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ORIGINAL ARTICLE

On high-speed turning of a third-generation gamma titanium aluminide

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Abstract Gamma titanium aluminides are heat-resistant intermetallic alloys predestined to be employed in components suffering from high mechanical stresses and thermal loads. These materials are regarded as difficult to cut, so this makes process adaptation essential in order to obtain high-quality and defect-free surfaces suitable for aerospace and automotive parts. In this paper, an innovative approach for longitudinal external high-speed turning of a third-generation Ti-45Al-8Nb-0.2C-0.2B gamma titanium aluminide is presented. The experimental campaign has been executed with different process parameters, tool geometries and lubrication conditions. The results are discussed in terms of surface roughness/integrity, chip morphology, cutting forces and tool wear. Experimental evidence showed that, due to the high cutting speed, the high temperatures reached in the shear zone improve chip formation, so a crack-free surface can be obtained. Furthermore, the use of a cryogenic lubrication system has been identified in order to reduce the huge tool wear, which represents the main drawback when machining gamma titanium aluminides under the chosen process conditions.

Keywords High-speed turning · Third-generation gamma titanium aluminide · Surface integrity · Lubricoolant strategy

1 Introduction

The development of advanced lightweight structural materials is a key point for automotive and aerospace applications in order to improve engine performances and efficiency and to satisfy the always more restrictive environmental regulations aimed at reaching a decisive decrease of CO_2 emissions responsible for the greenhouse effect. In this context, gamma titanium aluminides, due to a favourable combination of mechanical and thermal properties, have been identified as predestined candidates to substitute nickel-based materials [1–3]. In general terms, γ-TiAl alloys presents a remarkable strength-to-weight ratio, their density being approximately half that of nickel-based superalloys, together with high stiffness, high elastic modulus and strength retention at elevated temperatures, high refractoriness and oxidation/ignition resistance, and good creep properties.

Promising fields of application have been identified both in rotating and non-rotating parts, such as low-pressure turbines, compressor vanes, swirl nozzles, automotive engine valves and turbocharger wheels [4–6]. The relatively low density of the material leads to reduced engine weights, resulting in higher thrust-to-weight ratios, whilst its higher operating temperatures at the pressures acting upon them allow improving the engine efficiency. The reduced inertia

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is also an advantage for rotating parts. The adoption of smaller components, and hence smaller-sized engines, consequently limits fuel consumption. Such alloys have advantages versus nickel-based alloys in the intermediate temperature interval of 650–800°C, whilst in comparison to titanium-based alloys like Ti-6Al-4V, gamma titanium alloys could be employed at decisively higher temperatures. Therefore, in aircraft engines, this material is destined to substitute nickel-based alloys in the hot parts of aircraft engines, whilst the usage of conventional titanium alloys is limited to the cold part in front of the combustion chamber.

Up to now, a wide-ranging usage of this material in serial applications is limited despite the attractive mechanical and thermal properties. This can be traced back to high material and processing costs, especially due to its poor machinability. In fact, gamma titanium aluminides are regarded as difficult-to-cut alloys because of their low ductility combined with high hardness and brittleness at room temperature, low thermal conductivity and high elevated temperature strength, low fracture toughness and chemical reactivity with many tool materials [7]. One of the main problems related to the poor machinability of these materials is the formation of defects in the form of micro-cracks and micro-fractures on the workpiece surface [7, 8]. These defects act as the initial point for crack propagation resulting in part failure, which is completely unacceptable for safety-critical components, whereas surface integrity is indispensable.

Machining investigations with defined cutting edges published in the literature highlight that under conventional process conditions (at a relatively low cutting speed), it is impossible to obtain crack-free surfaces and that the subsurface microstructural damages consist also of material pullout, surface drag with deformed lamellae, cracked TiB_2 particles and hardened layers [9, 10]. One opportunity to avoid the occurrence of cracks was identified in grinding [11, 12] and in high-speed milling with ball end tools. In particular, the results presented by Mantle and Aspinwall [13] have shown that samples without cracks and with an average surface roughness (R_a)<1.5 μm could be obtained, although microstructural alterations were detected. These studies, executed on a cast and treated Ti-45Al-2Mn-2Nb+0.8 vol% TiB_2 XD alloy, evidence a strong correlation between process parameters and workpiece surface integrity and suggest that high-speed cutting strategies result in better surface conditions.

Interest in the machinability of gamma titanium aluminides is still increasing, focussing on milling [14, 15], drilling [16] and turning [17–20] processes. However, further work is needed to optimize machining strategies leading to high productivity at aerospace quality levels, where surface integrity is indispensable for the in-use component, focussing on tool and process design as well as the development of the adopted high-performance lubricoolant strategies. With respect to this last aspect, the potential benefits of cryogenic lubrication, which have been proven to be effective in the machining of other conventional titanium alloys, have not been investigated yet.

In the presented machining trials, demanding cutting conditions using round inserts were selected to guarantee thermal softening in the shear zone and, furthermore, to produce satisfying surfaces. After confirming the high quality of the produced surface under these conditions, strategies have been identified to focus more on industrial applicability, meaning especially the usage of C-geometry inserts and lubricoolant strategies to reduce the thermal tool load without preventing thermal softening in the shear zone.

2 Experimental approach

In longitudinal external turning investigations, the machinability of the gamma titanium aluminide alloy Ti-45Al-8Nb-0.2C-0.2B (proportions in atomic percentage) TNB-V3 was investigated. This material belongs to the third generation of high-performance gamma titanium aluminides, which have been developed in the past few years. From the chemical composition standpoint, the main difference with the predecessors is related to the increased content of niobium: this allows higher strength values and enhanced thermal stability. It has also been shown that a 5–10 at.% addition of Nb significantly improves oxidation behaviour and increases creep resistance [21]. Figure 1 shows the fully lamellar microstructure of the workpiece: the grains consist of γ- and α_2-lamellae, and the presence of borides is detected.

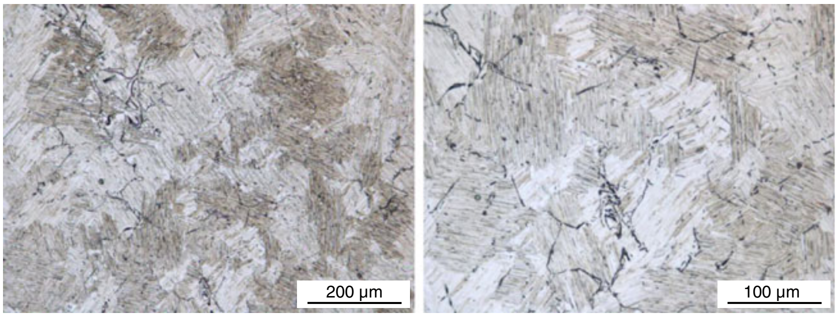


Fig. 1 Optical micrograph showing the microstructure of workpiece Ti-45Al-8Nb-0.2C-0.2B alloy at ×100 (*left*) and ×200 (*right*) magnifications

Machining trials were performed on an Index GU 800 CNC lathe. TNB-V3 rods of Ø=15 mm diameter were clamped in a three-point chuck, with an overhang of 20 mm. Prior to each experiment, a preliminary roughing operation was made in order to remove the cast skin and to guarantee a constant diameter of the samples (Ø=14 mm). Afterwards, the cutting tests were executed with uncoated cemented carbide inserts, adopting different tool geometries (Fig. 2), process parameters and lubrication conditions. The cutting length in the feed direction, l_f, was limited to 10 mm.

Round RCMX 120400 inserts have been applied using Microjet MKS-G260 minimum quantity lubrication (MQL) system and cutting conditions ranging as follows: cutting speed, v_c, from 60 to 100 m/min; feed f from 0.05 to 0.2 mm; and depth of cut, a_p, from 0.1 to 0.4 mm. Furthermore, in order to reduce the huge tool wear related to severe cutting conditions and due to the thermal and mechanical stresses that affect the cutting edge, the effects of an intensive cooling with liquid nitrogen (LN_2; boiling point, −196° C) were investigated. A tool holder for C-geometry tools (provided by Iscar) was used, representing a common tool holder used for high-performance machining operations in the aircraft industry (Fig. 3). The directed lubricoolant supply with an adapted nozzle intensifies the cooling effect, meaning that the thermodynamical impact of the expanding liquid nitrogen could be applied directly close to the cutting zone. Therefore, at fixed process parameters (v_c=100 m/min, f=0.1 mm and a_p=0.4 mm), negative geometry CNMA 120408 inserts with different chamfer dimensions (Fig. 2) have been applied under cryogenic lubrication, and the results were compared with MQL and dry conditions.

For the evaluation of the machinability, chip morphology, tool wear and corresponding surface roughness, surface integrity and cutting forces were considered. More in detail, worn tools were observed with a Keyence digital microscope, surface roughness profiles were measured by means of a Mahr perthometer PGK120, cross-sections of the machined surfaces were analysed by a scanning electron microscope (SEM), and cutting forces were acquired using a three-component Kistler dynamometer.

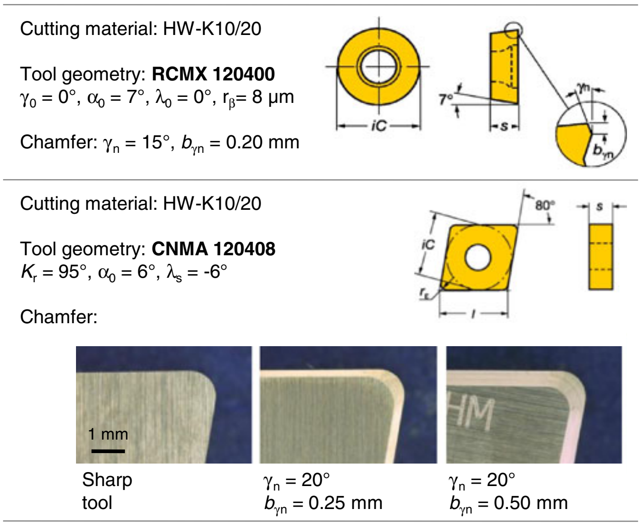


Fig. 2 Cutting insert specifications (tool geometry sketches are from Sandvik Coromant)

3 Results and discussion

The main objective of the experimental results obtained in longitudinal high-speed turning operations was to describe the correlation between tool geometry, cutting conditions and lubricoolant strategy under exaggerated temperatures caused by high cutting speeds and its impact on surface quality.

3.1 Chip morphology

The high brittleness of gamma titanium aluminides retained up to high temperatures and the poor material behaviour of deforming plastically complicate the machining decisively, mainly due to the formation of segmented chips [22]. Therefore, the machined workpiece material is ripped out of the machined surface, resulting in surface defects such as fracture structures and extensive cracks [9]. The chip cross-section in Fig. 4 illustrates the longitudinal section of a typical saw-tooth chip showing the angular, needle-shaped chip lamellae obtained during a turning operation.

Figure 5 depicts the correlation between the chip shape/size and the cutting parameters for the tests executed with round and chamfered RCMX inserts by adopting the MQL lubrication conditions. Under the chosen range of parameters, chip size increases with the increase of the depth of cut, especially with the transition from a_p=0.3 mm to a_p=0.4 mm, and with the increase of the cutting speed up to v_c=100 m/min. In addition, an amplification of the chip size due to an increase of feed, within the range f=0.05–0.2 mm, is slightly perceivable. The high temperatures achieved in the shear zone, as a consequence of the high deformation of the material, allow softening the material and improving the chip formation. In particular, the heat in the shear zone can be traced back directly to the cutting speed, and coiled chips are formed.

On the other hand, as shown in Fig. 6 for CNMA cutting inserts, at fixed process parameters, chip dimension increases directly with stronger material deformation, resultant to the different cutting tool geometries, and, hence, with the rise of the thermal softening of the gamma-TiAl alloy. The use of chamfered tools instead of sharp ones allows increasing the average chip size and length, both with dry and cryogenic lubrication conditions. Moreover, with the liquid nitrogen lubricoolant, the huge reduction of the

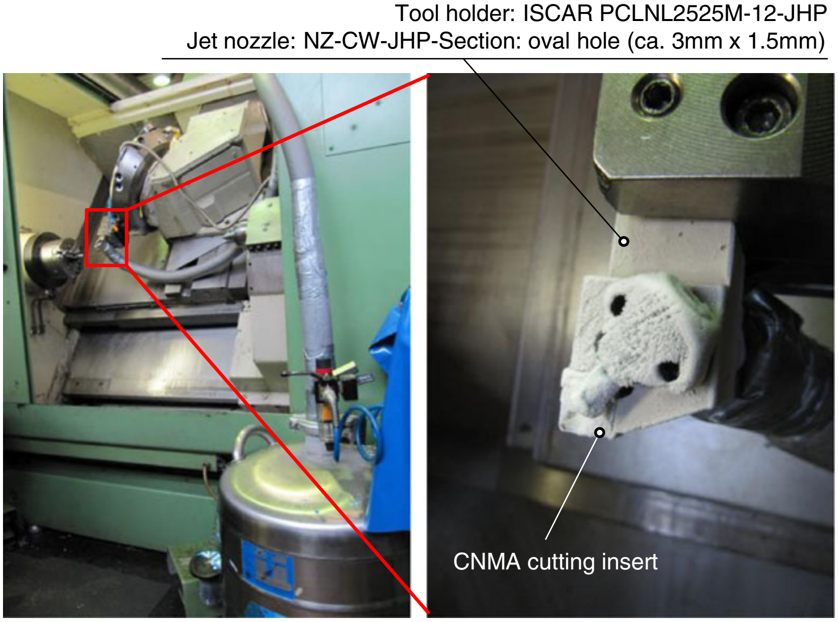


Fig. 3 Experimental setup with cryogenic lubrication equipment. The detail (*right*) shows a CNMA insert clamped on an Iscar tool holder at the end of a cutting test

temperatures in the tool/workpiece contact area reduces the size and fragments the chips, as expected. The higher temperatures reached in dry conditions are confirmed by the different colour of the chips, which are darker than those obtained with the cryogenic lubrication system.

3.2 Surface quality

As far as surface integrity is concerned, it has been shown by Sharman et al. [9] that surface crack formation has a dependence on process parameters similar to that of surface roughness: crack density increases if the feed increases and the cutting speed decreases. Thus, as surface finish improves, the number of detected cracks is reduced.

In Fig. 7, some of the outcomes achieved in terms of arithmetic mean roughness, R_a, and maximum roughness profile height, R_z, are compared, considering different tool geometries, cutting parameters and lubrication conditions. The average roughness indices were calculated by considering the overall cutting length (10 mm) in the feed direction, and the error bars show the range obtained with the repeated tests.

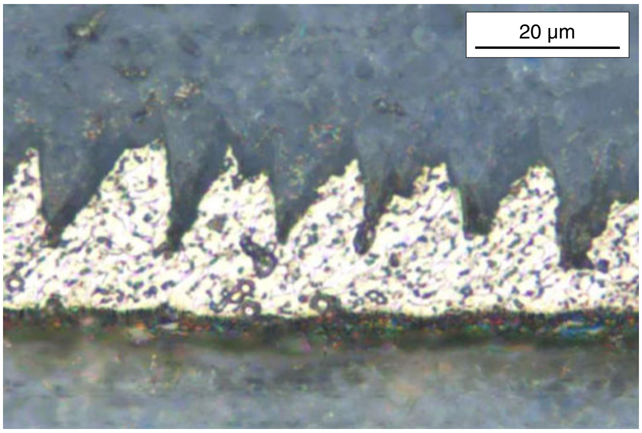


Fig. 4 Longitudinal section of a typical saw-tooth chip obtained in turning tests with the RCMX cutting inserts for MQL lubrication conditions

With an appropriate selection of the process variables, it is possible to maintain the roughness indices below the tolerance limit (R_a=0.4 µm), imposed by the rigorous demands of the aerospace sector [23]. More in detail, by using the minimum quantity lubrication system, the results obtained with the uncoated carbide round and chamfered RCMX inserts highlight that a high-speed turning strategy could be successfully implemented. The effects of process parameters follow the literature. Fig. 7a shows for instance, for the test executed at v_c=80 m/min and a_p=0.2 mm, the decrease of roughness indices R_a and R_z, with an approximately linear trend, as a result of the reduction of the feed from f=0.2 mm down to 0.05 mm. According to Section 3.1, a favourable chip formation was achieved influencing the machinability directly. Some samples, characterized by satisfactory values of surface roughness, were sectioned and analysed by SEM: high-quality and crack-free surfaces can be produced, as shown in Fig. 8. Subsurface microstructural alterations were noticed, and in particular, the effects of surface drag can be evidenced by the lamellae deformation. As reported by Mantle and Aspinwall [13], this phenomenon indicates strain at high temperatures.

For CNMA inserts with both sharp and chamfered cutting edges, the effect of the lubrication conditions is highlighted in Fig. 7b at constant process parameters: a significant roughness reduction was achieved applying cryogenic cooling, also in comparison with MQL lubrication. The improvement of the surface finish could be traced

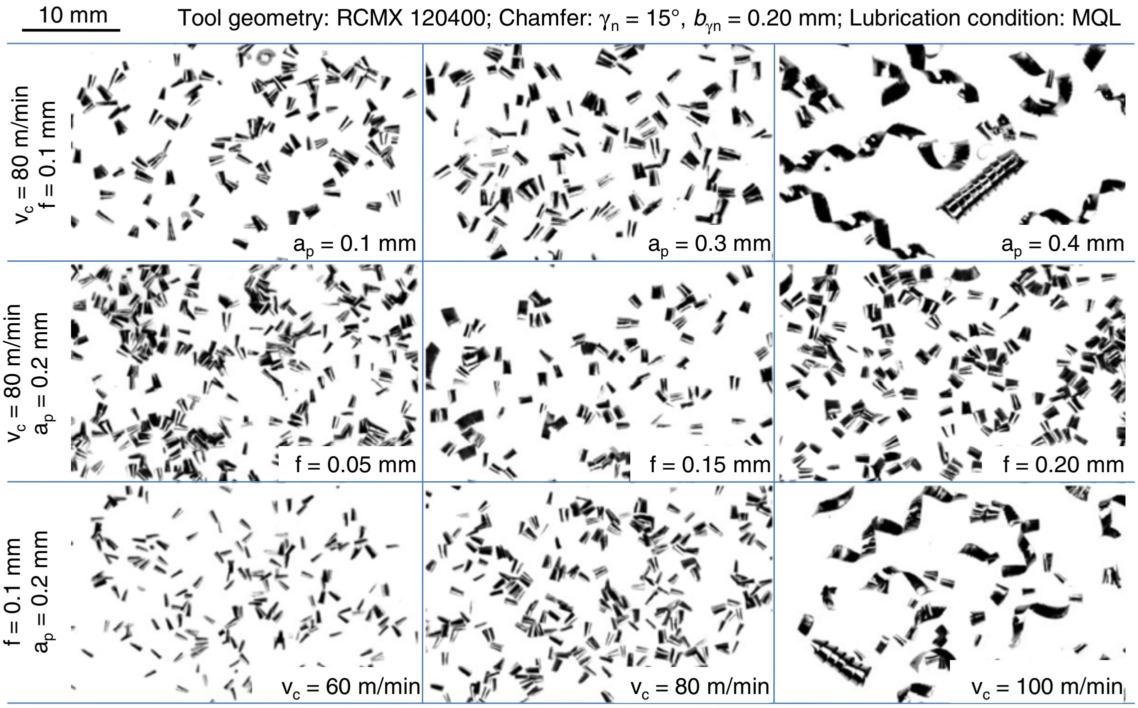


Fig. 5 Chip morphology as a function of cutting parameters for MQL lubrication conditions

back directly to the reduction of tool wear. In Fig. 9, showing the roughness profiles and the machined surfaces from the beginning to the end of the tests, the deterioration of quality due to tool wear is easily perceivable in dry conditions. With a heavily worn tool (see also Fig. 11, Section 3.4), surface cracks with a characteristic dimension of about tens of microns appeared. This unsatisfactory result could be averted by the adoption of a cryogenic lubrication strategy resulting in a stable cutting process which reduced the flank wear decisively. In spite of the benefit of the lubricoolant strategy in terms of flank wear reduction, the surface quality is basically influenced by the edge radius. Therefore, at fixed process parameters, due to the impact of the corner radius, higher surface qualities were produced in dry conditions (Fig. 7) with the applied RCMX inserts (edge radius, r_ε=6 mm) than with CNMA tools (r_ε=0.8 mm). Focussing on the industrial needs, the use of C-geometry inserts is demanded, meaning furthermore that applying

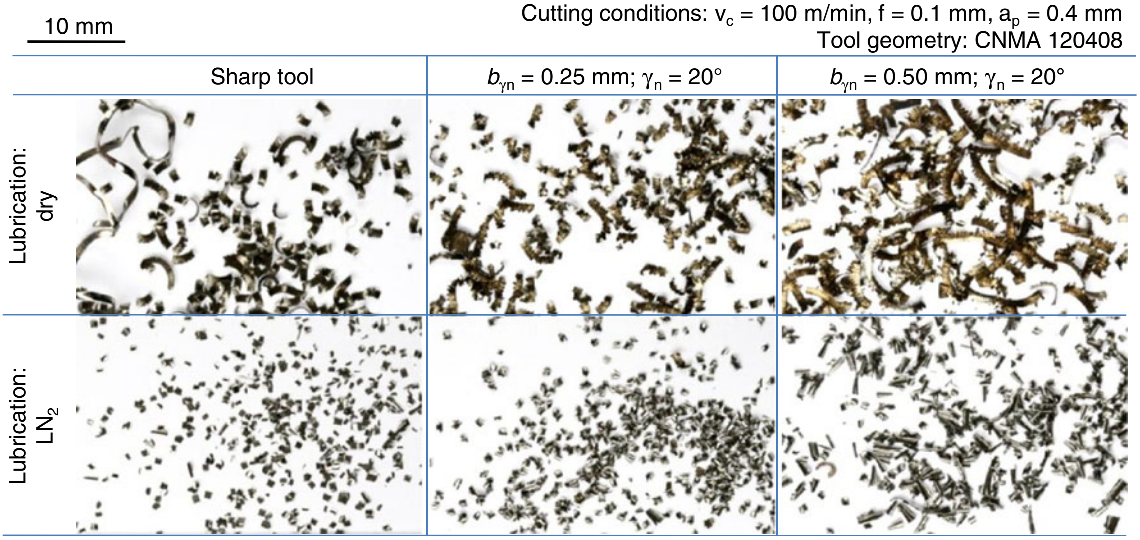
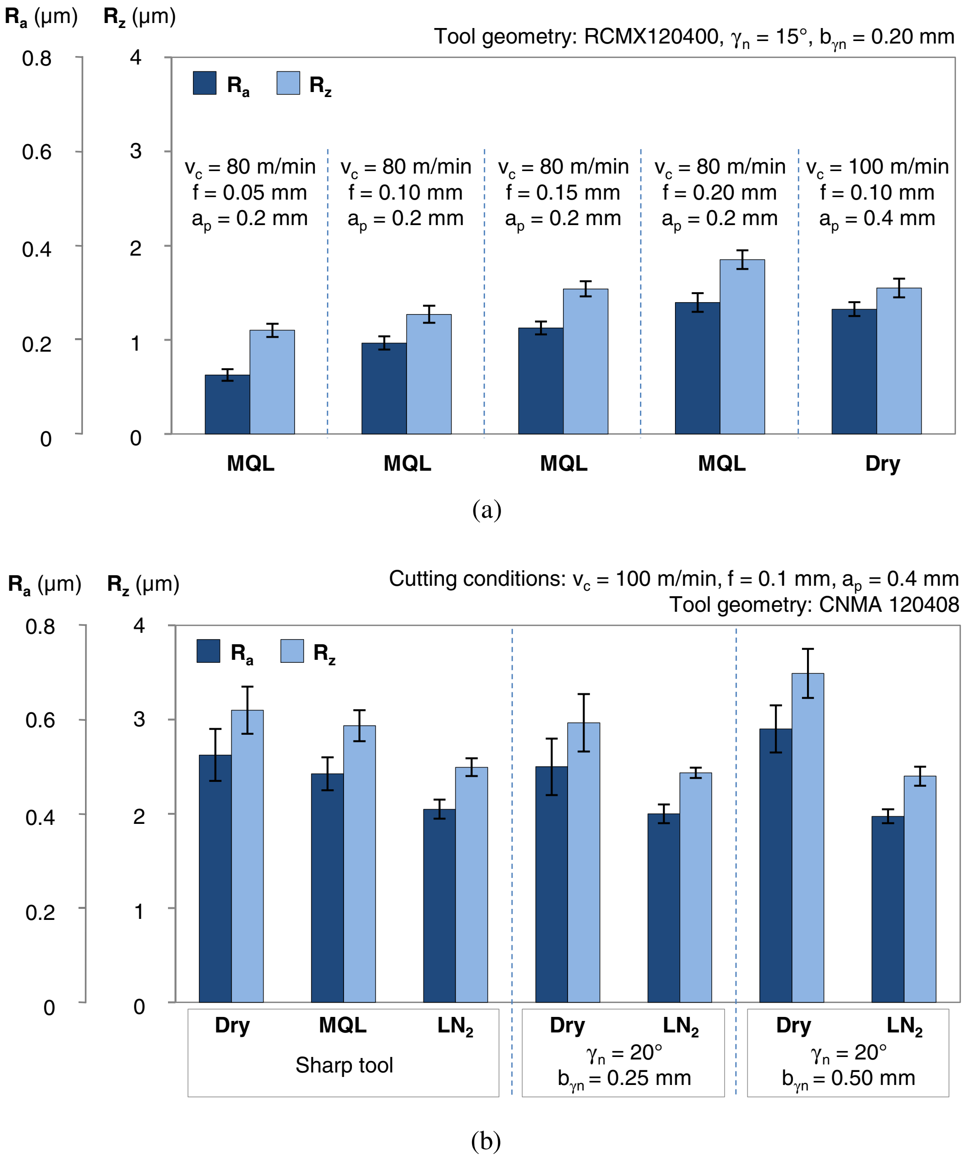


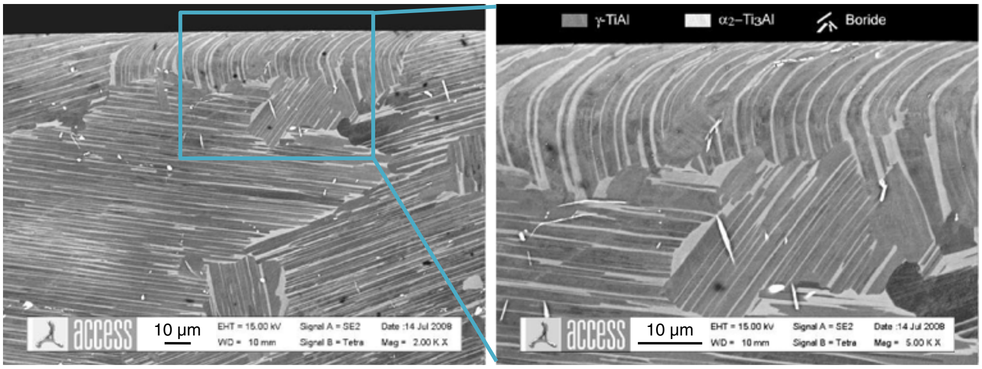
Fig. 6 Chip morphology for dry and cryogenic (LN_2) lubrication conditions: comparison between different CNMA tool geometries at fixed process parameters

Fig. 7 Roughness results for RCMX (**a**) and CNMA (**b**) cutting inserts



round inserts is not possible for industrial machining operations. Therefore, the adoption of the lubricoolant strategy was focused on the C-geometry inserts where its huge impact could be proven.

Fig. 8 Cross-section of the machined surface showing surface integrity with lamellae deformation in cutting direction (courtesy of Access)



Cutting conditions: v_c = 80 m/min, f = 0.1 mm, a_p = 0.4 mm, MQL
Tool geometry: RCMX 120400, γ_n = 15°, $b_{\gamma n}$ = 0.20 mm
Surface Roughness: R_a = 0.21 µm, R_z = 1.4 µm

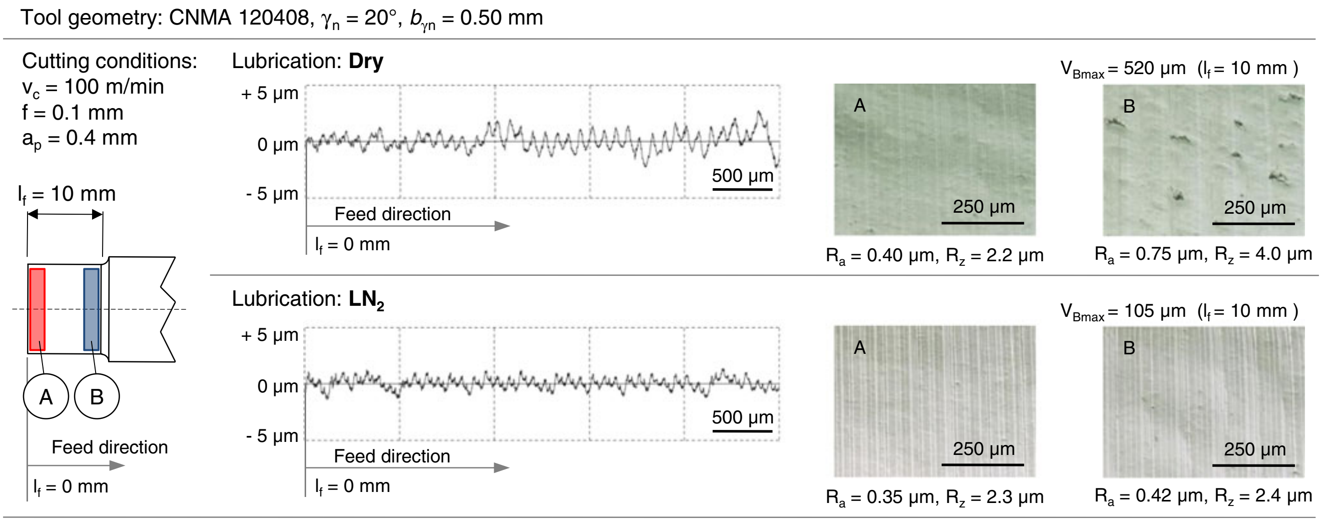


Fig. 9 Machined surfaces with fresh/worn inserts and roughness profiles (type R). Comparison between dry and cryogenic cooling at fixed process parameters

3.3 Cutting forces

The measured cutting forces for turning with RCMX tools are shown in Fig. 10. The average values of the three force components (passive force, F_p; feed force, F_f; and cutting force, F_c) refer to fresh cutting inserts, considering the measurements taken immediately after the tool–workpiece engagement. Variability of results for the repeated experiments remained lower than 10 % in terms of relative range.

It is implied that passive forces are always higher than the other components, whereas the influences of process parameters on the forces are clearly visible. The cutting speed, v_c, has the slightest impact on the cutting forces in comparison to the other considered variables, with a moderate increase of the measured values. Much more distinctive effects are due to the increase of feed and depth of cut, particularly on passive and cutting forces. The graphs suggest that a gain in material removal rate should be possible by increasing the chip cross-section through variations of feed rather than of depth of cut.

Cutting forces increase rapidly as a result of tool wear, and this observation can already be pointed out in the first seconds of machining time and for all the executed tests. Adopting the strict process parameters chosen for the experimental plan, this phenomenon is particularly evident in absence of a lubricoolant supply (Fig. 11). Furthermore, the cutting forces are influenced by the tool geometry. A comparison between the CNMA inserts with varied geometries highlights that passive and cutting force measured with chamfered tools are slightly higher than those

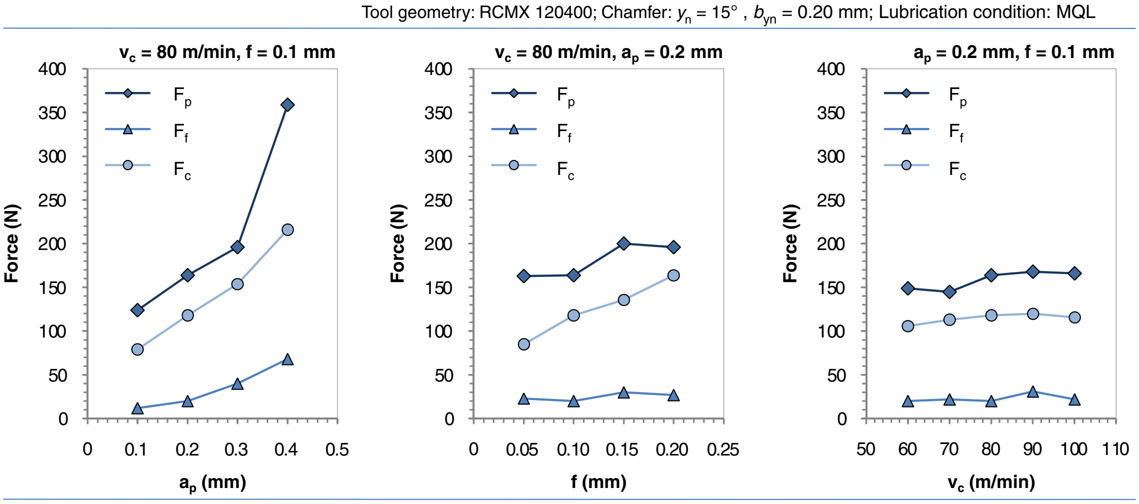


Fig. 10 Cutting forces results (F_c cutting force, F_f feed force, F_p passive force) with the RCMX round inserts and for MQL lubrication conditions

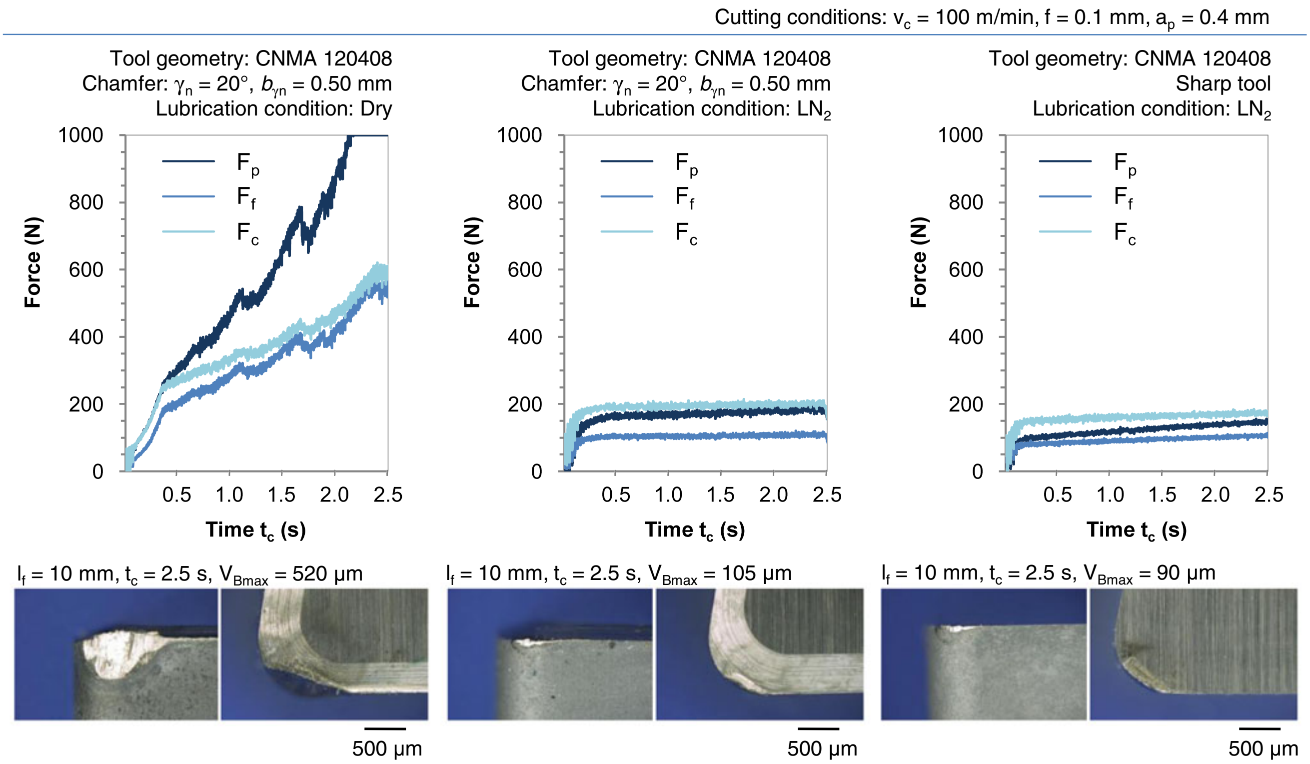


Fig. 11 Cutting force measurements and tool wear with the CNMA inserts referring to dry and cryogenic (LN_2) lubrication conditions

measured with sharp tools as a result of the aforementioned increase of the grade of material deformation in the shear zone.

3.4 Tool wear

The previous considerations have proven that the machining of the hard-to-machine alloy was improved by evoking high temperatures in the shear zone, allowing overstepping the brittle/ductile transition and softening the material in order to obtain high-quality and crack-free surfaces. Therefore, heat itself can be considered as a tool. Conversely, the main drawback regarding this machining strategy is that the increased thermal impact to the cutting edges of the tools results in stronger tool wear, as shown in Figs. 11 and 12 for the CNMA and RCMX inserts, respectively. In addition, the discontinuous formation of lamellar chips, which involves a constant shift between compression and sliding phenomena in the shear zone, subjects the tool to a mechanical and thermal alternating load [22]. Cutting operations with worn tools result in poor surface quality, especially the presence of micro-cracks, surface hardening and residual stresses [7, 13].

The results show that effective cutting in dry conditions is not practicable due to a sudden tool failure. Also, with MQL lubrication, the tool life is extremely short, especially with the chosen strict process parameters needed to overstep the brittle/ductile transition. Cryogenic cooling (Fig. 11) could be successfully applied to counteract the huge thermal load on the cutting edges, providing potentially enormous benefits: the improvement of effective cooling action due to the lower temperature of the cooling medium increases the thermal gradient between the cutting zone and tool, with a higher heat removal rate.

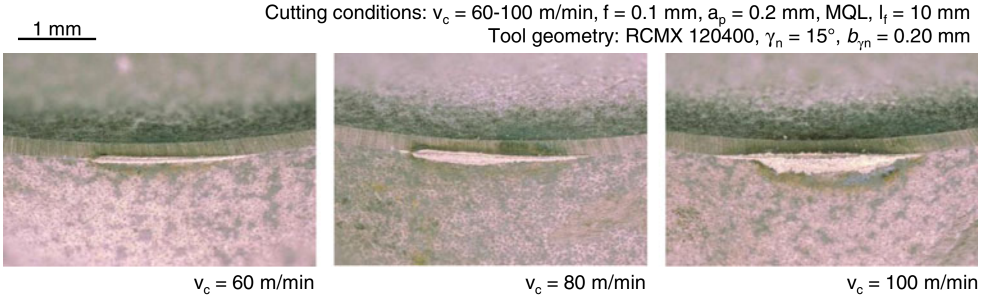


Fig. 12 Tool wear for RCMX inserts and minimum quantity lubrication

4 Conclusion and outlooks

Poor machinability of gamma titanium aluminides and, furthermore, the high manufacturing costs limit the widespread use of those material in the market, although a few production processes have already been qualified for aerospace engine components in which surface integrity is of major importance.

As these presented results have proven, the machining of the Ti-45Al-8Nb-0.2C-0.2B intermetallic γ-TiAl alloy can be enhanced significantly, as far as the surface quality is concerned, by an adjustment of the process parameters and of the cutting edge geometry. In particular, with cutting speed up to $v_c=100$ m/min, the brittleness of this material drops off, due to the high temperatures reached in the shear zone, and chip formation is improved. Adopting the minimum quantity lubrication, in longitudinal external turning tests with round, chamfered and uncoated RCMX inserts, it was possible to obtain smooth ($R_a<0.4$ μm) and crack-free surfaces, even if transverse cross-sections of the machined samples highlighted deformation of the lamellae. The tests performed with the CNMA inserts show roughness results slightly superior to the tolerance limit imposed by the aerospace industry: consequently, small ratios of depth of cut, a_p, to the corner radius, r_ε, should be suggested in turning operations.

The described and adopted strategy for the high-speed machining of this material increases, on the one hand, the machinability, but results, on the other hand, in a high thermal load of the cutting edge. The poor tool life is still the main disadvantage to be optimized. A promising opportunity which yielded interesting results is the use of cryogenic lubrication with liquid nitrogen.

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