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ORIGINAL ARTICLE

Tool life and surface integrity when turning titanium aluminides with PCD tools under conventional wet cutting and cryogenic cooling

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Abstract The high-performance machining of difficult-to-cut alloys requires the development and optimization of high-performance tools, able to withstand the thermo-mechanical tool load without compromising the surface quality of produced components. In this context, the machinability of titanium aluminides still represents a demanding challenge. In this paper, the performance of cubic boron nitride (CBN) and polycrystalline diamond (PCD) cutting inserts is compared to that of uncoated and coated carbide tools. Longitudinal external turning tests were performed on a Ti-43.5Al-4Nb-1Mo-0.1B (TNM) at.% cast and hot isostatically pressed (HIPed) γ-TiAl alloy, by using a conventional lubrication supply. In addition, PCD tools were also applied under cryogenic cooling with liquid nitrogen. Results proved that PCD cutting tools have the potential to improve the machining productivity of titanium aluminides, due to their high hardness and excellent thermal conductivity. A noteworthy further increase of tool life was possible by using PCD cutting inserts under cryogenic cooling conditions.

Keywords PCD · CBN · High-performance cutting · Titanium aluminide · Cryogenic-assisted cutting · Surface integrity

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1 Introduction

Advanced lightweight and thermally stable alloys have been receiving an increasing industrial attention. In this scenario, titanium aluminides (TiAl) were identified as alternative to more traditional materials for thermally and mechanically stressed components [1]. These materials are basically compounds formed from two metals, titanium and aluminum, showing structures and properties completely different from their basic constituents. In addition, alloying elements improve properties as ductility, strength, and creep and oxidation resistance [2]. Titanium aluminides exist in different phases, but only the α_2 (Ti_3Al) and γ (TiAl) phases are of interest. Such phases by themselves have scarce engineering significance, but a combination of them, which exists between 40 and 48 at.% of Al content, has proved to be valuable for structural applications. TiAl intermetallic alloys have an attractive combination of strength-to-weight ratio (being the density of titanium aluminides approximately half that of nickel-based superalloys), refractoriness, oxidation resistance, high elastic modulus, strength retention at high temperatures, and good creep resistance [3, 4]. Commercial interest is centered mainly in aerospace and automotive sectors, and possible fields of application can be detected in both rotating and non-rotating parts. Low-pressure turbine blades, compressor vanes, swirl nozzles, automotive engine valves, and turbochargers could be made of these alloys [5–8]. Investment casting, ingot metallurgy, and powder metallurgy [9, 10], usually coupled with a series of post-processing steps (as hot isostatic pressing, aging, annealing, and hot working) were used to produce TiAl parts. Several thermo-mechanical routes as hot rolling, forging, and extrusion were also utilized [11, 12]. Moreover, aiming to reduce the post-processing steps, some advanced techniques as direct rolling, laser forming, spark plasma sintering, and mechanical alloying were applied, as highlighted by Kothari et al. [3].

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As far as machining is concerned, titanium aluminides are classified as difficult-to-cut materials (more than standard titanium alloys), because of their high hardness and brittleness, low thermal conductivity, strong tendency to hardening, and high chemical reactivity [13, 14]. On the workpiece side, these characteristics result into residual stresses and surface damage with poor finish [15, 16]. One of the key problems related to the poor machinability of these materials is the formation of defects in the form of microcracks and microfractures on the workpiece surfaces [17, 18]. Such defects may act as the initial point for crack propagation resulting in part failure, which is completely inacceptable for safety critical components, whereas surface integrity is indispensable. Nevertheless, the influence of surface and subsurface defects on fatigue life might be reduced by the compressive residual stress near the surface due to the cutting process and/or by the deformation of the lamellae restricting crack growth [19, 20]. Literature still lacks information about machining performance whether involving conventional or non-conventional processes. This is apparently in contrast to the numerous publications regarding development/processing of TiAl alloys, fatigue behavior, microstructure and mechanical properties, oxidation, and thermal protection. Moreover, the extremely challenging machining of titanium aluminides is one of the major reasons that so far these alloys are hardly used in series products.

Focusing on cutting operations with defined cutting edges, a limited number of publications analyzing processes as turning (e.g., [19–22]), milling (e.g., [23–27]), and drilling (e.g., [28–30]) can be found. In addition, the obtained results are strongly dependent on the specific alloy and its production technology [31]. Hard metals are widely applied [22, 23, 32], even if some attempts using other cutting tool materials were carried out (as reviewed by Aspinwall et al. [13]). Apart from some promising results, workpiece surface integrity requirements are quite far to be achieved, and the machinability with high-performance cutting materials is still an open research task. In this context, diamond is the hardest and most conductive known material. Even if it is usually unsuitable for machining ferrous materials, because of the high chemical affinity between carbon and iron, diamond has a wide range of applications due to its peculiar properties [33, 34]. For instance, ceramics (e.g., zirconia [35]), metal matrix composites, carbon-fiber-reinforced plastics [36], and wood-based composites [37] were successfully machined with diamond-based tools. Polycrystalline diamond (PCD) exists in different grades, depending on the diamond particle size. Abrasion resistance increases when increasing grain size, while edge quality increases when decreasing grain size (under comparable conditions) [38]. Cubic boron nitride (CBN) is another superabrasive cutting material with high hardness, and its potential applications in machining have been widely investigated for several workpiece materials, as Inconel [39] or steels [40]. The machinability of difficult-to-cut materials and, in particular, of gamma titanium aluminides by using PCD and CBN tools still represents an area to be explored. The research activities presented in the present paper aim to analyze the performance of PCD and CBN tools in comparison to that of uncoated and coated carbide cutting inserts. Tools with different CBN content and PCD inserts with grain size of 2 and 7–10 μm were tested under conventional flood cooling lubrication. Moreover, PCD tools were also applied under cryogenic cooling, as detailed in Sect. 2. Results are discussed in Sect. 3 focusing on tool wear/life and machined surface quality.

2 Experimental approach

2.1 Cutting tests

In order to define the influence of different cutting materials on machining performance, experimental trials were carried out. The workpieces were rods of 16-mm diameter and 160-mm length, made of a Ti-43.5Al-4Nb-1Mo-0.1B (TNM) at% γ-TiAl alloy. The rods were produced by Access GmbH (Germany) via an investment casting process [41] and hot isostatically pressed (HIPed) afterward for 6 h at 1185 °C, at a pressure of 172 MPa, in a pure argon atmosphere. The effects of such treatment on the alloy's microstructure and mechanical behavior are highlighted in Fig. 1. Other information concerning the material properties is detailed in [31]. A preliminary rough-turning operation was executed in order to remove the cast skin and to guarantee the cylindricity of the samples.

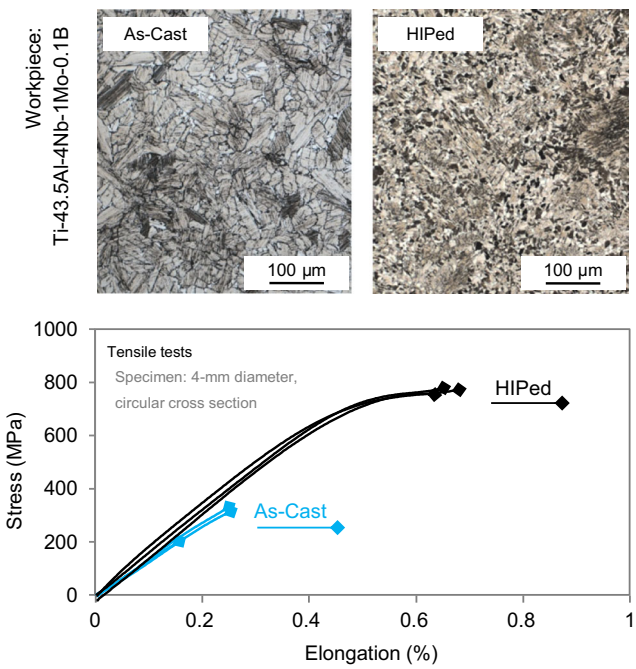

Fig. 1 Effects of HIP treatment on microstructure and properties of the TNM alloy [31]

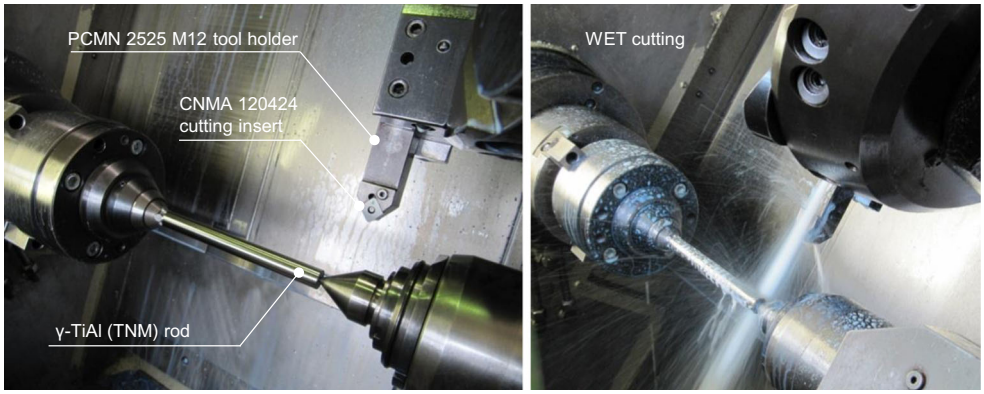

Fig. 2 Experimental setup for wet cutting

Longitudinal external turning tests were performed on a CNC Index GU 800 lathe. Tool geometry and finishing process parameters were chosen according to previous researches [31, 32]. Cutting speed was v_c=80 m/min, feed was f= 0.1 mm, and depth of cut was a_p=0.25 mm. A 6 % emulsion of Fuchs Ecocool TN 2525-HP oil in water, supplied at a pressure of 6 bar, was selected as lubrication condition (conventional flood cooling). Figure 2 shows the experimental setup. The performance of CNMA 120424 coated and uncoated carbide tools, supplied by Febametal S.p.A. (Italy), as well as of cubic boron nitride (CBN) and polycrystalline diamond (PCD) cutting inserts, provided by Cate S.r.l (Italy), was investigated. Cutting inserts with large tool corner radius (equal to 2.4 mm for CNMA 120424 geometry) show lower wear progression and lower surface roughness indices in comparison to those of cutting inserts with small corner radius [32]. Carbide and PCD inserts were sharp, while CBN tools were prepared with a chamfer on the cutting edge (γ_n=20°; $b_{\gamma n}$= 125 μm). More in detail, carbide ISO K10-grade inserts were tested either uncoated or coated with AlCrN and TiAlN coatings. Tools with low (50 %) and high (92 %) CBN content were compared, with titanium nitride or titanium carbide binders. PCD was characterized by a grain size of 2 and 7–10 μm. For PCD tools, the grade of bonding determines the tool resistance against abrasive wear, while the size of the crystals determines the sharpness of the cutting edge. The tools produced with small crystals (applied in the present tests) are expected to generate better surface finish than tools produced of large crystals [33]. Tool wear was checked at regular time steps with a Keyence digital microscope, and surface roughness was acquired by a portable tester. The arithmetic mean roughness R_a and the maximum height of profile R_z were measured in the feed direction at regular time steps. Worn tools and machined surfaces were observed by means of a scanning electron microscope (SEM).

2.2 Characterization of PCD cutting material

At the end of turning tests, focusing onto the tools which had provided the best performance, a characterization of PCD

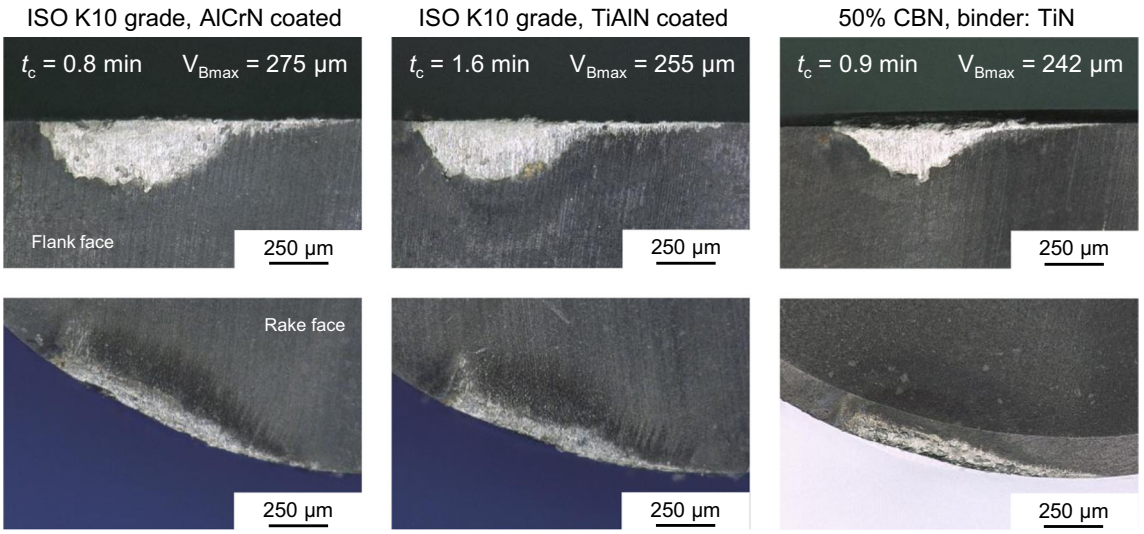

Fig. 3 Tool wear observations for coated carbide and low-content CBN cutting inserts

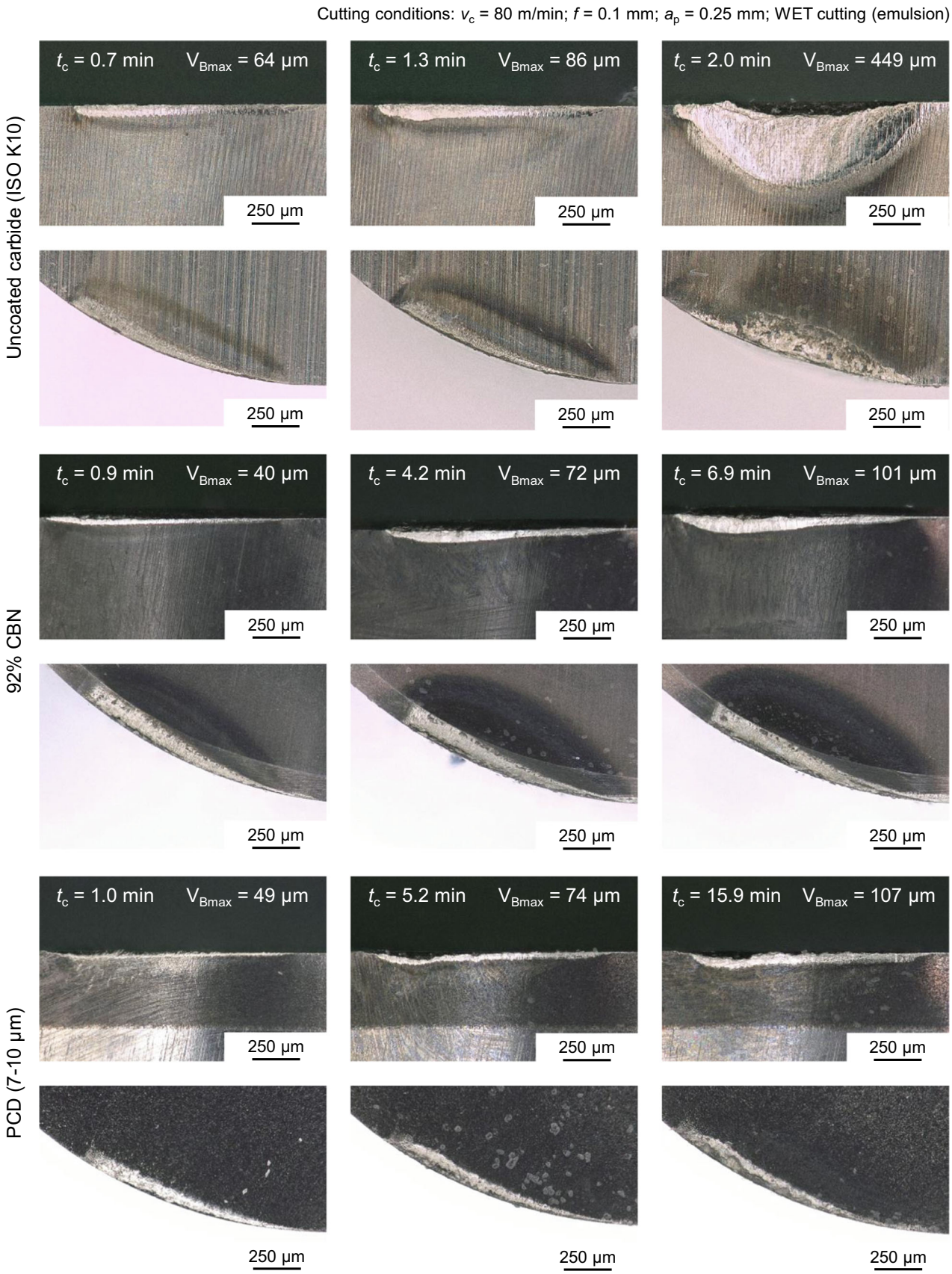

Fig. 4 Tool wear observations for uncoated carbide, 92 % CBN, and PCD 7–10-µm cutting inserts

cutting materials was performed. Microhardness and Young modulus were measured by a Fisherscope HM2000XYm nanoindentation tester equipped with the WIN-HCU software. For this tester, the load ranges between 0.4 and 2000 mN, with a resolution of $4 \cdot 10^{-2}$ mN. A typical Vickers indenter (pyramid shape, with a square base, having a vertex angle of 136°) was adopted. By using this computer-controlled measuring system, test force and indentation depth were measured and recorded continuously, during increasing and decreasing load. Five measurements were acquired per each sample. In addition, the microstructures were studied by using a Scanning Electron Microscope Zeiss EVO 50 fitted out with an energy dispersion spectroscopy (EDS) analyzer for elemental composition detection. A LaB_6 filament was employed, using secondary and backscattered electrons to acquire the micrographs.

2.3 The use of PCD tools under cryogenic cooling

It has already been shown that cryogenic cooling with liquid nitrogen (LN_2) could be a suitable strategy to enhance cutting performance when turning titanium aluminides [32, 42]. The increase of cooling action due to the extremely low temperature of LN_2 is expected to increase the thermal gradient between cutting zone and tool, thus reducing the thermal load on the cutting edge [32]. This effect, matched with the superior thermal conductivity of diamond [34], should enhance the tool life further. Therefore, longitudinal external turning tests combining PCD tools (with the grain size of 7–10 μm) and cryogenic cooling were also executed. The Index GU 800 CNC lathe was set up with a LN_2 supply system (as described in [42]), and CNMA 120424 PCD inserts were clamped in an Iscar PCLNL 2525M-12-JHP tool holder designed to direct the LN_2 flow on the rake face of the tool. LN_2 supply pressure was 2 bar, with a flow rate of 2.3 kg/min. The process parameters were unchanged (v_c=80 m/min, f=0.1 mm, a_p=0.25 mm).

3 Results and discussion

3.1 Tool wear results under conventional flood cooling

Tests continued until reaching a maximum flank wear land (V_{Bmax}) limit of 0.1 mm. The choice of such restrictive value for the wear limit is consistent with previous research studies [31], and it was adopted with the aim of retaining a low tool wear to preserve the surface integrity of the machined parts. The TNM γ-TiAl rods were replaced as the diameter was reduced to 10 mm, in order to avoid dynamic instability problems during the turning process. Experimental evidence demonstrated that a huge tool wear was detected since the beginning of the cutting tests for both AlCrN- and TiAlN-coated carbide tools. Similar results were obtained with 50 % CBN content cutting inserts, in spite of the type of binder (titanium nitride or titanium carbide) used. For all those cutting materials, tool life was less than approximately 1 min (Fig. 3).

For the other cutting materials, tool wear optical images are shown in Fig. 4, and typical tool wear curves are plotted in Fig. 5. It is worth to remark that tool life results are strongly dependent on the workpiece material, as evidenced by the benchmark trials detailed in [31]. The progression of predominantly abrasive wear on the flank side of uncoated carbide inserts is quite regular, up to the achievement of a sudden catastrophic tool failure. A tool life T_L of approximately 2 min was obtained. CBN and PCD tools have the potential to improve the machinability of titanium aluminides, consequently increasing machining productivity. In particular, thermal conductivity and resistance against abrasive wear increase with increasing CBN content and grain size [43]: 92 % CBN content inserts lead to a more stable process, with average tool life of T_L= 7.2 min. Diamond is superior to all the other known materials with respect to hardness and thermal conductivity [34]. An increase in tool life up to $T_L \approx 14$ min was obtained

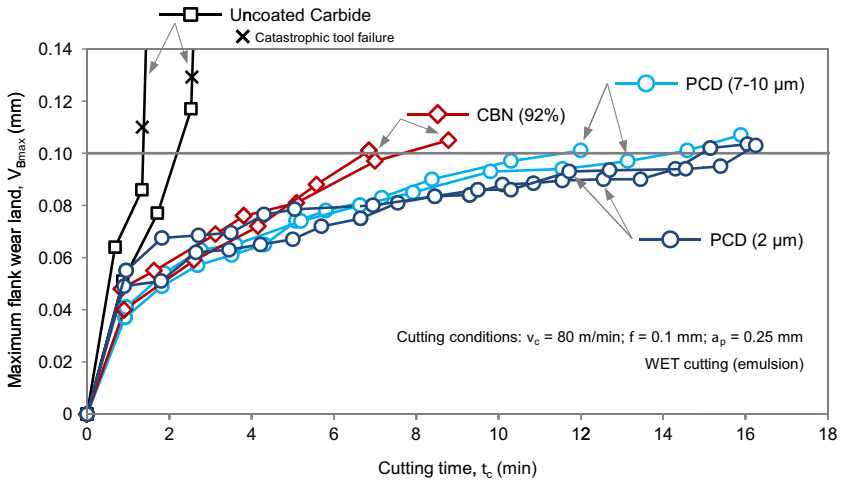

Fig. 5 Influence of cutting material on tool wear curves

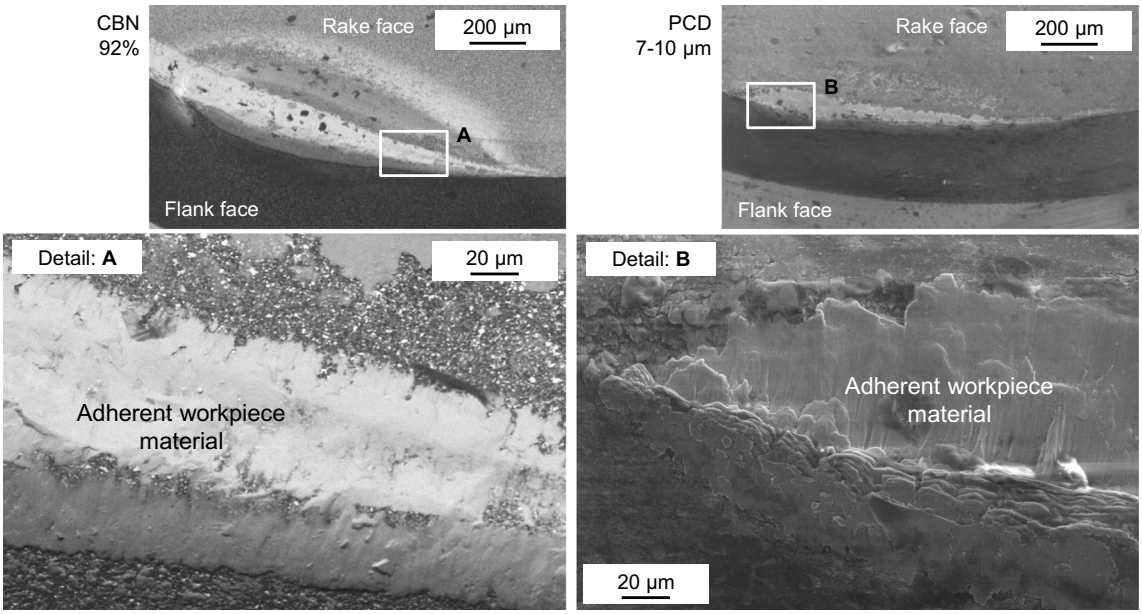

Fig. 6 Adherent workpiece material on worn CBN and PCD cutting inserts

by using PCD tools with 7–10- and 2-µm grain sizes. As shown in Fig. 5, limited differences in tool wear evolution between 7–10- and 2-µm grain sizes were noticed. The abrasive wear mechanism of PCD cutting tools is dominated by cleavage/breaking of individual grains of diamond on microscopic scale [33]. Moreover, the high-magnification pictures obtained by means of SEM (in Fig. 6) highlight that adhesion of workpiece material on the wear scar was detected [44, 45].

3.2 Main properties of PCD cutting material

It is well known from literature that, for PCD tools, each combination of grain size and microstructure results in specific mechanical/thermal properties and wear resistance [33]. In order to better explain the experimental evidences, characterization tests for PCD tool materials were made. The typical elemental composition as well as the microstructures is shown in Fig. 7.

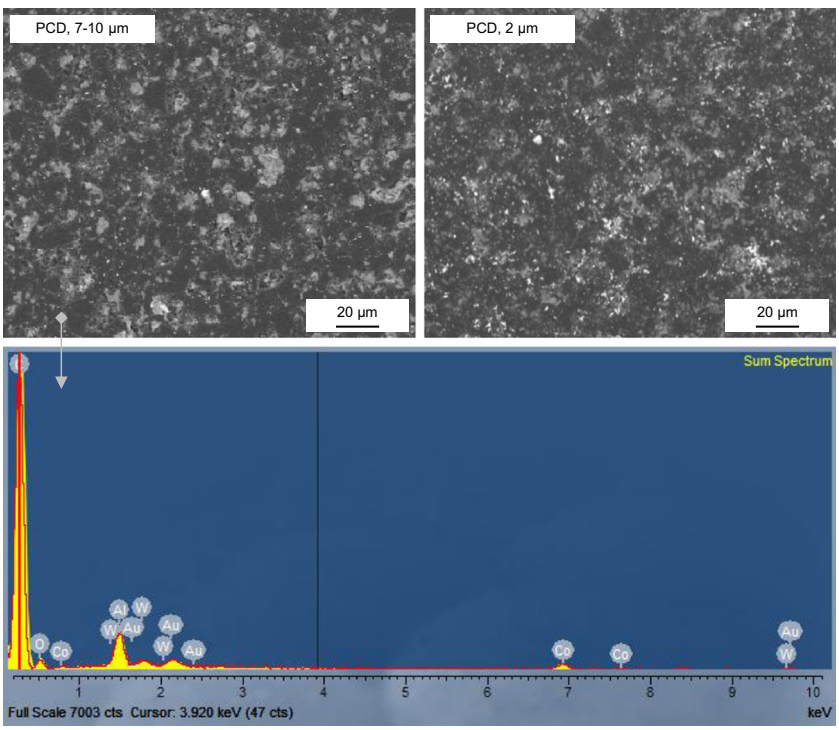

Fig. 7 Microstructures and elemental composition of PCD material

Table 1 Mechanical properties of PCD cutting materials

PCD grain size (μm)	Vickers hardness (HV)		Young modulus (GPa)	
	Average	Std. dev.	Average	Std. dev.
2	6597	1513	612	115
7–10	7442	634	627	68

As far as the elemental composition is concerned, yellow spectrum shows the peaks directly obtained during the acquisition, while the red line corresponds to the theoretical spectrum reconstruction, after the peak assignation, obtained by software. The spectrum evidences the presence of carbon, oxygen, tungsten, and cobalt. The gold arises from the layer (of few nanometer in thickness) sputtered on the surface prior to the sample analysis, aimed to prevent an electrical charging of the insulating material. The amount of aluminum, tungsten, and cobalt ranges between 2 and 3 at.% for all the samples. Therefore, the semiquantitative analysis does not show any significant difference in terms of binder content, so that no influence on the thermal properties is expected to arise from the amount of metals in tool materials. On that basis, thermal conductivity should depend only on diamond particle size, which increase is known to enhance the conductivity. However, no significant differences are expected increasing the size from 2 to 7–10 μm [46]. Vickers hardness and Young modulus for PCD cutting tools are listed in Table 1. PCD inserts of 2- and 7–10-μm grain sizes show comparable hardness average values, since the difference is not statistically different. Two-micrometer PCD has the highest standard deviation because of the difficulty, arising from the grain size, to limit the measurement only to diamond particles that are embedded in the binder. As far as the Young modulus is concerned, the same consideration can be done: 2-μm PCD and 7–10-μm PCD present comparable average values. Such results are in agreement with the unmeaning differences observed in tool wear curves (Fig. 5).

3.3 Surface quality/integrity results

During each cutting test, roughness was monitored by means of a portable tester. Measurements were sampled after each cutting pass, until reaching the end-of-tool life criterion. For all the tests, the average values of the roughness indices were lower than 0.4 and 3 μm for R_a and R_z, respectively. For PCD tools, R_a was 0.28 μm and R_z was 1.8 μm. For CBN tools, R_a was 0.24 μm and R_z was 1.5 μm. The catastrophic tool failure negatively affects the surface integrity of machined components, particularly when using uncoated carbide inserts. As soon as the tool is no longer sharp, a visible worsening of the workpiece machined surface occurs, with the appearance of numerous surface cracks (Fig. 8). Owing to CBN and PCD high hardness and high melting point, high-performance tools

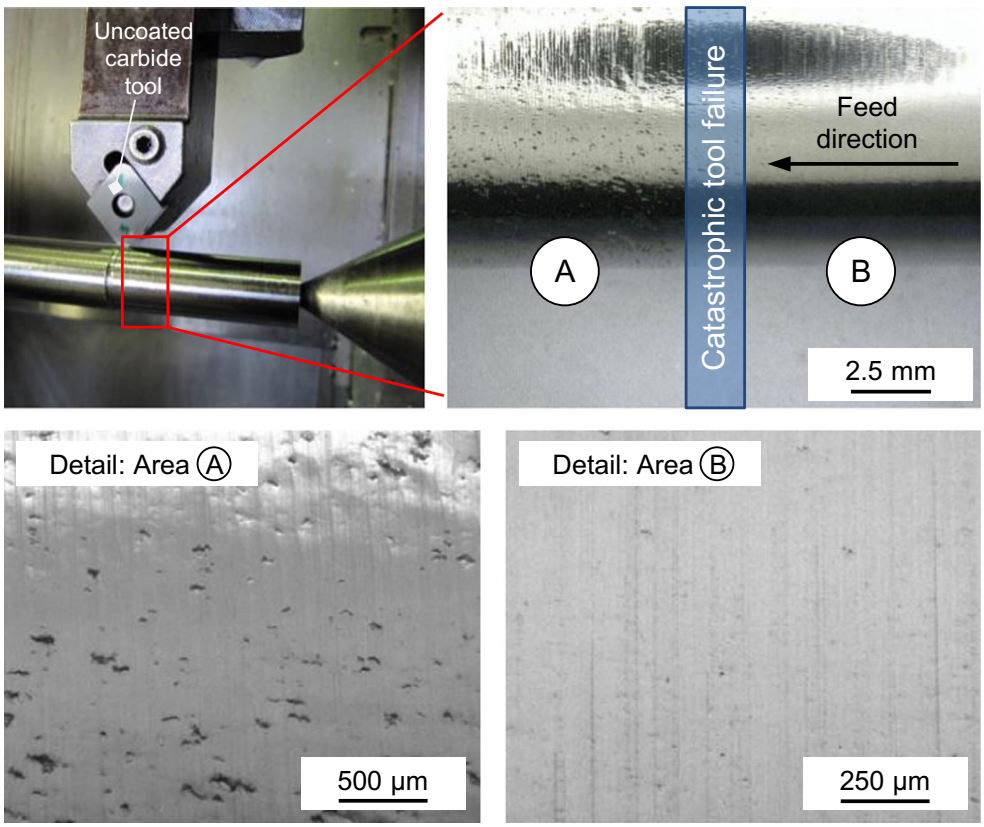

Fig. 8 Effects of tool failure on surface integrity

withstand the heat and pressure developed during cutting without compromising surface integrity of the machined component, because of their ability to maintain a sharp cutting edge for longer periods [47, 48]. Figure 9 shows SEM pictures of the surfaces machined using PCD tools (i.e., the cutting material suitable for attaining the highest tool life). At the end of tool life, surface quality is acceptable, with a limited amount of defects. These ones, according to the previous investigations, could be hypothetically traced back to the presence of borides [31, 32]. Furthermore, crack density is low. In comparison to literature [17, 18], the size of the defects is quite small, being the length in the order of a few tens of microns.

3.4 Cryogenic-assisted turning applying PCD tools

Turning tests under traditional wet conditions and characterization data indicated that the differences between 2-μm PCD and 7–10-μm PCD are poorly relevant. Based on this similarity, only one type of PCD was considered for cryogenic-assisted tests. Figure 10 presents the results of turning trials carried out with 7–10-μm PCD tools and applying cryogenic cooling with liquid nitrogen (boiling point, −196 °C). In comparison to conventional flood cooling, with cryogenic-assisted cutting, a significant increase in tool life was achieved, up to $T_L \approx 30$ min (assuming the tool wear limit criterion of $V_{Bmax} = 100$ μm). As shown by R_a values, roughness rises with the increase of tool wear.

The high thermal conductivity of PCD prevents a high heat accumulation on the cutting edge, and the extremely low temperature of the cooling medium (LN_2) increases the thermal gradient between cutting zone and tool, with a higher heat removal and a huge reduction of thermal load [49, 50]. In addition, the use of an adapted nozzle directing the coolant supply at the tool/workpiece/chip interface should intensify the cooling effect, being the thermo-dynamical impact of the expanding liquid nitrogen close to the cutting zone [51]. An improvement in performance of machined components

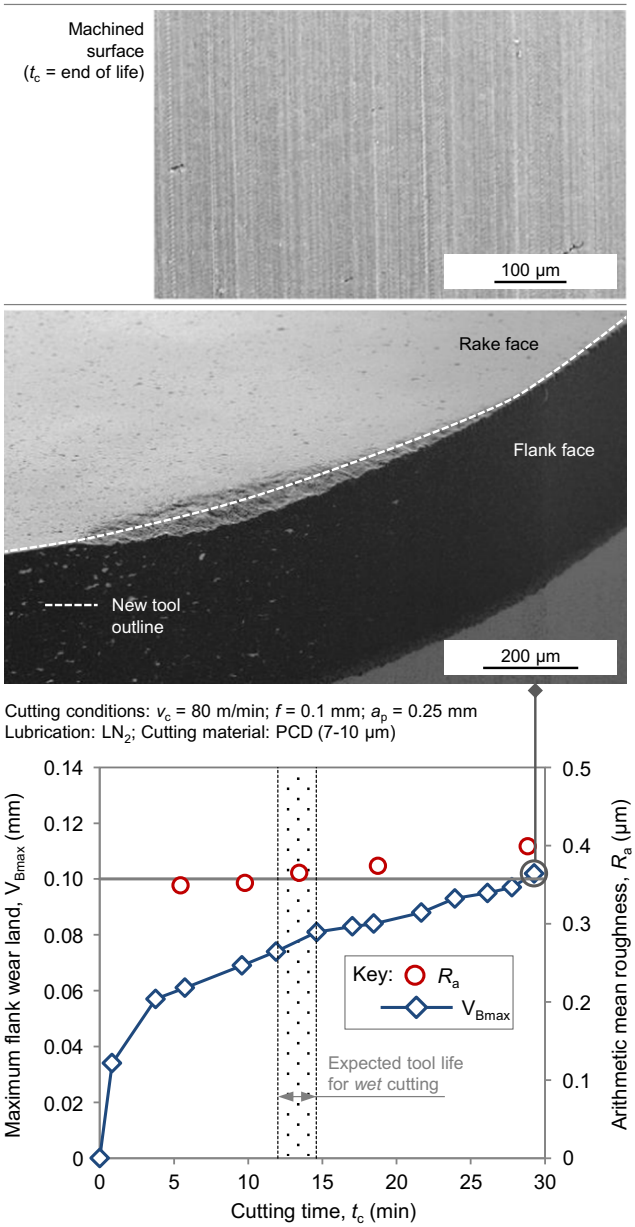

Fig. 10 Typical results for cryogenic-assisted turning of TNM alloy with PCD tools

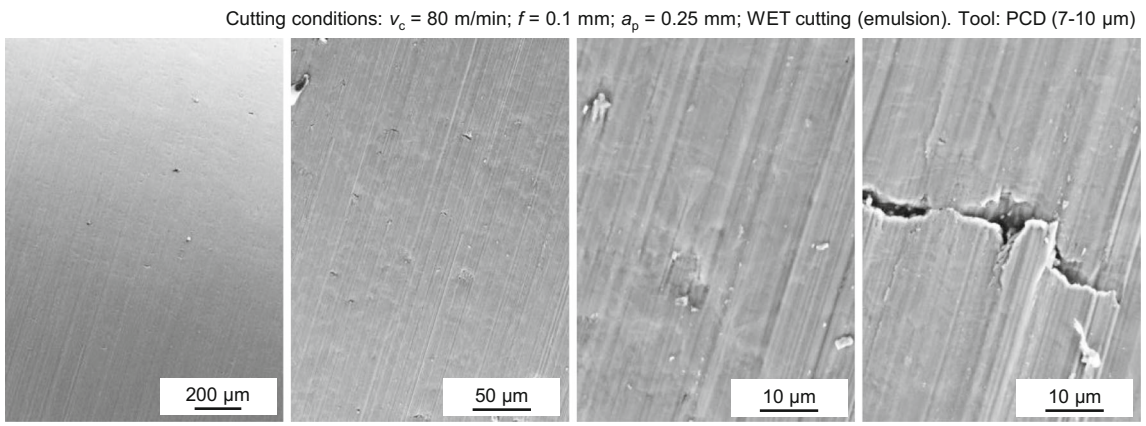

Fig. 9 SEM observations of machined surfaces, at the end of tool life (V_{Bmax}=100 μm), when applying PCD cutting inserts

through a superior surface integrity characteristic is expected [52]. As already discussed in [32], a hardened layer below the surface appears when turning titanium aluminides. The increase in subsurface hardness indicates the susceptibility of the workpiece material to strain hardening. When the tool wear increases, the thermal and mechanical load increases too. With cryogenic cooling, due to the reduction of the tool wear, a reduction of the measured subsurface hardness values (which corresponds to the reduction of the depth of subsurface microstructural alterations) was detected [32].

4 Conclusions and outlooks

Longitudinal external turning tests were performed on an investment-casted and HIPed TNM gamma titanium aluminide, adopting finishing process parameters. The performance of CNMA 120424 uncoated and (AlCrN- and TiAlN-) coated ISO K10 grade carbide tools was compared to that of CBN and PCD cutting inserts, under standard flood cooling lubrication (a 6 % emulsion of cutting oil in water). The CBN content was varied from 50 to 92 %, with TiN or TiC binders, while PCD was characterized by a fine grain size of 2 or 7–10 μm.

Experimental results proved that tool failure was suddenly reached when using coated carbide and low-content CBN inserts. At fixed cutting conditions, the tool life of approximately 2 min achieved with uncoated carbide tools can be extended to 7.2 min with 92 % content CBN tools and to about 14 min by using PCD tools with 7–10- and 2-μm grain size (assuming V_{Bmax}=0.1 mm as tool wear limit). Overall, high-performance cutting tools can improve machining productivity due to the outstanding thermal conductivity, high hardness, and wear resistance. The poorly significant differences in tool wear results between 2-μm PCD and 7–10-μm PCD inserts should be traced back to the limited differences in cutting material properties, as supported by the characterization data.

Tool wear directly affects surface quality results. When the tool wears, the worsening of machined surfaces occurs and surface defects as microcracks appear (in some cases likely due to the presence of titanium diborides within the workpiece microstructure). CBN and PCD are suitable to withstand the heat and pressure developed during material removal without compromising surface integrity, because of their ability to retain a sharp cutting edge for longer cutting time. Moreover, tool life can be enhanced applying cooling strategies to effectively remove heat from the cutting area. When using 7–10-μm PCD inserts, characterized by high thermal conductivity, and increasing the thermal gradient by exploiting the expansion of liquid nitrogen directly supplied on the tool rake face, the heat accumulation on the cutting edge is reduced, further increasing the tool life.

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