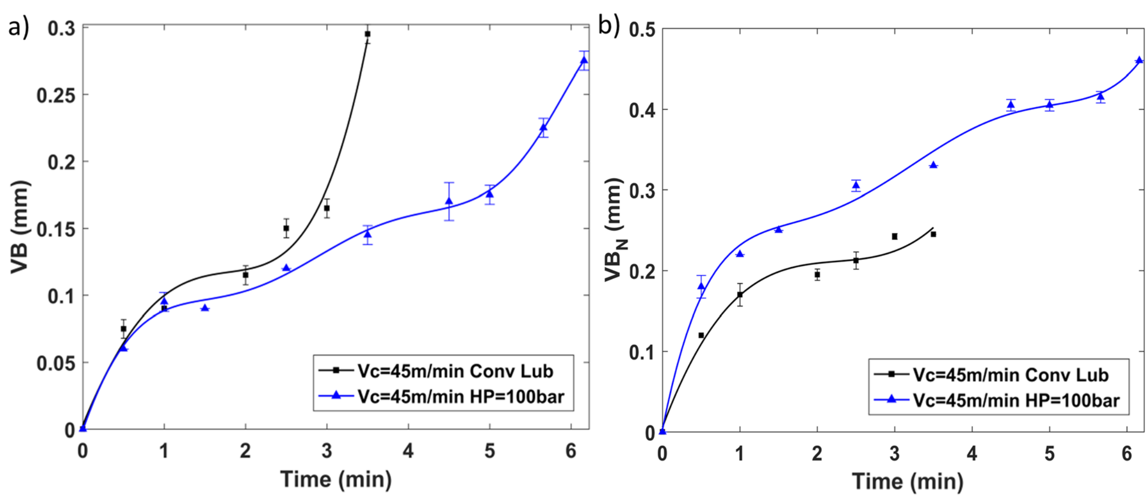


Fig. 11 Evolution of tool wear at cutting speed of 45 m/min: **a** flank wear, **b** notch wear

temperature levels at the contact zone are induced, hence accelerating the tool wear rate and reducing the tool life [24].

The comparison of the tool notch wear curves versus machining time under conventional and HPC lubrication is given in Fig. 11b. After a running phase, the curves show a steady gradual growth regardless of the cooling pressure. Pronounced notching occurs while machining with HPC lubrication. In fact, the notch wear reaches 0.33 mm only after 3.5 min face to 0.245 mm under conventional lubrication during the same time. Similar to the machining test performed at a cutting speed of 35 m/min, the application of HPC lubrication is not effective in reducing the notch wear.

Figure 12a represents the evolution of the forces over machining time. Under HPC lubrication, the force grows approximately linearly until the end of cutting test. On the contrary, after 2 min of machining time, both cutting and axial forces generated under conventional lubrication go up exponentially. This trend corresponds well with the increase in the tool flank wear. The application of HPC lubrication always provides lower force values. Figure 12b shows the evolution of the average value of cutting and axial forces over the flank wear. Similar to V_c= 35 m/min, it can be observed that the cutting force is less sensitive to the coolant pressure than the axial force.

It is also worth pointing out that the growth of the tool wear during machining has a significant effect on the chip morphology. This can be observed in Fig. 13, where the collected chips at the beginning and the end of the machining test conducted under HPC lubrication are presented. The obtained chips after the first pass are short and have nearly the similar size and shape. After 6 min of machining time, longer chips are produced with different sizes.

Tools are progressively worn with the progress of machining time, which leads to a gradual modification of the tool rake

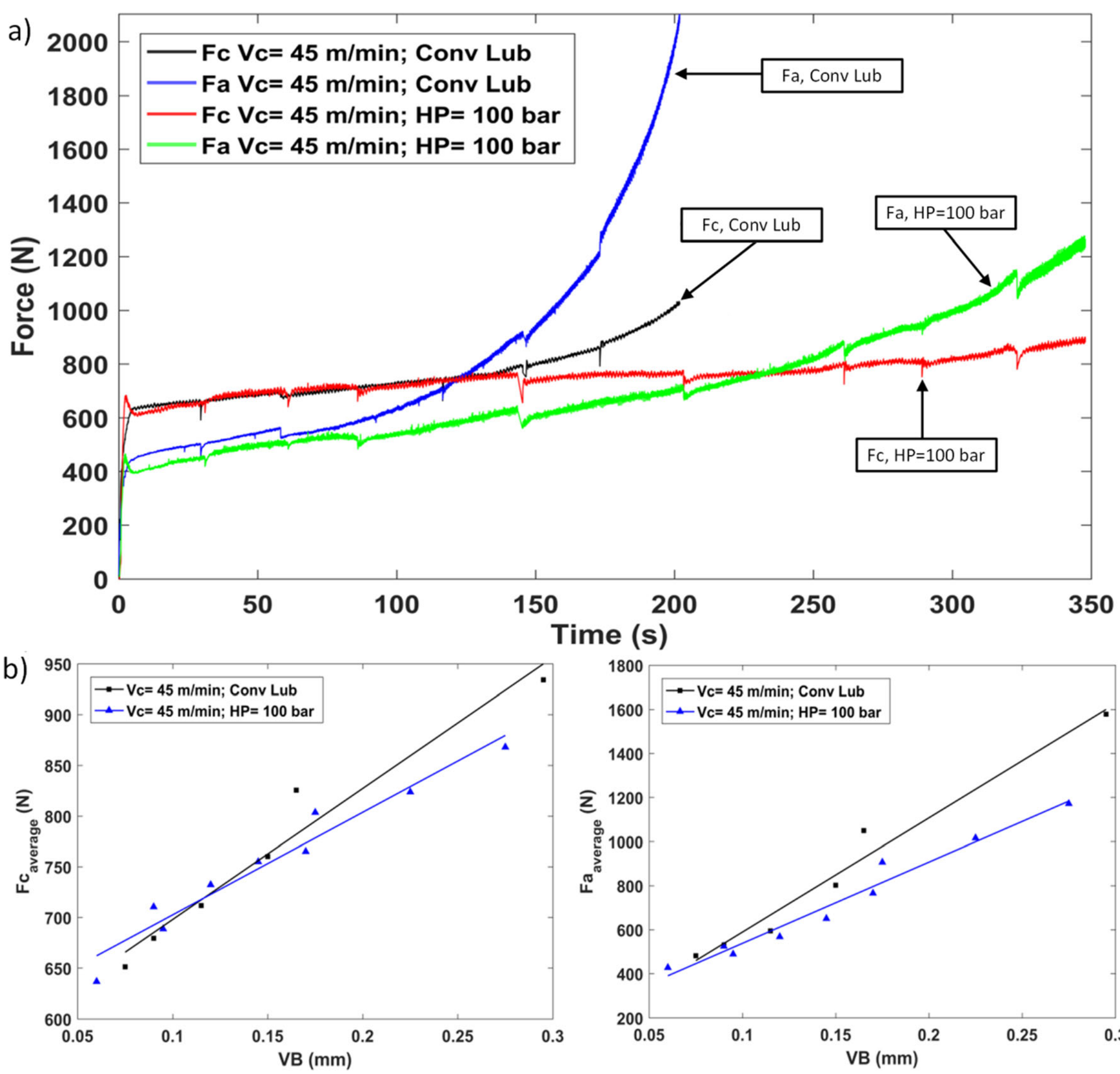
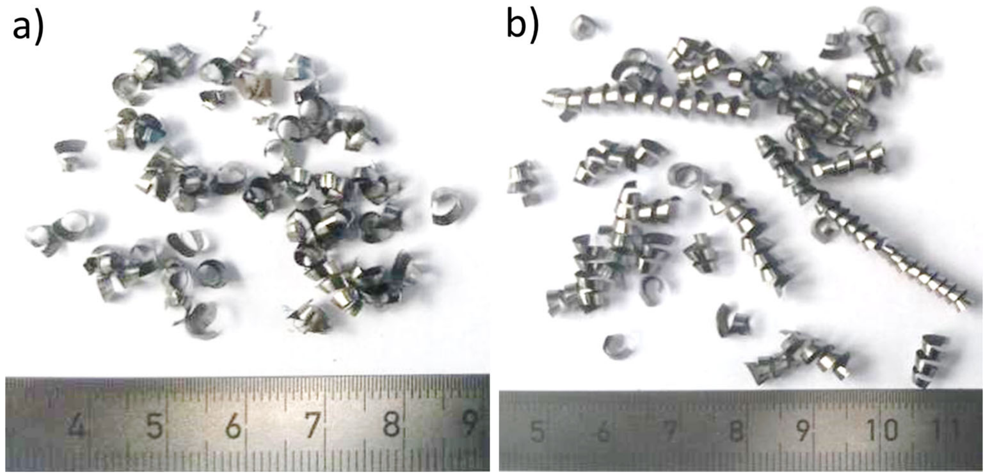


Fig. 12 Evolution of cutting and the axial force (F_c, F_a) when machining at cutting speed of 45 m/min under conventional lubrication (Conv Lub) and high-pressure (HP) coolant lubrication as a function of **a** machining time and **b** flank wear

Fig. 13 Chip morphologies at cutting speed of 45 m/min and cooling pressure of 100 bar: **a** at the beginning of machining test, **b** at the end of machining test



face mainly due to the growth of the crater wear. This will change the inward flow of the workpiece material and thus the chip geometry. Since the tribological phenomenon at the tool-chip interface plays a key role in controlling the chip formation and the tool wear rate, the crater wear would affect the chip formation to a larger extent than the flank wear.

Figure 14 and Fig. 15 show typical SEM photographs of the worn inserts when machining at a cutting speed of 45 m/min under conventional and HPC lubrication, respectively. Figure 16 illustrates the corresponding EDS mapping performed to look for the remaining elements adhered at the tool rake face.

As it can be seen from Fig. 14, the cutting edge is severely flattened. This generally leads to increasing the tool-workpiece contact area, which enhances frictional heat generation. Due to the low heat dissipation of nickel alloys, the temperature rises rapidly, and the effectiveness of the coolant is further reduced [25]. In addition, the flattened area acts as a chamfered cutting edge giving a local negative rake angle. Hence, additional thermomechanical loads are generated as the cutting tool rubs the work material. This can explain the significant increase in the axial force and the shorter tool life when machining with conventional lubrication. Similar conclusions were drawn by Sharman et al. [26] who found out that enlarging the contact area between the flank face and the machined surface would result in a greater "push-off" force.

The SEM micrographs conducted under conventional lubrication reveal an extensive transfer of the work material onto the tool rake face. The BUL covers most of the crater region. The same wear mechanisms observed under a cutting speed of 35 m/min are retrieved during this machining test. Particularly, more intense deposited layers can be found in the tool tip, which results in a BUE formation. Another interesting feature can be seen in Fig. 14 and Fig. 16a, where large patches of Fe elements, coming from the workpiece material, adhere on the tool coating in the outer edge of the crater. EDS mapping also reveals small patches with low concentration scattered in the crater region underneath the cutting edge. As revealed in Fig. 15, the application of HPC lubrication gives rise to a less pronounced BUE. The measured maximum tool-chip contact length is reduced from 0.492 mm under conventional lubrication to 0.345 mm under HPC lubrication.

As illustrated in Fig. 16, the examination of the worn insert when machining under both cooling strategies reveals a strong W-signal, especially under conventional lubrication. This

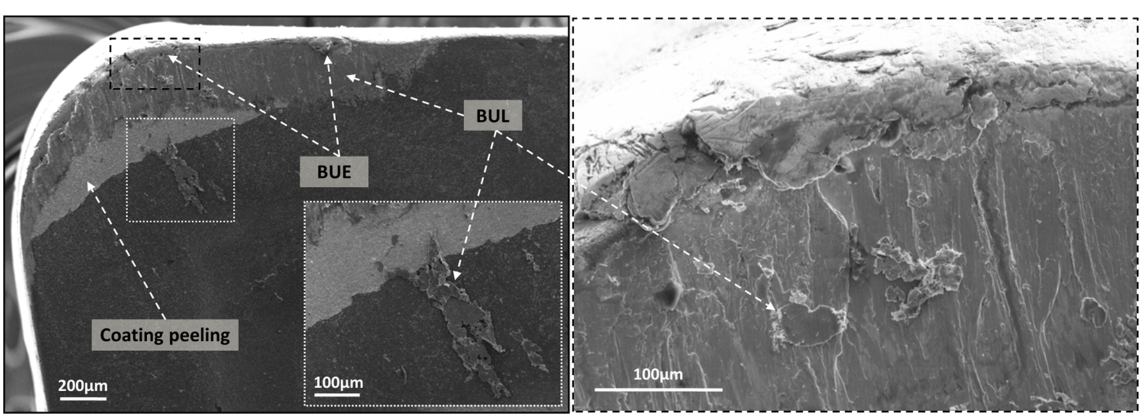


Fig. 14 SEM micrographs at end of machining test at cutting speed of 45 m/min under conventional lubrication

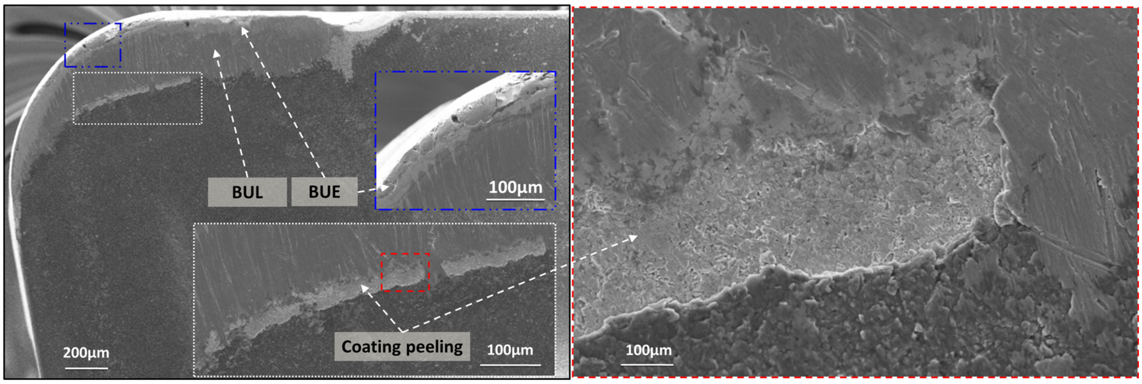


Fig. 15 SEM micrographs at end of machining test at cutting speed of 45 m/min under HPC lubrication

phenomenon is generally referred to as coating delamination. It is quite common when machining a hard to cut material and often localized at the vicinity of the cutting edge. Previous coating delamination findings suggest that coating peeling can be attributed to the chemical reaction [27] or a combination of a high interfacial temperature and an elevated stress at the sliding zone with a start of diffusion wear [28], whereas others have argued that it is due to crack propagation at the substrate interface [29].

Under conventional lubrication, the tool-chip contact area is almost totally covered by adhering layers, indicating adhesion while large patches of coating are plucked off beneath the contact zone. Under HPC lubrication, coating delamination occurs mainly at the tool-chip contact zone, while the rest of the tool rake face is almost intact. Coating layers can improve wear resistance significantly and enhance the sliding of adhering materials at the tool rake face, but it cannot stand for long before it is worn. When coating worn out or coating delamination occurs, the substrate beneath the worn out coating is directly exposed to the adhesion of the workpiece material, which accelerates the rate of the tool wear. Generally, the heat generated at the cutting zone plays an important role in preserving the structural integrity of the cutting tool. Providing an efficient heat removal through the application of HPC can help protect the cutting tool and subsequently the coating layer from a delamination process.

The EDS analysis, presented in Fig. 16, reveals adherent layers of nickel-based alloys attached to the valley of the crater. This suggests that adhesion also plays a part on the crater wear formation. On the other hand, Fig. 17 depicts the 3D scanning of the worn out insert at a cutting speed of 45 m/min. An example of the region profile, evaluated from a cross section perpendicular to the tool cutting edge and approximately located at the maximum depth of the region, is given in Fig. 17. It is noted that the adhered workpiece layers at the tool rake face were not removed prior to the 3D scanning, so the actual geometry of the crater region is not revealed. For this reason, only qualitative analysis is suitable to draw a conclusion about the crater wear formation.

When the coolant is applied under conventional lubrication, the topography of the crater region after 3.5 min of machining time at a cutting speed of 45 m/min shows an irregularity in depth. Although a longer tool engagement of 6.16 min is achieved under HPC lubrication, less irregularity with no remarkable or obvious change of the depth can be observed. It is also worthy to point out that after 9.5 min and 20 min of machining at a cutting speed of 35 m/min under conventional and HPC lubrication, respectively, the surface

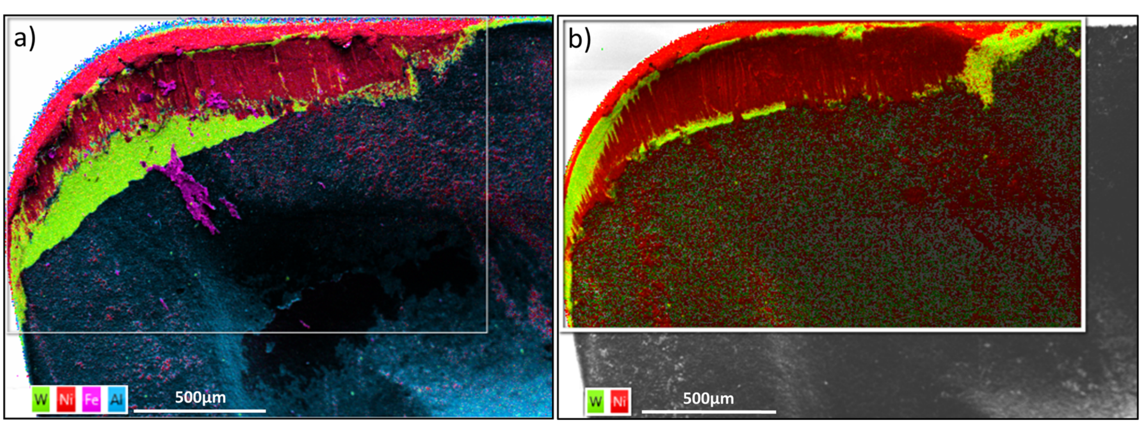


Fig. 16 EDS analysis at end of machining test at cutting speed of 45 m/min under **a** conventional lubrication and **b** HPC lubrication

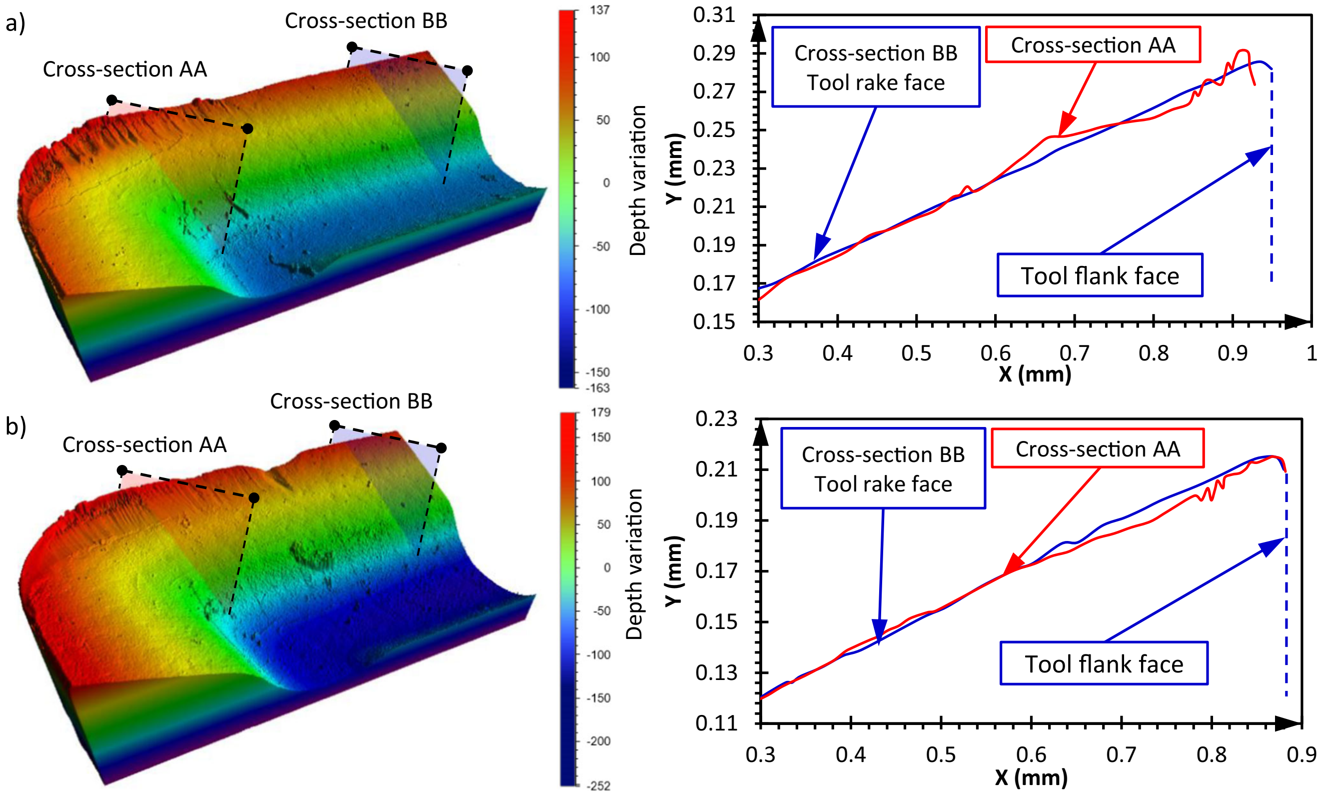


Fig. 17 Surface topography developed at the end of machining test at cutting speed of 45 m/min under **a** conventional lubrication and **b** HPC lubrication

topography of the rake face is not significantly affected by the crater wear, especially under HPC lubrication. This can be also attributed to the significant adhesion of the workpiece material.

Generally, the formation of the crater wear is related to a diffusion wear mechanism activated at high temperature. It is commonly observed on the tool rake face at a short distance from the cutting edge. The increase in the coolant pressure up to 100 bar ensures more effective cooling of the cutting tool. This may slow down the crater wear by diffusion. However, with the increase in the cutting speed, the tool experiences higher cutting temperature, and the effectiveness of HPC is further reduced.

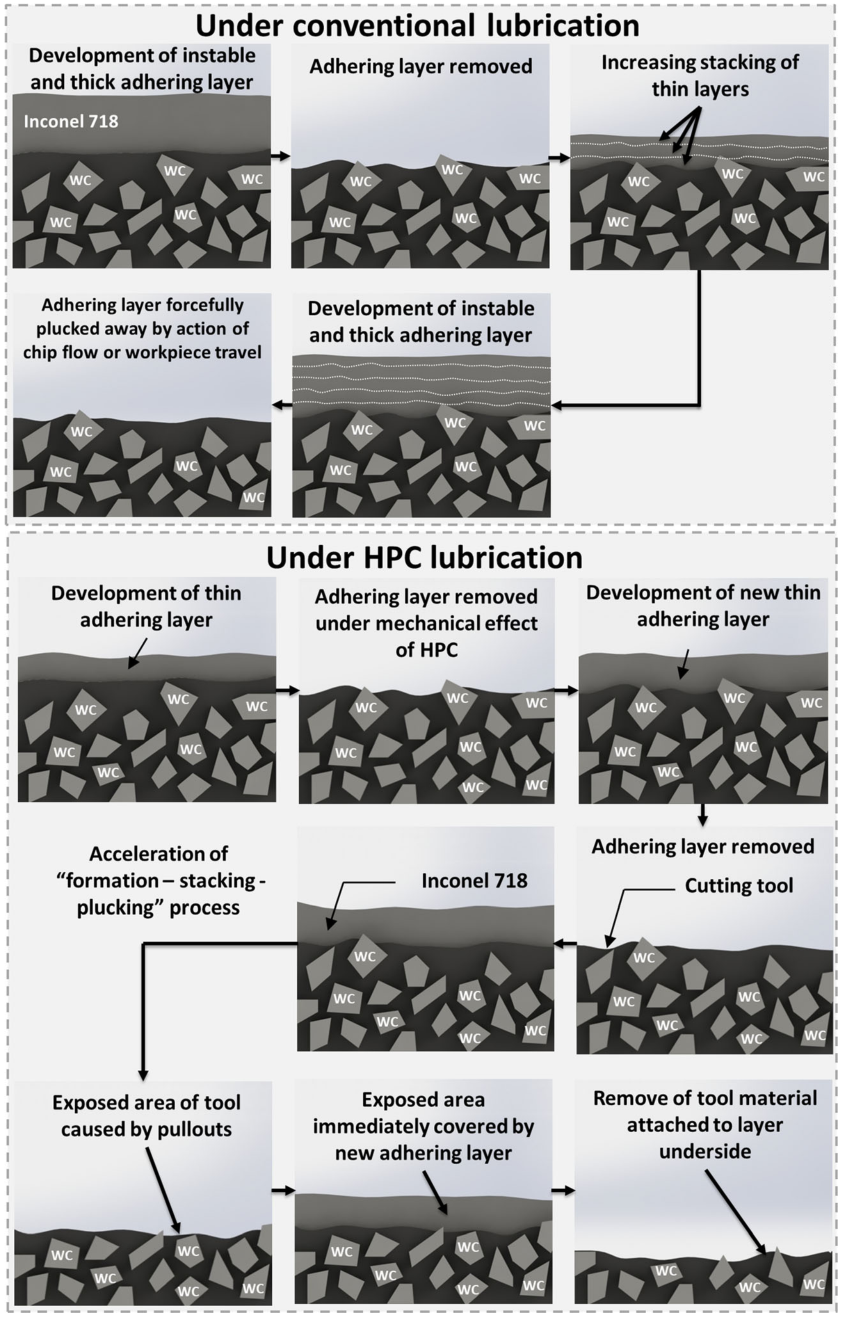
Additionally, the crater wear may be also accelerated by an adhesive wear mechanism, especially under HPC lubrication. The formation of adhered chip material on the tool rake face will never be completely stable, but it will be peeled off when the BUL becomes thicker. This cyclic phenomenon will be accelerated under HPC lubrication as the pressurized fluid can directly remove the deposit layers. Since the actual geometry of the crater region is not evaluated, this phenomenon is not observed in this investigation. However, it aligns with the observation reported in Fig. 7(b) and Fig. 10, where the HPC lubrication enhances the removal of tool fragments attached to the underside of the adhered chip material at the notch region and the tool tip, respectively.

3.3 Tool wear mechanisms

It is a well-known fact that tool wear mechanisms depend on cooling strategies, in addition to several factors including the used coolant, the workpiece/tool material characteristics, the cutting condition, and the lubrication condition. Therefore, different conclusions regarding the tool wear mechanisms (e.g., adhesion, abrasion, etc.) involved during machining the nickel-based alloys have been reported. Thus, in this investigation, an attempt is made to shed light on the potential contributions of some wear mechanisms to the overall tool wear under conventional and HPC lubrication for two cutting speeds.

By observing and measuring the tool wear morphologies during the process of tool wear, it can be stated that roughly turning Inconel 718 under conventional lubrication leads to a rapid growth of the tool flank wear and higher forces when compared to HPC lubrication. This is expected since the heat generated at the cutting zone plays an important role in wear mechanisms. Nickel-based alloys such as Inconel 718 are characterized with a low thermal conductivity. This will consequently result in lower heat dissipation and a significant rapid rise in the temperature of the cutting tool. For machining under a conventional coolant supply and due to the lack of cooling and lubrication, a severe tribological behavior acts at the tool/chip and tool/workpiece interfaces. The higher

Fig. 18 Mechanism of adhesive wear under conventional and HPC lubrication



friction and the higher cutting temperature enhance thermal wear mechanisms and consequently cause a higher flank wear rate. When the coolant supply is applied under 100 bar, the convective heat transfer coefficient increases, and the cooling phenomenon is further improved. The mechanical effect of the HPC enhances chip breakability, reduces the tool-chip contact length, enables a closer access to the tool tip, and thus further improves the effectiveness of the coolant to evacuate the generated heat from the cutting tool. This is supported by the experimental findings of Klocke et al. [11] when machining Inconel 718 in a similar cutting condition, where a considerable tool temperature reduction by almost 30% (by up to 200 °C) is reported owing the use HPC lubrication when compared to conventional lubrication. The temperature reduction will slow down the thermal wear mechanisms, resulting in a lower flank wear rate and so lower generated forces.

On the contrary, the HPC lubrication results in a higher notch wear rate. Similar results were reported by Klocke et al. [11] and Ezugwu et al. [12]. A possible explanation can be attributed to a combination of adhering layer instability and the acceleration of adhesive wear mechanisms under the mechanical effect of the pressurized coolant. In fact, adhering layers are periodically formed and removed when they become thicker and instable. When they pull off from the interface, they take fragments from the tool material. Contrary to the flank wear region, the notch region is directly exposed to the pressurized water jet. Thus, the frequency of removed layers seems to increase, and the wear rate is therefore expected to rise, as illustrated in Fig. 18. This statement is reinforced by the observation reported in Fig. 10, where HPC lubrication enhances tool chipping caused by BUE removal. In fact, by inspecting the tool worn areas, a significant adhesion of the workpiece material at the cutting edge can be observed. The observations of the binocular microscope reveal that the BUEs are turned off smoothly without any remarkable damage to the cutting edge, whereas under HPC lubrication, BUEs are removed with a small material fragment from the tool cutting edge.

Although abrasive and adhesive wears are the main tool wear mechanism responsible for the flank and notch wear formation, no severe scratch marks caused by abrasive wear are observed at the tool worn areas. In fact, the adhering layers cover all or most the worn area and consequently the majority of the scratched marks caused by abrasive wear. Similar observations are reported at the tool rake face, where the BULs cover almost the entire crater area. This suggests that BULs are continuously formed and removed during the cut process, creating protective layers spatially at the notch region where a smoother surface can be observed.

The impact of wear mechanisms differs according to the cutting conditions. By increasing the cutting speed from 35 to 45 m/min, the cutting tool undergoes more severe wear, and the tool life decreased by nearly the half. Apparently, a higher cutting speed gives an adverse effect on the performance of the tool by releasing more heat, hence increasing the wear rate.

Finally, it is also worth pointing that several theoretical analysis [30, 31] and finite element models [32, 33] have been conducted to predict the tool wear. However, and due to the complexity of physical phenomena involved during a cut operation under HPC lubrication, no model has been developed to predict the tool wear during such conditions.

4 Conclusion

This paper has focused on the effect of conventional and HPC lubrication on tool wear during the rough turning of Inconel 718 with coated carbide inserts. Instrumented experimental tests have been conducted at two cutting speeds of 35 and 45 m/min. Based on the results of these experimental trials, the following conclusions may be drawn:

– In general, HPC lubrication enables substantial improvement in chip fragmentation, lowers the generated forces, and almost doubles the tool life. When compared to conventional lubrication, a tool life improvement by up to 110% and 76% is achieved owing to the use of HPC lubrication at a cutting speed of 35 and 45 m/min, respectively.
– The lowest flank wear is recorded under HPC lubrication where a smoother evolution of flank wear can be also observed. On the contrary, notch wear is more pronounced under HPC lubrication.
– From the examination of tool surfaces by SEM and EDS analyses, adhesion is the most evident wear mechanism observed in this investigation. Adhered layers cover almost the entire cutting zone suggesting that adhesion plays also a part in the crater wear, the notch wear, and the flank wear.
– A combination of the layer instability and the acceleration of the adhesive wear mechanism under the mechanical effect of the HPC can explain distinguished notching developed under HPC lubrication.
– The notch wear developed under HPC lubrication can be also associated with the burr formation.
– The formation of BULs at the tool flank face protects the tool from extensive abrasive wear.
– The use of HPC lubrication can significantly reduce the BUE. However, tool chipping caused by the removal of adhered material at the tool tip is more pronounced under HPC lubrication, mainly due to the acceleration of the adhesion mechanism under the pressurized jet action.

Authors' contribution Haithem Khochtali: Investigation, methodology, writing—original draft, software

Yessine Ayed: Conceptualization, methodology, validation, investigation, writing—original draft, supervision, project administration, resources

Farhat Zemzemi: Validation, supervision

Wacef Bensalem: Methodology, investigation, supervision

Availability of data and materials The authors confirm that the data supporting the findings of this study are available within the article.

Declarations

Ethics approval The authors confirm that the paper has not been published previously in any form or language, that it is not under consideration for publication elsewhere, and that it does not contain material which has been published previously. The results are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

Consent to participate Not applicable

Consent for publication Not applicable

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