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ORIGINAL ARTICLE

Wear mechanisms of uncoated and coated carbide tools when machining Ti6Al4V using LN2 and cooled N2

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Abstract One of the main challenges of the manufacturing industry is to optimise the cutting tool life in order to increase both the process productivity and the product surface quality in machining operations. Several innovative strategies were developed and tested as function of both the workpiece material and the peculiar machining operation, being the most interesting in case of difficult-to-cut alloys, the use of low-temperature cutting fluids that would be able to inhibit the thermally activated wear mechanisms responsible of the cutting edge geometrical alterations. In this context, the aim of the paper is to investigate the effect of cryogenic cooling technologies based on the use of liquid nitrogen (LN2) and gaseous nitrogen (N2) cooled at − 100 °C on the tool wear when using uncoated and coated cemented carbide inserts in semi-finishing turning of the Ti6Al4V titanium alloy. Four commercially available insert grades commonly used in machining difficult-to-cut alloys were tested using the cutting parameters recommended by the tool manufacturer. The investigation combined scanning electron microscopy and optical profiler analyses to efficiently define and quantify the main tool wear mechanisms. The study proved that the innovative technology based on cooled N2, regardless of the adopted insert grade, determined the best results in terms of tool life improvement since it simultaneously inhibited the cratering phenomenon onto the tool rake face and produced the lowest flank wear with respect to both the dry cutting, wet strategy, and LN2 cooling cases. It was also proved that the best results were obtained for the uncoated insert when using cooled N2.

Keywords Ti6Al4V · Tool grade · Tool wear · Cryogenic

1 Introduction

Titanium alloys are being extensively used in numerous fields such as aerospace, biomedical, military and petrochemical ones, thanks to their excellent mechanical and physical properties, and high corrosion resistance at elevated operating temperature associated to their low density. On the other hand, they are classified as difficult-to-cut (DTC) alloys [1] due to their poor machinability attributable to the high temperature generated in the cutting zone as a consequence of their low thermal conductivity [2], strong chemical affinity with the conventional cutting tool materials [3], high stresses generated as a consequence of the short chip-tool contact length [4] and low Young's modulus, as well as due to the characteristic saw-tooth shape of the chip resulting from adiabatic plastic deformation [5]. Effective methods for lengthening the tool life consist of applying suitable cutting fluids to the cutting zone as well as using proper cutting tools with engineered coatings whose choice must be function of the cutting parameters.

The former solution represents the current state-of-the-art, being the most common cutting fluids either water- or oil-based enriched with additives (anti-wear, friction modifier, corrosion inhibitor, antioxidants, biocides, emulsifiers, etc.) [6]. However, the extensive use of large quantities of these cutting fluids raises important environmental issues in terms of their recovery and disposal, in addition to the needed time-consuming cleaning steps in order to guarantee the required cleaning specifications of the machined product surfaces, especially in the case of the biomedical components. The

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concept of sustainability manufacturing has become of great interest within the international community due to the stricter and stricter regulations imposed by the international agreements; therefore, the manufacturing companies are nowadays exploring new solutions to reduce or completely eliminate the conventional cutting fluids in favour of more efficient, less-polluting and cheaper technologies. The simplest solution consists in machining without cutting fluids, namely carrying out dry cutting, but this means accepting a lower machinability of the workpiece alloy.

An interesting solution, recently developed, is represented by the use of low-temperature fluids, as the liquid nitrogen (LN2) that can be identified as one of the best candidates since it is safe, clean, non-toxic and non-inflammable. The first studies, carried out to identify the experimental configuration giving the best performances, highlighted that the most effective approach consisted in simultaneously applying the LN2 to the tool rake and flank faces [7]. Several advantages have been found in machining heat-resistant and DTC alloys, such as titanium or nickel alloys, especially in roughing turning during which the low temperatures of the cutting fluid showed to be able to limit the main wear mechanisms responsible of the rapid failure of the tool insert, [8–10], and to improve both the machined surface integrity in terms of residual stresses and surface defects [11], and the tribo-corrosion behaviour during the machined part service life [12]. As example, its use during machining of the novel Ti5553 titanium alloy determined a reduction of the thrust cutting forces with respect to the flood-cooled technique up to 30%, as well as less nose wear was detected as a consequence of the reduced material adhesion [13]. The extension of the tool life wear under cryogenic cooling could be attributed to a more effective control of the cutting temperature, since during machining of titanium alloys, the adhesion and diffusive wear responsible to the cratering phenomenon onto the tool rake face, which are thermally activated mechanisms, were inhibited [14].

In terms of surface integrity, instead it was demonstrated that the use of LN2 in turning of nickel alloys produced more compressive residual stresses with respect to the wet and dry cutting [15], while an increase of the machined surface hardness was found as a result of the grain refinement when a drastic cooling was applied [16].

Furthermore, a costs analysis carried out considering the economical, environmental (energy consumption, waste management,...) and social (operational safety, personal health,...) aspects highlighted how the cryogenic machining reduced the overall production costs in comparison with the conventional strategy up to 30% [17]. Despite the several advantages highlighted hitherto, the industrial application of this technology is still limited due the cryogenic coolant extremely low temperatures that could damage the mechanical parts of the CNC machine tool and cause thermal distortions of the machined components with loss of dimensional accuracy especially when finishing and semi-finishing operations are addressed.

TUSAS Engine Industries Inc. found that the excessive cooling of the workpiece generated geometrical distortions and that the dimensional tolerances were not respected, making necessary further machining operations. On the basis of this outcome, the company abandoned the cryogenic strategy and continued to use the standard flood cooling techniques [18]. The cryogenic turning of acetabular cups made by additive manufacturing (AM) techniques was not able to manufacture products with geometrical tolerances close to those obtainable under dry cutting or flood cooling strategy. In fact, the cryogenic cooling induced a thermal contraction of the tool holder that was more critical than the contraction of the workpiece: however, it was shown that for short turning lengths, the cryogenic turning was applicable leading to geometrical deviations comparable to the reference condition [19]. On the basis of the latter results, the tool holder was redesigned in order to minimise its thermal contraction and developed a reliable thermo-mechanical numeric model able to predict the behaviour of the new apparatus that could be further applied to improve the tool holder redesign [20].

The second method to improve the DTC alloy machinability consists of adopting surface engineered tools: the scientific literature suggests that the tool inserts should exhibit characteristics of hot hardness (to maintain a sharp and stable geometry of the cutting edge at elevated temperatures), thermal shock resistance (not to be affected by the cyclic heating and cooling), low chemical affinity (to limit the build-up-layer formation), oxidation resistance (to resist at the accelerated wear rate at elevated temperature) and toughness (to withstand high cutting forces and mechanical socks) [21]. The most common inserts used in titanium alloy machining are made of cemented carbide (WC), though at high cutting speeds the WC is subjected to a rapid deterioration due to its chemical reactivity that actives the adhesion and diffusion wear mechanisms [22]. The studies of the effects of the WC grain dimensions on the tool wear resistance highlighted that finer grains improved the tool life with respect to coarser ones [23]. Another way to improve the surface characteristics of the cutting inserts is based on the use of coatings deposited by means of chemical vapour deposition (CVD) and physical vapour deposition (PVD) techniques, able to reduce both the friction coefficient, thanks to their self-lubricant properties, and the wear mechanisms since they present chemical inertness and high mechanical properties. TiN, TiCN, TiC, TiAlN, Al_2O_3 and TiB_2 are common materials used in single, multiple and nano-layers to enhance the DTC alloy machining performances: their

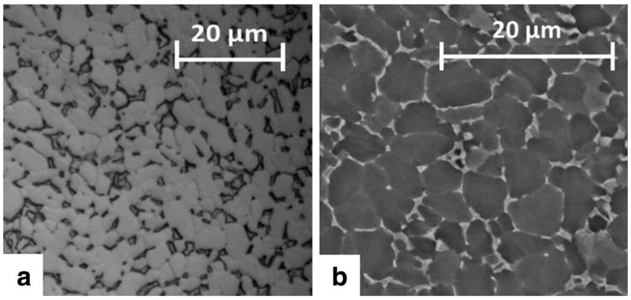

Fig. 1 Ti6Al4V microstructure in the as-received state. **a** Optical microscopy image and **b** SEM image

influence on the tool life and surface integrity of the machined components has been extensively investigated, highlighting how the best solution does not exist, but it changes as function of the machined material, machining operation (milling, turning,...), cutting parameters set (feed rate, cutting speed and depth of cut) and cooling strategy (dry, wet, MQL, etc.) [24–26].

The performances of uncoated, TiAlN-coated, CBN-coated and multi-layer CBN + TiAlN-coated tungsten carbide inserts during rough turning the Ti6Al4V alloy, evaluating the machinability in terms of cutting forces and tool wear, highlighted that CBN and TiAlN + CBN-coated WC/CO inserts, although exhibited the largest cutting forces at the highest cutting speeds, showed favourable wear development [27].

A comparative study on flank wear, surface roughness, tool life, volume of chip removal and economical feasibility in turning high carbon high chromium AISI D2 steel with multi-layer coated (TiN/TiCN/Al2O3/TiN) and uncoated carbide inserts under dry cutting demonstrated as the chipping was the main wear mechanism for uncoated inserts while abrasion was for the coated ones. The high observed erosion wear resistance associated to the TiN layer (three times better than uncoated carbide insert) determined a tool life improvement of about 30 times [28].

The present study is aimed at evaluating the performances of four commercial inserts under semi-finishing machining conditions when using gaseous N2 cooled at − 100 °C using the innovative device called Cryofluid™. For each of the cutting inserts, the cutting parameters were chosen according to the tool manufacturer's recommendations. The analysis of the tool wear was conducted evaluating both the crater and flank wear comparing the results with those obtained under dry cutting, conventional flood strategy and LN2 cooling conditions.

2 Experimental setup

2.1 Material

A commercially available Ti6Al4V ELI titanium alloy provided in the annealed state was chosen for the turning tests (chemical composition according to the ASTM F1472 standard reported in [29]). As shown in Fig. 1, the annealing heat treatment produced equiaxed α grains with 8% of β phase at the boundary grains, namely a microstructure that allows improving both the mechanical and corrosion resistance characteristics making it suitable for biomedical and aerospace applications [30].

The Ti6Al4V bars of 50 mm of diameter were supplied by Sandvik™ Bioline; the alloy main properties are reported in Table 1 according to the manufacturer's datasheets [31].

2.2 Turning experiments

The semi-finishing turning tests were carried out on a Mori-Seiki™ NL1500 CNC lathe using inserts supplied by Sandvik™ (CNMG 120404) with a radius of 0.4 mm and clearance angles of 0°. The inserts were clamped in a PCLNR 2020K 12 Sandvik™ Coromant tool holder with an approach angle of 95°.

In this study, four different commercial insert grades made of WC commonly used for machining DTC alloys as the titanium ones were tested, namely an uncoated insert (H13A), an insert coated with a single layer of (Ti,Al)N (GC 1105) and two inserts coated with a multi-layer (Ti,Al)N–(Al,Cr)2O_3 deposited through CVD (GC 1125) and PVD (GC 1115). Being the insert geometry, the same, the feed rate and depth of cut were chosen equal for each type of insert, namely 0.2 mm/rev and 0.25 mm, respectively. Whereas, as concerns the cutting speed, the maximum values recommended by the tool manufacturer were chosen (see Table 2). A fresh cutting edge was used for each trial, and 15 min were considered as turning time. The CNC lathe was implemented with two distinct self-designed lines able to apply the LN2 and the cooled gaseous nitrogen (N2) to the cutting zone. The LN2 apparatus includes a Dewar, in which the cryogenic fluid is stored and maintained at controlled temperature and pressure, a control unit, and a distribution system made of a plate mounted on the lathe turret and designed to deliver the LN2 to the tool rake and flank faces at the pressure of 15 bar using two copper nozzles with an internal diameter of 0.9 mm [32]. The second experimental apparatus, called Cryofluid™ and patented by

Table 1 Ti6Al4V mechanical properties in the as-received state [25]

	E (GPa)	UTS (MPa)	Y_S (MPa)	Elongation (%)	Hardness (HRC)
Ti6Al4V	118	940	870	15.0	31

Table 2 Experimental plan for the semi-finishing turning tests

Insert	Depth of cut (mm)	Cutting speed (m/min)	Feed rate (mm/rev)	Machining time (min)	Tested strategies
GC 1125	0.25	30	0.2	15	Dry/wet/LN2/N2(− 100 °C)
H13A	0.25	35	0.2	15	Dry/wet/LN2/N2(− 100 °C)
GC 1115	0.25	65	0.2	15	Dry/wet/LN2/N2(− 100 °C)
GC 1105	0.25	80	0.2	15	Dry/wet/LN2/N2(− 100 °C)

Air Liquide™ Service Italy, allows cooling the gaseous N2 in the range between 0 and − 150 °C, making use of an insulated chamber in which the LN2 is mixed with the N2 until reaching the desired temperature, while a feedback temperature control guarantees it for the whole test thanks to an internal PLC controller. The output pressure of the cooled gaseous N2 was set constant at 2.5 bar; a single nozzle with an internal diameter of 6 mm was positioned onto the tool holder in order to cool just the tool rake face, being this area the most exposed to the thermally activated wear mechanisms. On the basis of a previous work carried out by the authors [33], a testing temperature of − 100 °C was considered since it was the one that guaranteed the best results in terms of both tool wear reduction and product quality improvement. An overall image of the Cryofluid™ apparatus with a detail of the cutting zone is shown in Fig. 2.

Lastly, dry cutting and wet strategies were used as baseline. The wet strategy made use of the commercial semi-synthetic cutting fluid Monroe™ Astro-Cut HD XBP mixed with water obtaining a 5% emulsion coolant that was supplied at a pressure of 2 bar through the cooling system of the machine tool. Table 2 summarises the experimental plan in terms of turning parameters and adopted cooling strategies as function of the insert grade.

In order to compare the performances of the different low-temperature cutting fluids, in a previous work [33] the authors determined the cooling capacity of the LN2 and N2 cooled at different temperatures, as reported in Table 3. It is worth to note that the fluid cooling capacity expressed in terms of thermal power combines the most relevant process parameters, namely temperature, pressure and flow rate, with the physical and thermodynamic characteristics of the coolant as the density (calculated at the storage temperature of the cutting fluid) and the heat exchange with the environment at 20 °C and 1 bar. More details are present in [33].

The results in terms of cooling capacity shown in Table 3 highlight how the LN2 presents the highest cooling capacity (24.7 kW), one order of magnitude higher than the one of the N2 cooled at − 100 °C (1.39 kW).

3 Tool wear mechanisms and characterisation

The tool insert is subjected to different wear mechanisms because the interactions between the tool and workpiece material change depending on the different tool areas. In literature, different classifications have been proposed, the simplest one considering the temperature as the most critical parameter; in the tool areas interested by higher temperature values, the main wear mechanisms are diffusion and adhesion, while in those zones characterised by lower temperatures, the predominant mechanism becomes the abrasive one, mainly mechanically induced [34]. Another consolidated classification groups the tool wear mechanisms into five categories, namely adhesion, abrasion, diffusion, fatigue and tribo-chemical, considering the tool failure caused by their combination [35]. Generally speaking, the predominant wear mechanism depends on several factors, among which are the workpiece material, the tool insert geometry and material, the cutting parameters and the cooling strategies [36].

To determine the main wear mechanisms that are involved during titanium semi-finishing machining under different cooling strategies, a qualitative analysis of the tool rake face was conducted by means of a FEI QUANTA 450™ SEM equipped with the back-scattered electron detector, while a quantitative evaluation of the wear was

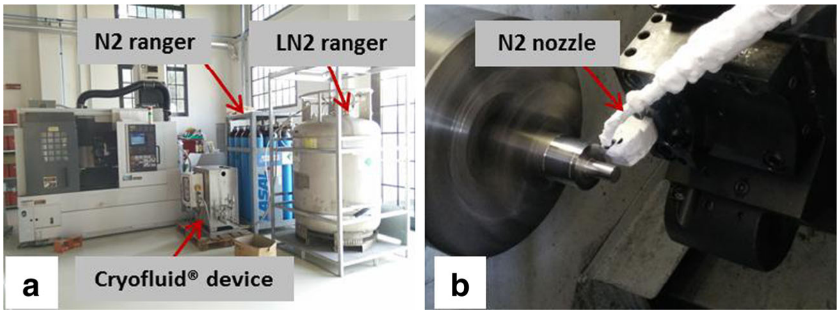

Fig. 2 Experimental apparatus for the Cryofluid™ technology. **a** Overall view of the equipment. **b** Detail of the cutting zone

Table 3 Cooling capacities defined as thermal power [33]

Coolant	Thermal power (kW)
LN2	24.7
N2 (− 100 °C)	1.39

carried out using a Sensofar Plu-Neox™ optical 3D profiler (see Fig. 3a). To evaluate the extent of the tool damage, the 2D profiles of the worn tool rake faces were compared with the unworn one. The 2D profiles were obtained in a fixed central position of the rake face from the 3D optical profiler images: using as baseline the change of the insert slope at the rake face, specifically designed to improve the chip breaking, it was possible to efficiently align the insert profiles. The maximum crater depth was measured following the approach shown in Fig. 3b. The tool profiles were rotated to make them aligned with the X-axis: the difference between the minimum value of the worn tool and the equivalent value of the unworn tool profile corresponds to the maximum crater depth.

On the other hand, the flank wear was quantified according to the ISO 3685:1993 standard [37] measuring the notch flank wear (VBc) on the SEM images. According to the standard, a limit value of 0.3 mm must not be exceeded; nonetheless in fields such as the aerospace and biomedical ones, this value is reduced to 0.1 mm in order to guarantee a better surface integrity.

4 Results

4.1 Crater wear

The SEM analysis of the tool rake faces highlighted adhesion as the main wear mechanism (see Fig. 4). The formation of the built-up-edge (BUE) onto the cutting edge due to the chip and workpiece material adhesion determines the tool geometrical alteration that may affect the machined product surface quality. On the contrary, the build-up-layer (BUL), which forms as a consequence of the BUE plastic deformation due to the chip sliding onto the tool rake face, represents the condition that actives the diffusion process responsible of the cratering phenomenon [38, 39]. The chip flowing, besides deforming the BUE, determines a mechanical abrasion of the rake face visible especially for the coated inserts in which the white areas represent the tool substrate made of WC as confirmed in previous works carried out by the authors [40]. The high chemical affinity between the titanium and the cobalt, which is present as binder in the tool matrix, together with the high cutting forces generated as a consequence of the cutting edge alteration, promotes further the adhesion process on the worn insert.

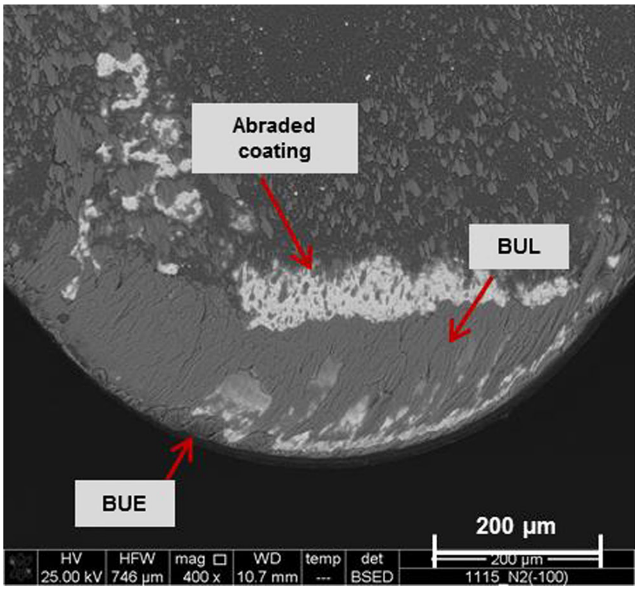

Fig. 4 Main wear mechanisms detected after 15 min of turning on the tool rake face

The abovementioned tool wear mechanisms were found in all the analysed inserts regardless of the cooling condition and adopted inserts grade and cutting parameters (see Fig. 5). The quantification of the adhered layer is commonly carried out through the measurements of the chip contact length (sticking zone) onto the tool rake face. A shorter value of the tool-chip

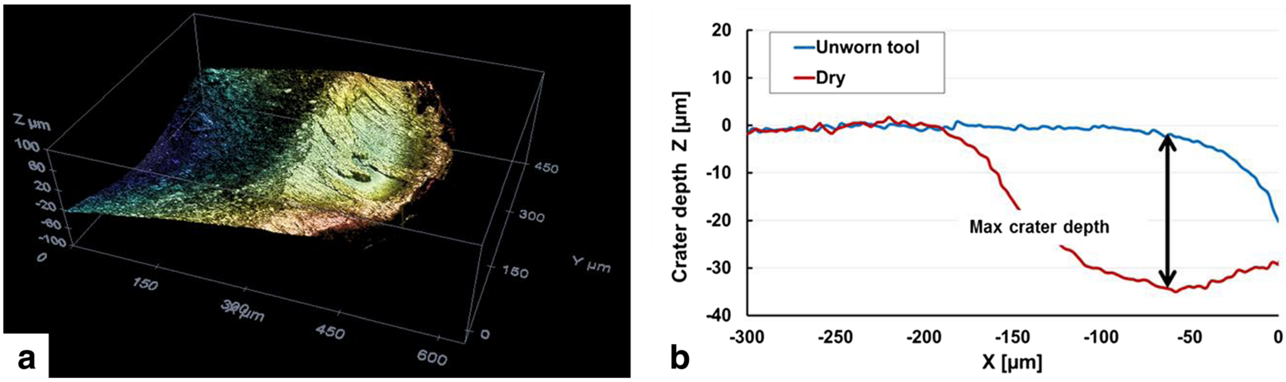

Fig. 3 **a** 3D image of the worn tool acquired by means of the 3D profiler. **b** Measuring approach to evaluate the tool maximum crater depth

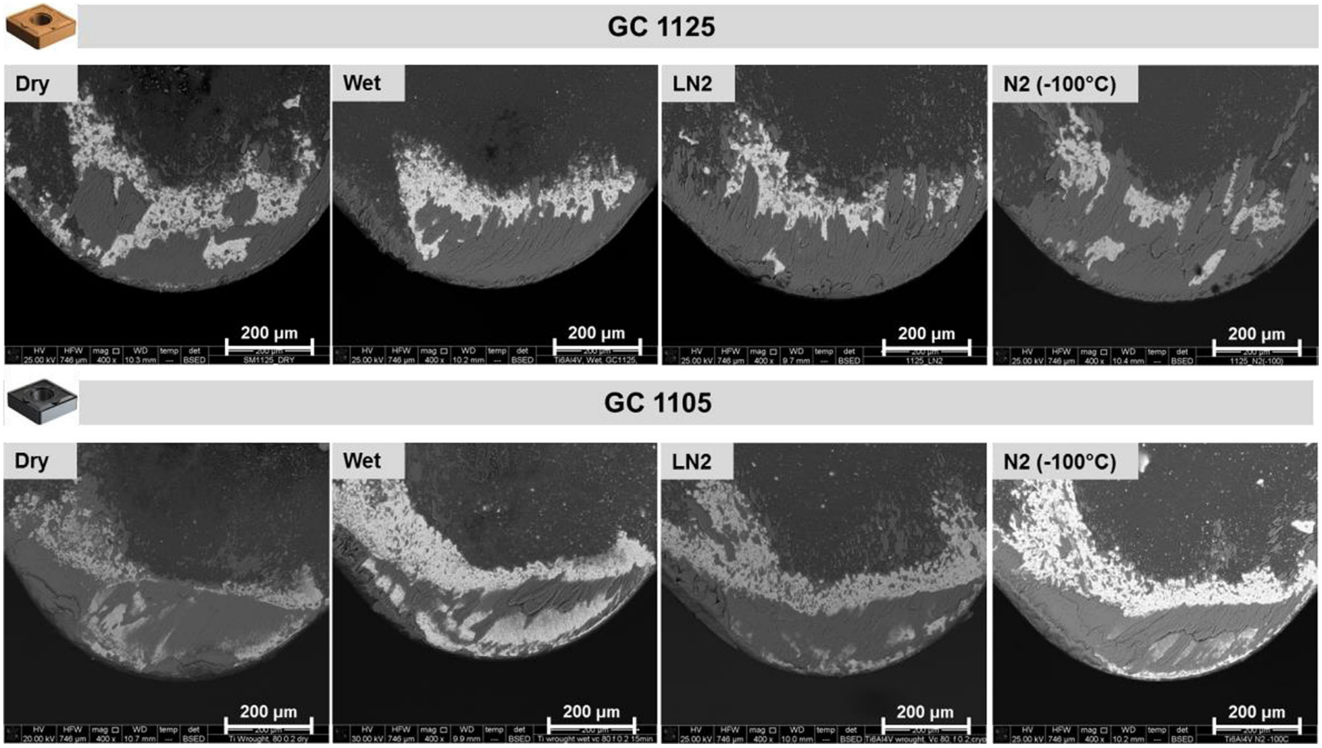

Fig. 5 SEM images of the worn tool rake faces after 15 min of turning under dry, wet, LN2 and cooled gaseous N2 conditions

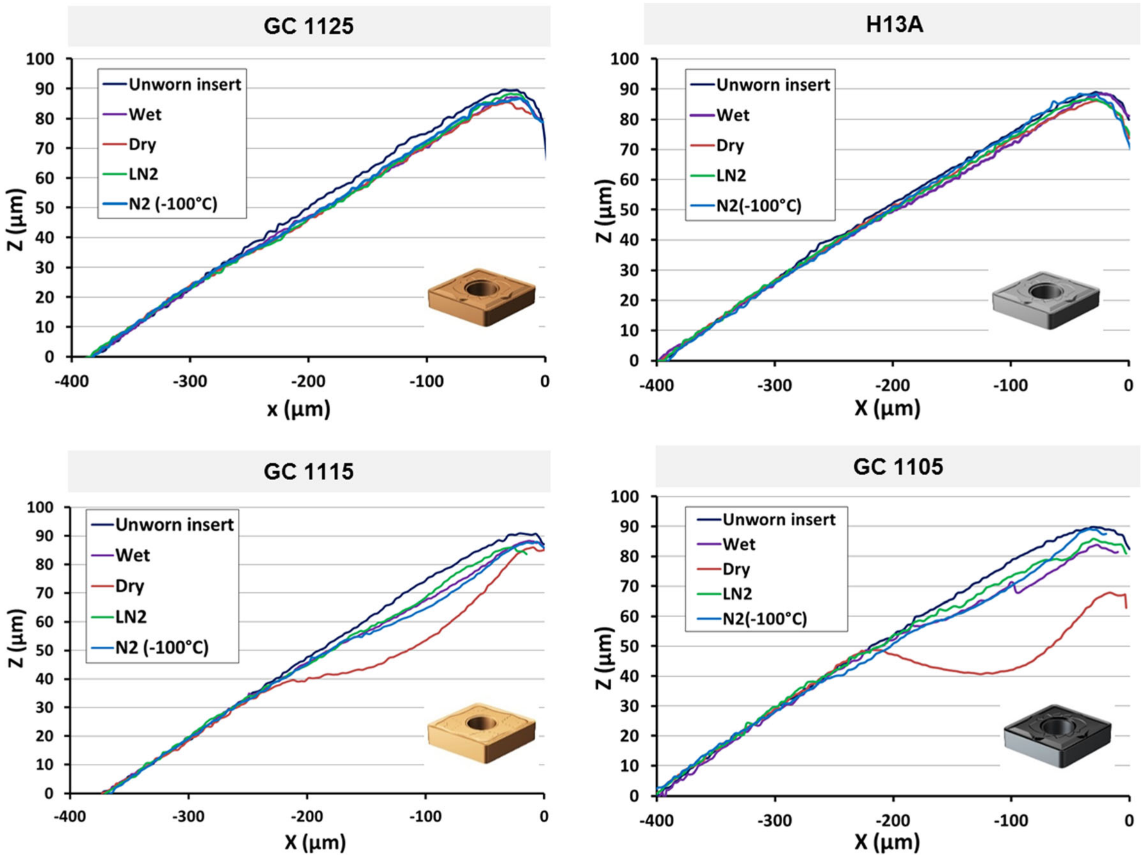

Fig. 6 2D profiles of the tool rake faces after 15 min of turning under dry, wet, LN2 and cooled gaseous N2 conditions

Table 4 Wear crater depth as a function of the adopted cooling strategies (measurement uncertainty equal to 6%)

	Max. crater depth (μm)			
Insert	Dry	Wet	LN2	N2 (− 100 °C)
GC 1125	–	–	–	–
H13A	–	–	–	–
GC 1115	17.96	6.09	5.68	7.31
GC 1105	32.72	8.31	7.55	6.17

contact length will result in a greater coolant penetration, reduced friction and greater cooling efficiency, thus longer tool life. However, the crater wear present in several tools did not make possible this type of analysis, as the chip sliding direction was altered by the loss of the tool geometrical tolerances. The use of low-temperature coolants has no significant impact on the occurrence of the adhesive wear. The differences in terms of sticking zone thickness visible in Fig. 5 between insert GC 1125 and GC 1105 inserts are the consequence of the different adopted cutting speeds and insert coatings.

Another typical wear mechanism associated to titanium machining is the formation of a wear crater onto the tool rake face, which, in most cases, represents the major cause of accelerated and catastrophic tool failure [41]. The pauperization of the tool matrix elements, primarily the cobalt, as a result of the diffusion process between the tool substrate and adhered workpiece material (BUL), determines the embrittlement of the tool that facilitates the removal process (abrasion and pull-out of the WC grains) associated to the chip flowing. Being the latter, a thermally activated process, those cutting parameters that favour the temperature increase, play a key role. In fact, several works demonstrated how the cutting speed represented the most influencing parameter [42], while it was shown that the adduction of cryogenic cutting fluids permitted to completely inhibit the crater wear formation [43].

The crater wear quantification was made according to the experimental procedure described in Section § 3, on the basis of the 3D scanning of the tools conducted by means of the optical profiler. Figure 6 reports the 2D profiles of the worn inserts that were used to machine under different cooling strategies (the purple, red, green and light blue lines represent the wet, dry cutting, LN2 and cooled gaseous N2 at − 100 °C conditions, respectively) compared to the unworn tool profile (blue line) for all the tested insert grades.

The analysis highlighted how the cooling strategies did not influence the crater wear of the uncoated insert (H13A) and the one coated with (Ti,Al)N–(Al,Cr)2O3 (GC 1125), while significant effects were measured for the other two tested inserts (GC 1115, GC 1105).

Table 4 reports the crater depth values: the maximum reduction of the wear crater was measured for the insert GC 1105 using cooled gaseous N2, being the percentage reduction with respect to the dry condition of about 81%, whereas the use of the LN2 led to an improvement of about 77%. Despite the different coatings and adopted cutting speeds, the crater depth values for the inserts GC 1115 and GC 1105 under cryogenic cooling were very similar, namely about 7 μm.

The flood strategy led to results very close to those obtainable using the low-temperature cooling technologies, only the GC 1105 insert presented a significant difference, as with respect to the cooled N2 the crater depth passed from 6.17 to 8.31 μm.

Overall, the analysis of the tool rake face wear showed that for all the tested conditions the cryogenic cooling strategies permitted to effectively reduce the cratering phenomenon with the best results measured for the LN2 case. However, despite the LN2 presents the highest cooling capacity, the results in terms of crater depth highlighted that the difference between

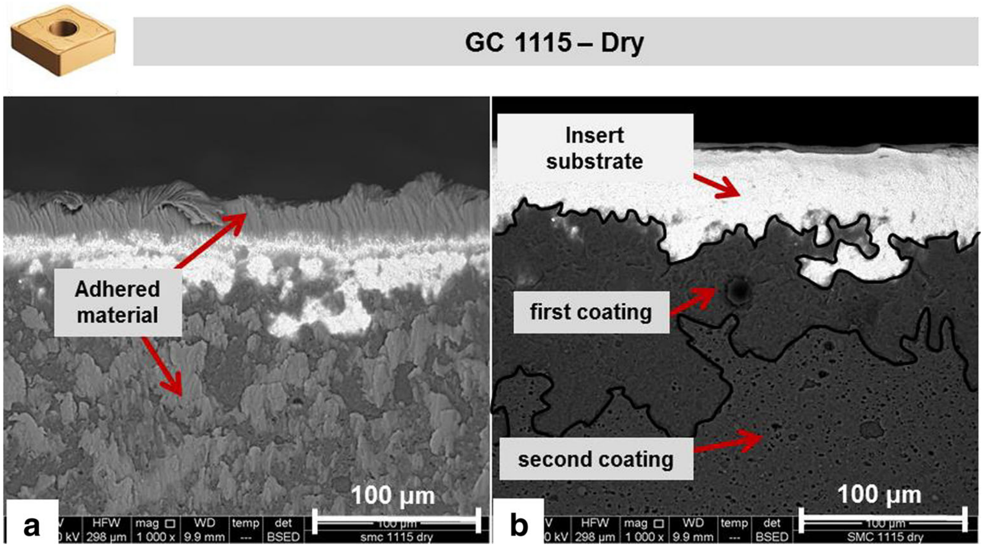

Fig. 7 Tool flank face after 15 min of turning for the insert GC 1125 under LN2 cooling conditions. **a** Before and **b** after the removal of the adhered material

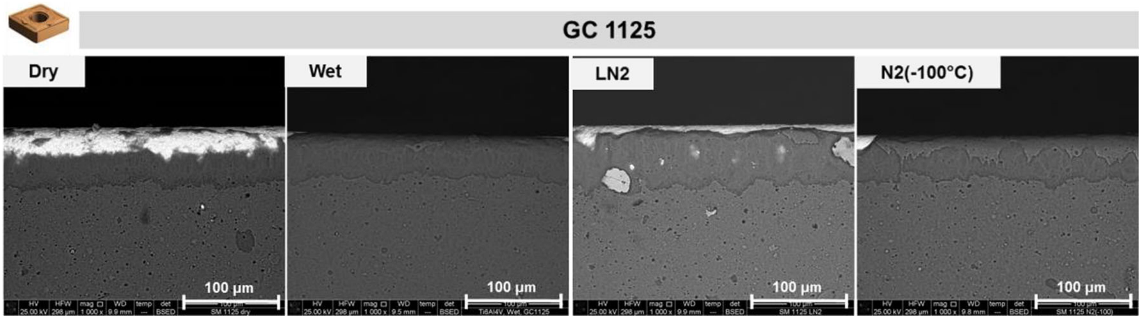

Fig. 8 Tool flank wear after 15 min of turning under dry, wet, LN2 and cooled gaseous N2 conditions for the insert GC1125

the LN2 and cooled N2 were minimal, making them comparable.

4.2 Flank wear

The adhered material present onto the cutting edge made it difficult to effectively measure the VBc: to overcome this difficulty, a chemical etching made of 95% hydrofluoric acid was used to eliminate the workpiece material without damaging the insert substrate and the coating. An example of the result of such etching is shown in Fig. 7.

Figure 8 shows the effects of the different cooling strategies on the tool flank wear; the thickness average values of the abraded layer obtained from five measurements conducted on the SEM images are reported in Fig. 9.

In case of the uncoated insert, the use of cryogenic coolants allowed inhibiting or, at least, reducing the adhesion mechanism favoured during the cutting process by the high chemical reactivity between the cobalt of the tool matrix and the workpiece material; on the other hand, an excessive cooling may cause a material hardening with consequent increase of the abrasion effect. In fact, the percentage reduction of the flank wear when using the gaseous N2 cooled at − 100 °C compared to the dry and wet cutting conditions was about 55 and 41%, respectively, but decreased to 10% when using the LN2. A similar behaviour was highlighted also for the insert coated

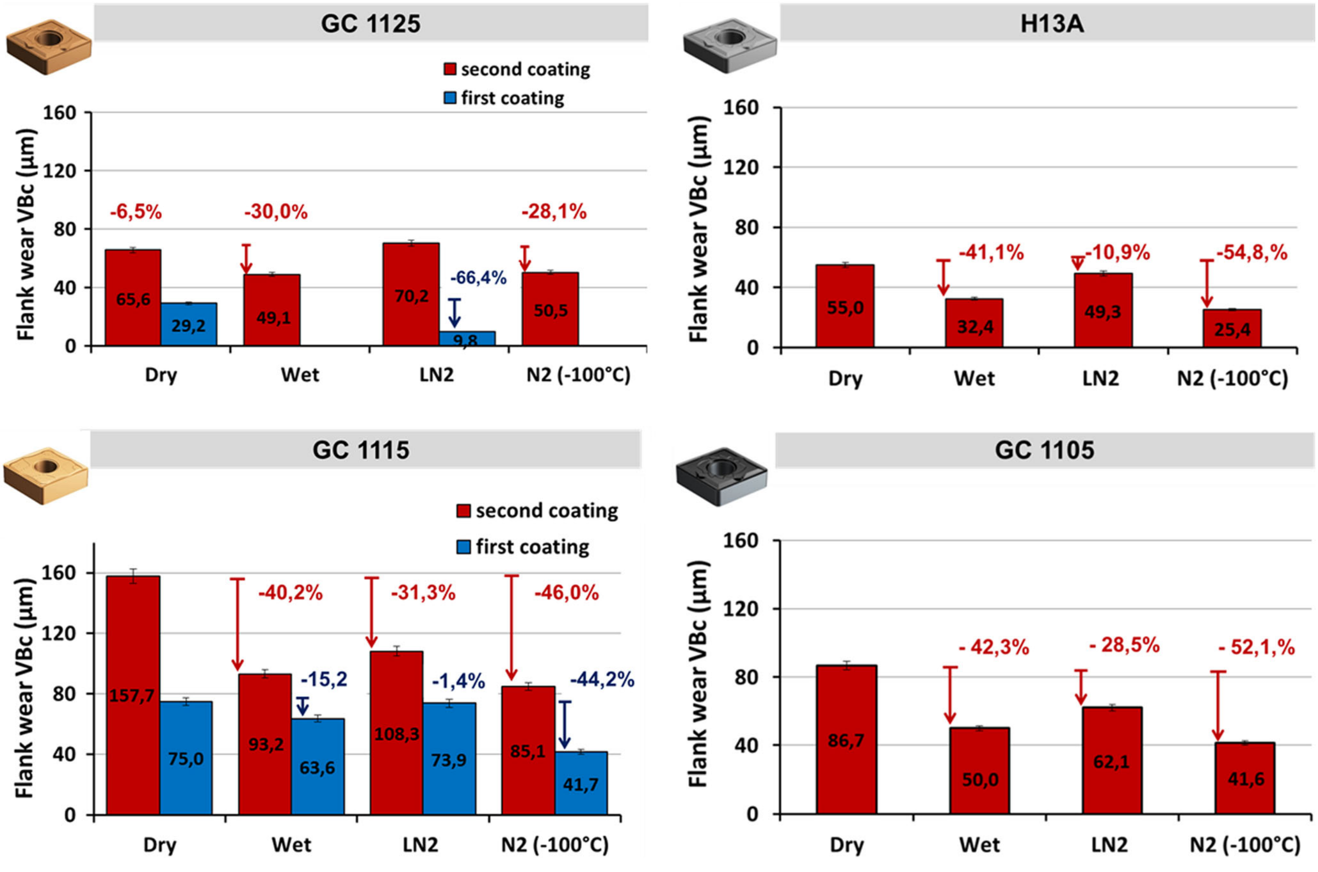

Fig. 9 Tool flank wear VBc values

with a single layer of (Ti,Al)N (GC 1105): with respect to the abovementioned case, the highest VBc measured in all conditions might be ascribed to the high cutting speed used in the turning trials as recommended by the tool's manufacturer, which would have accelerated both the abrasion and adhesion mechanisms. In this case, the LN2 use was more advantageous, with a VBc reduction of 28.5% compared to dry cutting, while the cooled N2 and conventional cutting fluid performed similarly.

Different considerations pertain to the inserts with a double coating (GC 1125 and GC 1115), in which the second deposited coating is composed by elements that do not exhibit chemical affinity with the workpiece material, thus minimising the adhesion process. The overcooling induced by the LN2 may cause an excessive embrittlement of the material determining high abrasion with just a limitation of the adhesion. This behaviour pertains especially to the insert with grade 1125, which was characterised by the highest abraded thickness when using the LN2.

The great potential of the cryogenic coolants was instead evident when the first deposited coating (as a consequence of the abrasion process) was exposed since it presented chemical affinity with the workpiece material; the use of the cooled gaseous N2 eliminated completely the abrasion, which was instead reduced of the 66% when using the LN2. For the insert GC 1125, the wet and cooled N2 strategies were comparable, as the same improvements with respect to the dry cutting were detected. Lastly, for the insert with grade 1115, the advantages of the tested cryogenic strategies with respect to the dry and wet cutting were highlighted in both cases, with more significant improvements than in the previous case.

The analysis of the flank wear of different commercial tool grades highlighted how the different cooling strategies produced different effects when using the cutting parameters recommended by the tool's manufacturer. The cooling technique based on the gaseous N2 cooled at −100 °C gave always the best outcomes regardless the tested grade, whereas the LN2 produced interesting effects only when the highest cutting speeds (65 and 80 m/min) were adopted, with, instead, minimal differences compared to dry cutting at lower cutting speeds. The reason may be ascribed to the temperature field generated during the cutting process, as the main effect of the cutting speed increase consists in higher heat production that can be better dissipated when adopting the LN2 characterised by a higher cooling capacity than the cooled N2.

On the other hand, even if the LN2 is able to assure a drastic cooling to completely eliminate the temperature effects, especially in those conditions in which the generated heat is low, it causes a material hardening effect that favours the flank face abrasion, thus limiting the overall advantages.

5 Conclusions

The paper reported the results of an experimental wear analysis conducted on four different commercial inserts commonly used in Ti6Al4V semi-finishing turning using for each of them the maximum value of the cutting speed recommended by the tool's manufactures. The innovative cooling technique based on gaseous N2 cooled at − 100 °C was tested using dry cutting, conventional flood strategy and LN2 cooling as baseline. The main findings of this investigation can be summarised as follows:

- The use of different inserts significantly influenced the tool wear: the uncoated insert H13A and the coated one GC 1115 did not present the cratering phenomenon regardless the cooling strategy, whereas the measured deepest crater was found in the coated insert GC 1105 under dry cutting. After 15 min of turning, the minimum flank alteration was highlighted for the uncoated insert, whereas the use of a double coating produced by means of PVD and CVD techniques (GC 1115 and GC 1125) determined the highest measured VBc.
- Regardless of the tested inserts, the use of the LN2 as coolant did not produce the best results, as the excessive workpiece cooling determined a material embrittlement/hardening with consequent increase of the abrasion effect, although the thermally activated wear mechanisms were reduced limiting the crater wear formation. On the contrary, the gaseous N2 cooled at − 100 °C allowed reducing the heat generated during the cutting process, thus limiting the crater wear, but without modifying the initial material characteristics and thus limiting also the flank wear.
- The highest improvements in terms of flank wear were highlighted using the uncoated insert (H13A) when using the N2 cooled at − 100 °C.

On the basis of the experimental results, the best performances were found for the N2 cooled at − 100 °C, making it an ideal substitute of the conventional wet strategy during semi-finishing turning operation of Ti6Al4V alloy.

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