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High performance cutting of gamma titanium aluminides: Influence of lubricoolant strategy on tool wear and surface integrity

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ARTICLE INFO

Article history:
Received 4 September 2012
Received in revised form
18 December 2012
Accepted 23 December 2012

Keywords:
Tool wear
Abrasion
Lubrication condition
Cryogenic cooling
Gamma titanium aluminide

ABSTRACT

Heat resistant gamma titanium aluminides are intermetallic alloys planned to be widely used in high-performance aircraft engines within the next few years. This application field is ascribed to the exceptional material properties, especially the low density and a unique strength-to-weight ratio for titanium-based alloys, good oxidation behaviour and thermal stability, limited ductility and fracture toughness below brittle-to-ductile transition, and good creep resistance.

The demanding machinability of gamma titanium aluminides can be traced back to these desirable material properties. Consequently, cutting process adaptation is essential to obtain components suitable to satisfy strong regulations regarding surface integrity, without neglecting an economical production. Previous research activities confirmed that thermal material softening during cutting due to the high speed machining is a key to reach high quality surfaces, but tool wear was identified as the limiting factor.

The relatively high cutting speed results in high temperatures in the shear zone and the low thermal conductivity of the γ-TiAl workpiece material leads to an extreme thermal tool load. Furthermore, in combination with the formation of saw-tooth chips and the discontinuous flow of the chip along the rake face, adhesive wear is caused.

The influence of conventional flood cooling and high pressure lubricoolant supply (wet conditions), cryogenic cooling with liquid nitrogen, and minimum quantity lubrication (MQL) were investigated in longitudinal external turning operations. Tool wear, cutting forces, chip morphology and surface roughness were evaluated. Surface integrity was analysed in terms of machined surface defects and sub-surface alterations.

The investigations indicate that cryogenic cooling is the most promising lubrication strategy, meaning that the thermodynamical impact of the expanding liquid nitrogen applied directly close to the cutting zone successfully counteract the huge thermal load on the tool cutting edges, providing potentially enormous benefits in terms of tool wear reduction and consequent surface quality improvement.

1. Introduction

Heat resistant intermetallic gamma titanium aluminides (γ-TiAl) have been identified as possible alloys for high-performance automotive components [1,2], and they are intended for a wide usage in aerospace applications, especially in the hot parts of aircraft engines [3,4]. This increasing interest can be traced back to the extraordinary material properties, which are not even comparable with conventional titanium-based alloys: low density and therefore favourable strength-to-weight ratio, good oxidation behaviour and thermal stability, limited ductility and fracture toughness below brittle-to-ductile transition, and good creep resistance properties. The poor machinability of gamma titanium aluminides has been reported in conventional machining such as turning and drilling, and in non-conventional machining, as EDM. In comparison to conventional titanium-based aerospace alloys (i.e. Ti–6Al–4V), the mechanical properties of gamma titanium aluminides show significantly higher brittleness at room temperature. Also, taking into account its tendency to rapidly wear cutting edges, it is not surprising that γ-TiAl alloys are considered notorious difficult-to-cut materials [5].

Surface quality is of major importance for the in-use component, and very high requirements for safety and durability are required for the application in aircraft engines. One opportunity to counteract the arise of surface and sub-surface cracks was identified in grinding [6] and high speed machining [7]. In turning

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http://dx.doi.org/10.1016/j.wear.2012.12.035

operations, it has been shown that with high temperatures in the shear zone, chip formation is improved and a high quality surface can be produced. The adoption of high speed machining conditions entails relevant effects on tool wear. On the one hand the relatively high cutting speed results in high temperatures in the shear zone, and on the other hand the low thermal conductivity of the γ-TiAl workpiece material leads to a high thermal load of the cutting edge, since a large portion of the heat produced during the process has to be dissipated by the tool. As a consequence, accelerated tool wear and relative deterioration of the machined surfaces are detected [8].

The aforementioned extreme thermal tool loads can be limited by lowering the cutting speed or the feed rate. In finishing operations, the feed rate is typically fixed due to its impact on the surface quality. Taking the hot hardness of the gamma titanium alloy and its resultant poor machinability into account, the demand of a huge temperature to overstep the ductile/brittle border can be explained. Based on these considerations, alternative ways have to be found to reduce the thermal impact on the tool and to produce satisfactory surfaces at the same time. In machining operations with geometrical defined edges, the temperature can be traced back to material deformation and to friction. While material deformation takes place mainly in the shear zone, most of the heat caused by friction is caused by the sliding chip between tool rake face and chip bottom side. As a result, the heat in the shear zone supports chip formation, while friction increases the thermal impact on the tool.

One approach to extend tool lifetime in high performance cutting of difficult to cut materials was identified in advanced lubricoolant strategies. In this context, the effectiveness of the cooling is improved by the usage of high pressure lubricoolant supply, leading to tool temperature and wear reduction [9–12]. One alternative to improve process cooling is cryogenic cooling [13–15], leading to a further reduction of tool temperature by using media with extremely low temperatures when expanding, as liquid hydrogen (boiling point: $-253\,^{\circ}$C), liquid nitrogen (boiling point: $-196\,^{\circ}$C), liquid oxygen (boiling point: $-183\,^{\circ}$C) and dry ice/CO_2 snow (sublimation point: $-79\,^{\circ}$C). For cryogenic jet cooling methods with liquid nitrogen, it was also stated that a reduction of friction coefficient is possible, being formed a fluid cushion between the chip and tool face [13]. A reduction of heat generated by friction during cutting, caused by a reduction of tool-chip contact length, was recently shown by Bermingham et al. [16]. From a sustainable point of view, cryogenic machining has also been identified to be useful to eliminate health and environmental drawbacks caused by conventional cutting fluids: health problems (i.e. as dermatitis) due to long term exposures to cutting fluids are avoided, the machined workpieces rests clean and dry, since liquid nitrogen evaporates and disperses in air, and chips are not contamined by cutting oil [17].

Objective of this work is to evaluate the benefits and the performances of different lubrication and cooling conditions on high performance machining of gamma titanium aluminides, considering high pressure lubricoolant supply and cryogenic lubrication in comparison with conventional flood cooling, and minimum quantity lubrication, which has been shown to be advantageous for milling operations [18].

2. Experimental approach

2.1. Workpiece material

Machinability investigations were performed on a 45-2-2 XD (45% Al, 2% Nb, 2% Mn and 0.8% B, proportions in atomic percentage) gamma titanium aluminide. From the chemical composition standpoint, Boron is used as grain refiner [19]. The material was produced in an investment casting process, using a centrifugal casting machine ALD-Leicomelt 5TP, a certified equipment for producing of TiAl aircraft components. The specimens, consisting of ∅ 16 mm diameter rods, were cast in one batch at the same time, and were analysed prior to machining operations performed in the as-cast condition.

Samples for microstructural analysis were cut from the workpieces, then ground, polished, and etched by Kroll's reagent. The fully lamellar microstructure consists mainly of two phases, α_2 (Ti_3Al) and γ (TiAl), with the presence of borides. No significant alterations of the microstructure were detected both in the axial direction (as shown in Fig. 1) than in the radial direction of the samples. X-ray analysis revealed shrinkage porosity in the centreline of the rods, which did not affect the turning process, since these were not located near the machined surface.

2.2. Set-up and lubrication conditions

Longitudinal external turning tests were conducted on a Monforts RNC 400*plus* lathe, with a maximum rotational speed up to 4000 rpm and a peak power of 30 kW. The workpieces were subjected to a preliminary roughing operation, in order to remove the cast skin and to guarantee a constant diameter (∅ 15 mm) of the samples. Afterwards the cutting tests were started with fresh tools: the diameter of the γ-TiAl rods was reduced to ∅ 14 mm, through two consecutive cuts having depth of cut $a_p=0.25$ mm and length in feed direction $l_f=15$ mm. Cutting time was limited in order to evaluate the impact of lubrication conditions on machinability, retaining low tool wear values. Moreover, to ensure a rigid clamping, the workpiece overhang was limited to 20 mm. A constant cutting speed $v_c=80$ m/min and feed $f=0.1$ mm were selected as fixed, finishing process parameters. Uncoated cemented carbide inserts (K10 ISO grade) with negative sharp CNMA 120424 geometry ($K_r=95^{\circ}$, $\alpha_o=6^{\circ}$, $\lambda_s=-6^{\circ}$) were applied. The cutting edge radius r_β and the cutting edge roughness $R_{a\beta}$ were measured, by means of a MikroCAD optical system, for 10 different cutting tools: the average values of $r_\beta=6.4$ μm

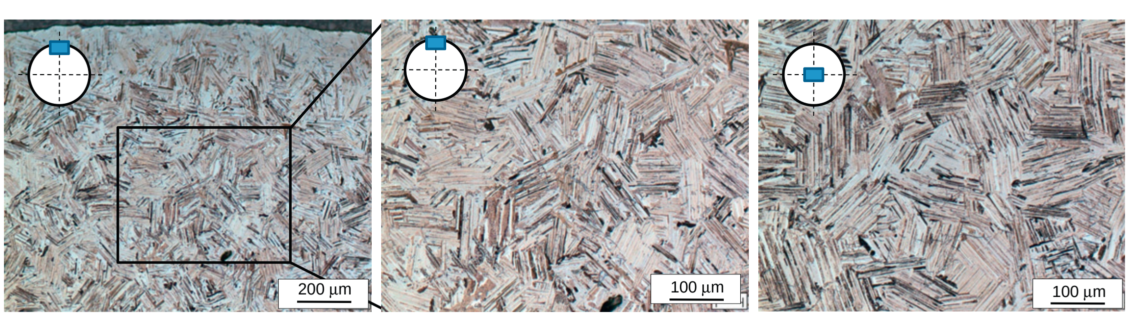

Fig. 1. Micrographs showing the microstructure of the 45-2-2 XD alloy, at the boundary zone and in the central position of the samples.

(with a standard deviation of 0.9 μm) and $R_{a\beta}$=0.44 μm (with a standard deviation of 0.07 μm) were respectively obtained.

Different lubrication/cooling strategies have been compared in this study: dry conditions, conventional flood cooling and high pressure lubricoolant supply (wet conditions), cryogenic cooling with liquid nitrogen, and minimum quantity lubrication (MQL).

More in detail, wet cutting was conducted with a 6% emulsion of a mineral oil. The conventional flood cooling system of the machine tool supplies cutting fluid through a standard ∅ 6 mm external nozzle at a pressure of p=6 bar and with a flow rate of Q=10 l/min. In case of high pressure lubricoolant supply, a ChipBlaster CV16-5000 unit, characterised by a continuously variable pressure regulation up to 350 bars, was exploited. The tests were performed by using a tool holder provided by Iscar (Fig. 2), designed to direct the high pressure jet flow on the rake face of CNMA inserts. It is useful to remark that, according to Bermingham et al. [20], the coolant delivery method is equally as important as the coolant itself: systems that deliver coolant precisely into the cutting zone should be used in order to maximise tool life. Three different levels for the supply pressure have been considered: 80, 150 and 300 bar. As a consequence, since the orifice cross-section of the nozzle was the same for all the tests, the resulting lubricoolant flow rate was 23, 31 and 42 l/min, respectively.

For the cryogenic cooling trials, the liquid nitrogen (LN_2, boiling point: $T=-196$ °C, density: ρ=808.6 kg/m^3) was stored in a Dewar vessel, it was delivered to the same Iscar tool holder/adaptor used for high pressure lubrication, by means of an insulated pipe, and it was supplied to the cutting insert through the nozzle which provides rake cooling. Supply pressure was p=2 bar, with a flow rate of Q=2.3 kg/min. Regarding the minimum quantity lubrication, a Microjet MKS-G260 system was exploited: a vegetable oil was split into ultrafine droplets with the help of compressed air at 5.5 bar, and two external nozzles were manually oriented to the tool rake face, in order to convey the MQL medium to the cutting zone. The flow rate of air and oil aerosol was adjusted to 70 l/min. The tests were executed following a random order and repeated to reduce the experimental error.

2.3. Machinability evaluation

The main focus of experimental investigations was to assess the effects of different lubrication and cooling conditions on machinability of the 45-2-2 XD alloy. For each test, tool wear was analysed by a Keyence digital microscope, at 200X magnification, for fixed cutting parameters and after the same cutting time. Corresponding surface roughness was evaluated by means of a Mahr Perthometer PGK 120, and the arithmetic mean roughness value R_a and the maximum roughness profile height R_t indices were measured in the feed direction. Furthermore, since surface integrity is recognised as one of the critical aspects to be considered during machining of gamma titanium aluminides, the presence of micro-cracks, micro-fractures and microstructural alterations below the machined surface was investigated by a scanning electron microscope (SEM). Subsurface micro-hardness profiles were also obtained. The cutting force measurements were performed by a Kistler 3-component sensor (at a sampling rate of 1 kHz) to deepen the effects of lubricoolant supply pressure during wet cutting. Lastly, chip morphology was analysed and compared.

3. Results and discussion

3.1. Tool wear

Although that dry cutting processes are to be aspired from the sustainable point of view, the results shown in Fig. 3 confirm that, for the chosen process parameters, dry machining is not suitable for turning the 45-2-2 XD gamma titanium aluminide. The consequences of the high thermal impact on the cutting edge are tremendous. Due to the absence of the primary cutting fluid functions of lubrication and cooling, strong frictional and adhesive processes between tool and workpiece material were observed. Effective cutting is not practicable due to the extremely poor tool life. Subsequently, the choice of the optimal lubrication/coolant system is a key point to reach a suitable and stable process.

The impact of the varied lubricoolant strategies on tool wear is shown in Fig. 4, after a cutting time of t_c=10 s. In these turning tests, uniform flank wear land due to the abrasive material behaviour was detected on the worn CNMA 120424 inserts. Fig. 5 compares the results obtained according to the maximum flank wear land V_{Bmax} criterion.

In contrast to conventional flood cooling (p=6 bar, Q=10 l/min), with high pressure lubricoolant supply maximum flank wear land V_{Bmax} progressively decreases up to 41% with p=300 bar and Q=42 l/min. This is due to the reduction of the tool temperature consequent to the better cooling, and to the enhanced lubrication close to the cutting edge due to the reduction of tool-chip contact area [10]. As reported by Klocke et al. [9], the effects are coherent with the vapour bubble theory: an increase of lubricant supply pressure raises the mechanical pressure of the lubricoolant jet acting on the vapour bubble formed by the boiling fluid close to the cutting edge, which insulate the cutting zone. As a result, the increased breaching of the cold lubricoolant leads to achieve better outcomes.

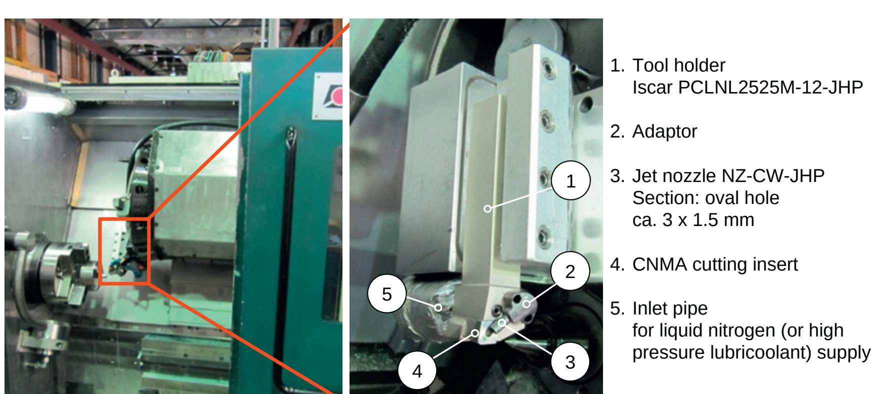

Fig. 2. Experimental set-up: the detailed picture shows the Iscar tool holder.

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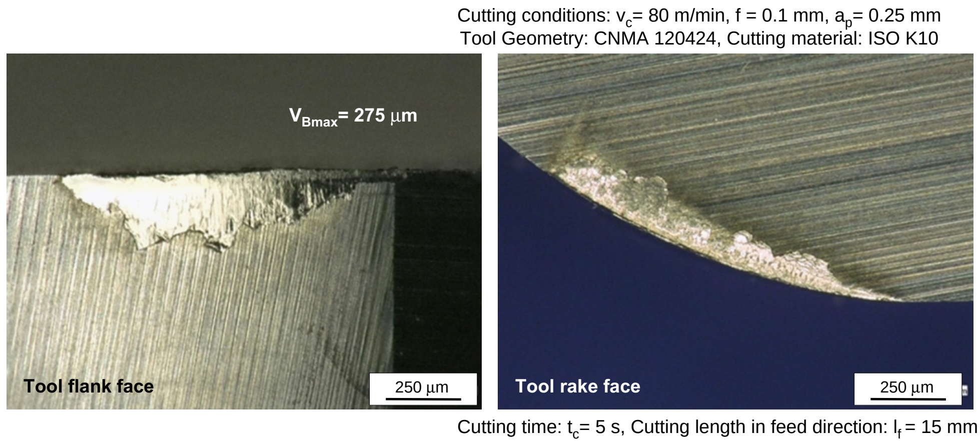

Fig. 3. Tool wear in dry turning. The V_{Bmax} value is the average of two repeated tests.

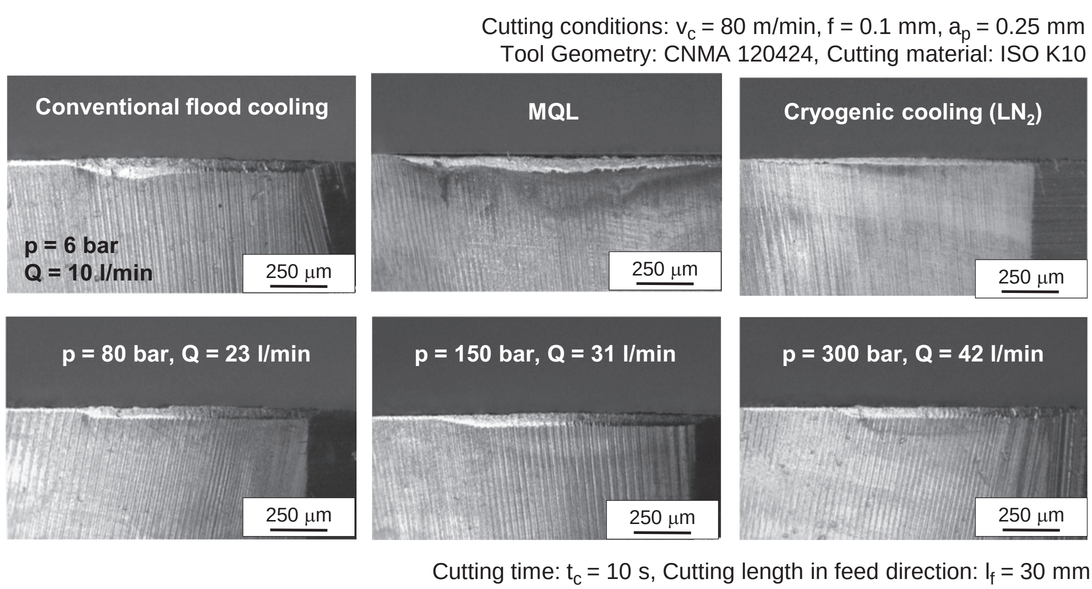

Fig. 4. Dependence of tool flank wear land on different lubrication/cooling strategies.

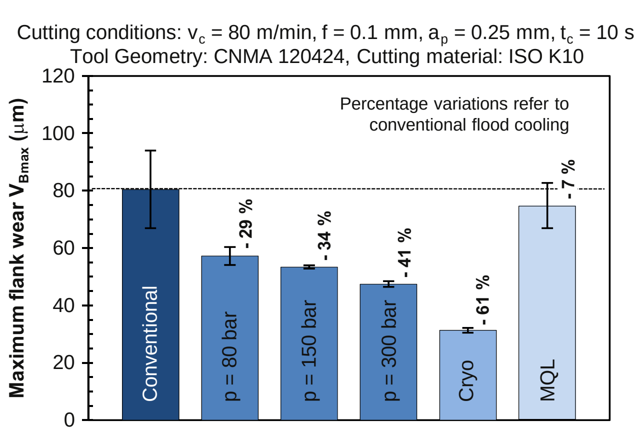

Fig. 5. Tool wear results after a cutting time of t_c=10 s, The error bars show the range of values obtained with the repeated tests.

Remarkable results can already be obtained by using p=80 bar (Q=23 l/min), whereby V_{Bmax} is reduced by 29%. In other terms, as far as tool wear is concerned, the effects related to the pressure supply are stronger within the transition from 6 (conventional flood cooling) to 80 bar, while a further pressure increase allows to obtain in proportion only modest benefits. According to Sharma et al. [12], this should correspond to the variation of the temperature at the interface that, following an initial reduction with the pressure increase, remains almost constant over a critical value of pressure supply.

Noteworthy results were obtained with near-dry lubrication conditions (MQL). In comparison with standard flood cooling, a slight decrease of tool wear has been detected, at least by considering the average V_{Bmax} values obtained with the two repeated tests for each lubrication condition. This result can be explained with the reduction of friction coefficient between tool and workpiece, leading to a reduction of frictional heat, whilst the direct cooling effect of the oil/air mixture is probably only of secondary importance [18,21].

The best outcomes were obtained with cryogenic machining: liquid nitrogen cooling decreases V_{Bmax} up to 61% in comparison with conventional lubrication. The improvement of effective cooling action due to the extremely lower temperature of the cooling medium increases the thermal gradient between cutting zone and tool, with a higher heat removal and a huge reduction of the thermal load of the cutting edge [13–15].

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3.2. Cutting forces and mechanical tool load

In addition to the tool wear, the influences of the mechanical tool load are also of major importance due to its impact on process stability. Concerning the cutting force components, a comparison between conventional flood cooling and high pressure lubricoolant supply is presented in Fig. 6, after a cutting time of $t_c = 10$ s.

The sequential rise of lubricoolant supply pressure/flow rate results in a slight increase of cutting force F_c (up to 13% with $p = 300$ bar), due to the increased material toughness in primary shear zone. This is caused by lower temperatures reached with a better cooling [9], and in a decrease of passive force F_p (by 17% with $p = 300$ bar). Furthermore, significant changes or clear trends were not detected for the feed force F_f.

After same cutting times, a progressive reduction of the tool/chip contact area A on the tool rake faces was identified with increasing lubricoolant pressures (Fig. 7). This phenomenon can be traced back to the use of a tool holder designed to supply the lubricoolant directly into the wedge between tool and chip: as a result, enhanced chip bending and breakage with the increase of pressure is achieved (see also Section 3.5), and a lower generation of heat in the shear zone is also expected [11,22].

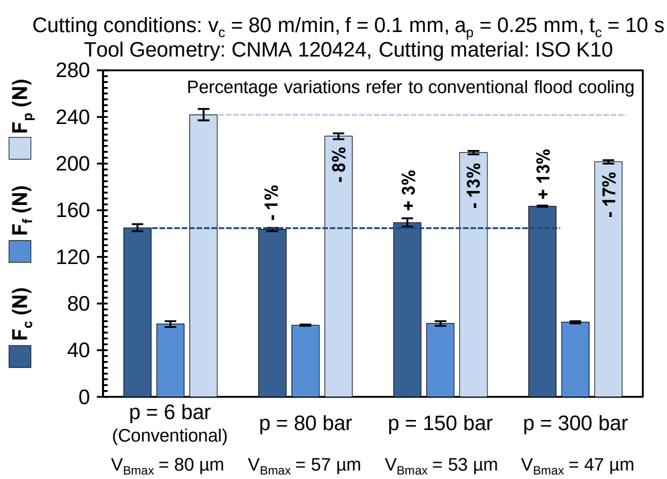

Fig. 6. Correlations between cutting forces components (F_c=cutting force, F_p=passive force, F_f=feed force).and lubricoolant supply pressure.

The graph of Fig. 7 also defines the ratio of cutting force F_c to tool/chip contact area A. This parameter is useful to provide a simplified and qualitative evaluation of the mechanical specific tool load, by assuming that the influence of lubricoolant supply pressure on friction force on the tool flank face is negligible, and that the tool load is constant within the tool/chip contact area [9].

A cross-analysis of Figs. 6 and 7 leads to the conclusion that the raise of jet pressure increases the cutting forces and decreases the contact area A (by 15% with $p = 300$ bar). Therefore, the ratio F_c/A increases up to 32%: as a result the concentration of specific mechanical tool load increases the risk of break-outs of the cutting edge, as shown in Fig. 8.

3.3. Surface roughness

At fixed process parameters, Fig. 9 offers a comparison between the arithmetic mean roughness R_a and the maximum roughness profile height R_t, as a function of lubrication and cooling conditions. In order to calculate these indices, six roughness profiles of total length $l_t = 5.6$ mm (with a corresponding measurement length of $l_m = 4$ mm) have been acquired for each machined sample. Measurements were performed on the surfaces obtained with the second workpiece cut. The experimental points plotted in the graph with the related range bars show the average, the maximum and the minimum value for each test, whilst the histograms have been obtained considering the mean values of the repeated machining trials.

The outcomes highlight that the worst results were obtained in dry machining. For wet cutting, the trend of average values of

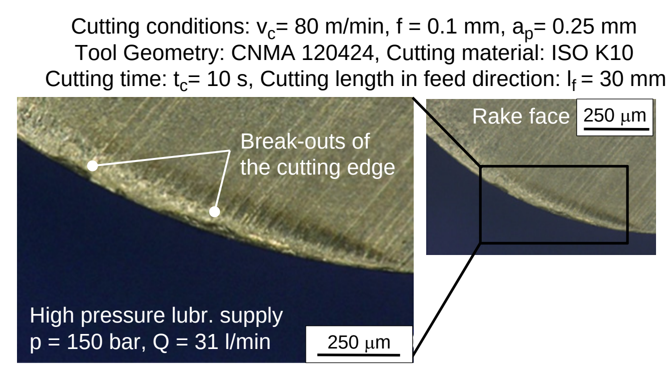

Fig. 8. Break-outs of the tool cutting edge with high pressure lubricoolant supply.

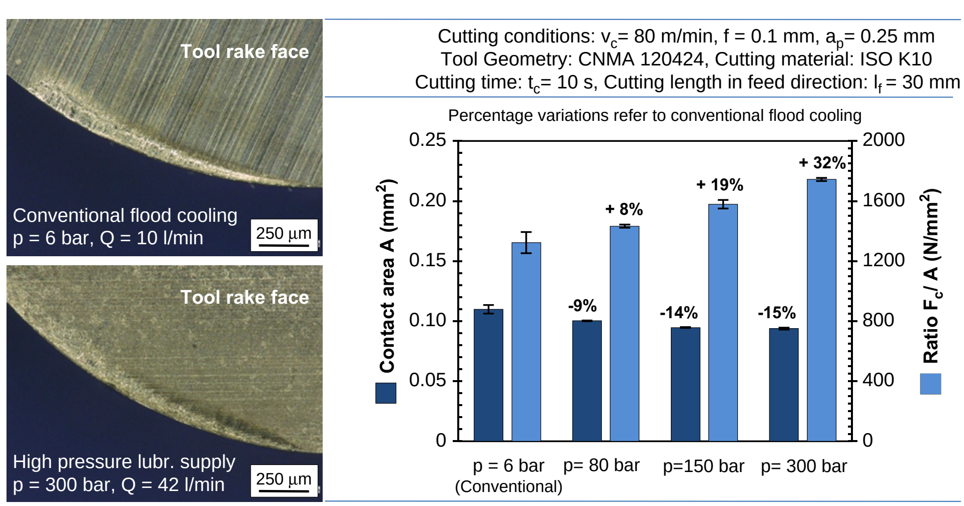

Fig. 7. Tool/chip contact area and ratio of cutting force to tool/chip contact area,as a function of lubricoolant supply pressure.

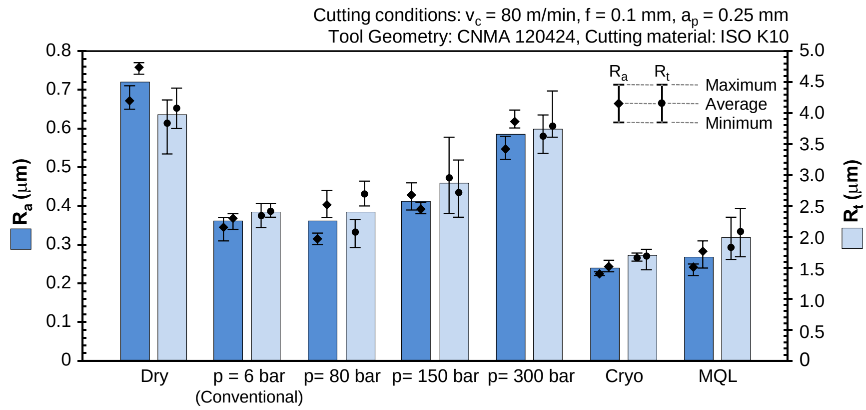

Fig. 9. Roughness results as a function of lubrication/cooling conditions.

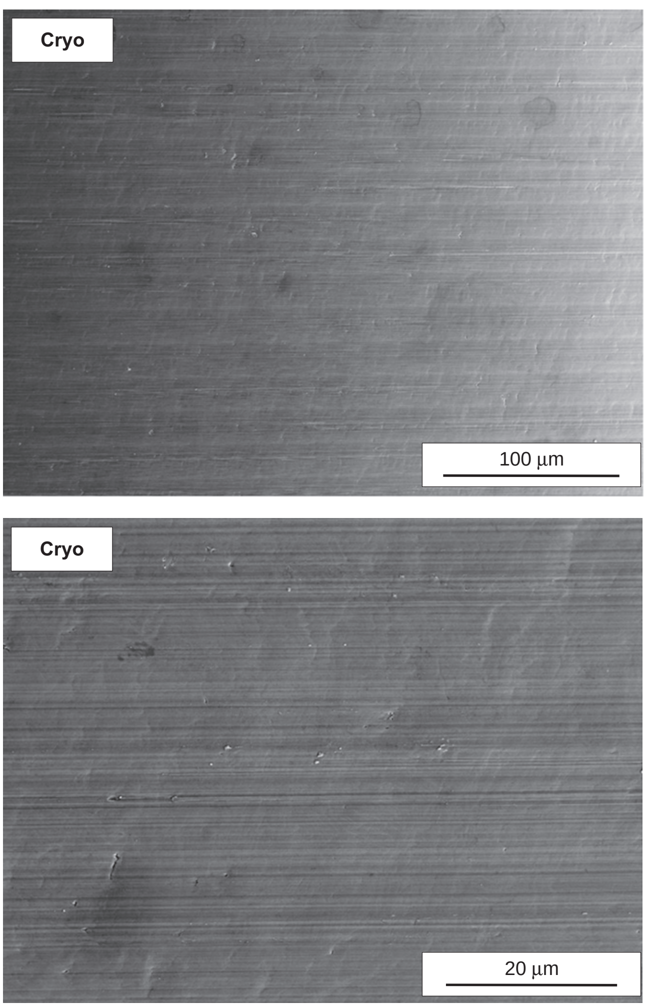

Fig. 10. SEM observations, with different magnifications, of the surface machined with cryogenic cooling.

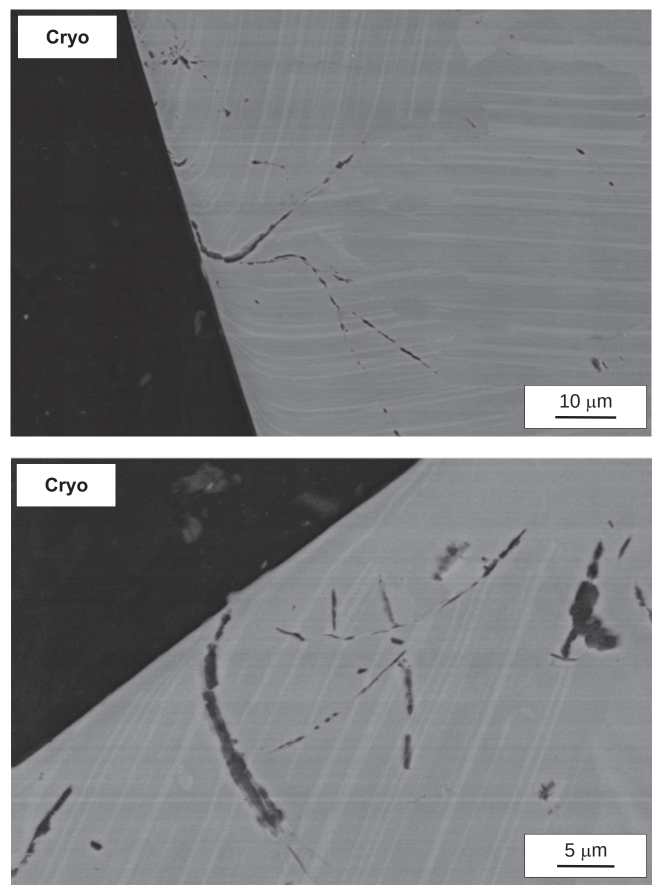

Fig. 11. Cross-section of the machined surface (cryogenic cooling) in two different randomly selected areas.

the roughness indices do not show significant changes between the conventional flood cooling and a lubricoolant supply pressure of 80 bar, whilst a progressive worsening of the turned surfaces has occurred with the increase up to $p=300$ bar. This effect has already been presented in literature. When finish turning of a γ-TiAl alloy, an increase of surface roughness with the use of high pressure cutting fluid (65 bar and 26 l/min versus 20 bar and 6 l/min) has been mentioned by Sharman et al. [23]. These findings reinforce the statement that, for industrial applications, it's necessary to define an optimum range of fluid supply pressure, taking into account not only the workpiece/tool combination, but also variables as size and positioning of the nozzles.

As well as the best tool wear results were obtained with cryogenic lubrication, also in terms of surface roughness the lowest indices have been achieved with the liquid nitrogen cooling. In comparison with standard wet lubrication, a percentage reduction of approximately 30% of R_a and R_t has been estimated. Finally, the surface finish gained with minimum quantity lubrication, allow to classify the MQL in an intermediate position between standard wet lubrication and cryogenic cooling.

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3.4. Surface integrity

SEM observations of the machined surfaces were performed after the second cut, within the range of cutting length of $l_f = 15–30$ mm. Then the workpieces were cut, by means of a metallographic cutter, and samples were embedded in a thermosetting phenolic resin, ground, polished and etched for the cross-section analysis.

The surface analysis confirmed the results obtained from the roughness measurements. Fig. 10 shows the surfaces produced with cryogenic cooling: smooth, high-quality, and almost defect free surfaces were obtained. By taking the tool wear into account, cracks or crack-like structures obtained on the investigated surfaces could be traced back to the presence of borides. Borides are present in the alloy's microstructure in large numbers, as thin and elongated structures. Below the machined surface, the presence of borides and of cracked/ripped out borides is observed, as shown in Fig. 11.

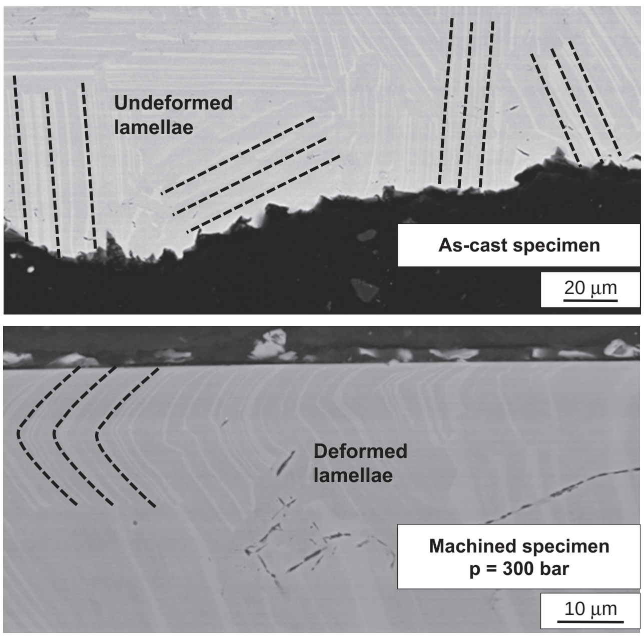

Fig. 12. Lamellae deformation due to the cutting process. Comparison between as-cast and machined specimens.

Sub-surface microstructural alterations were noticed in all the samples, and the effects of surface drag can be evidenced by the lamellae deformation, which is absent in the as-cast specimens (Fig. 12). This phenomenon indicates strain at high temperatures [7]. Borides are deformed as well as the surrounding lamellar structure, as shown in Fig. 11. A hardened layer below the surface is detected for all the lubrication conditions. The increasing sub-surface hardness (almost double the bulk hardness) indicates susceptibility to strain hardening, reducing the poor ductility at the surface further [23]. When the tool flank wear increases, the thermal and mechanical load of the workpiece subsurface zone increases too [24]. With cryogenic cooling, due to the reduction of the tool wear, a reduction of strain hardening is expected. This could explain the reduction of the measured hardness values (in comparison with conventional flood cooling), corresponding to the reduction of the depth of sub-surface microstructural alterations, as shown in Fig. 13.

3.5. Chip morphology

As for milling operations [18,25], the formation of small and segmented chips, due to the low deformability that those alloys retain up to high temperatures, was detected for all the turning tests (Fig. 14). Saw-tooth chips are composed of angular and needle-shaped lamellae, and therefore subjected to periodically varying shear deformation in the chip flow direction.

Chip size reduction with MQL and conventional flood cooling (in comparison with dry lubrication conditions) is clearly perceivable,

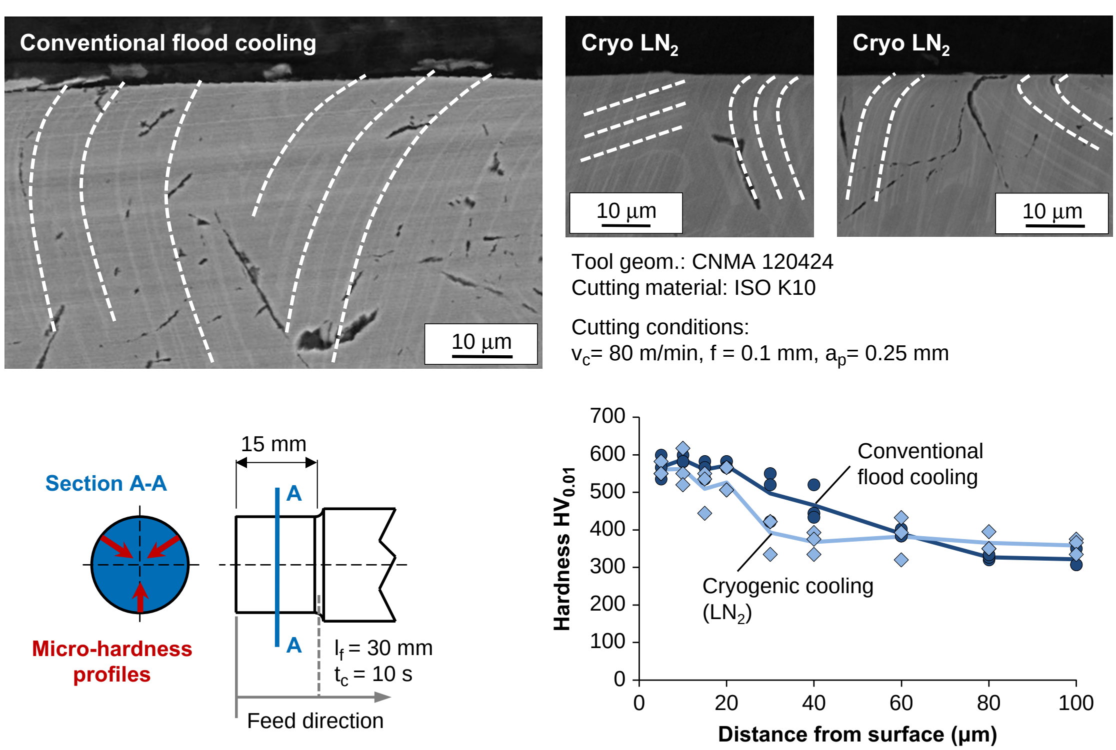

Fig. 13. Effects of lubrication conditions on sub-surface alterations.

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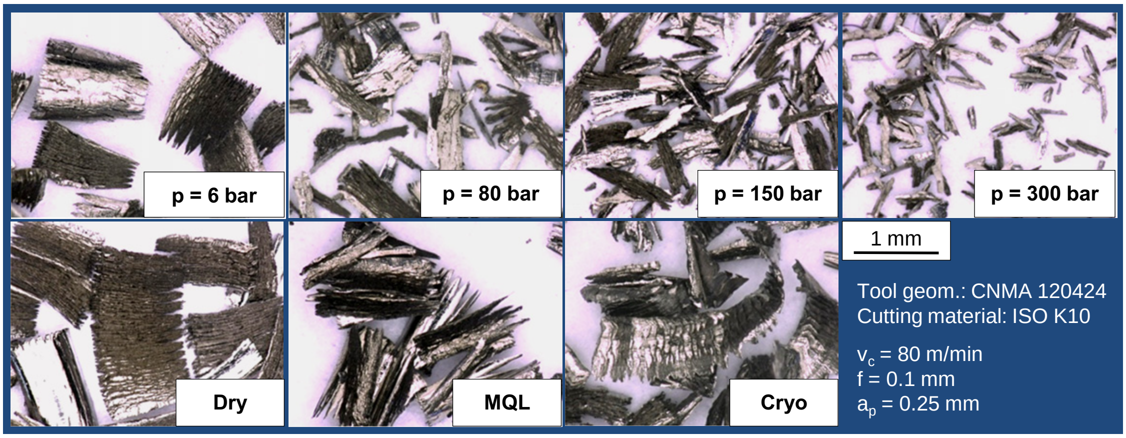

Fig. 14. Chip morphology.

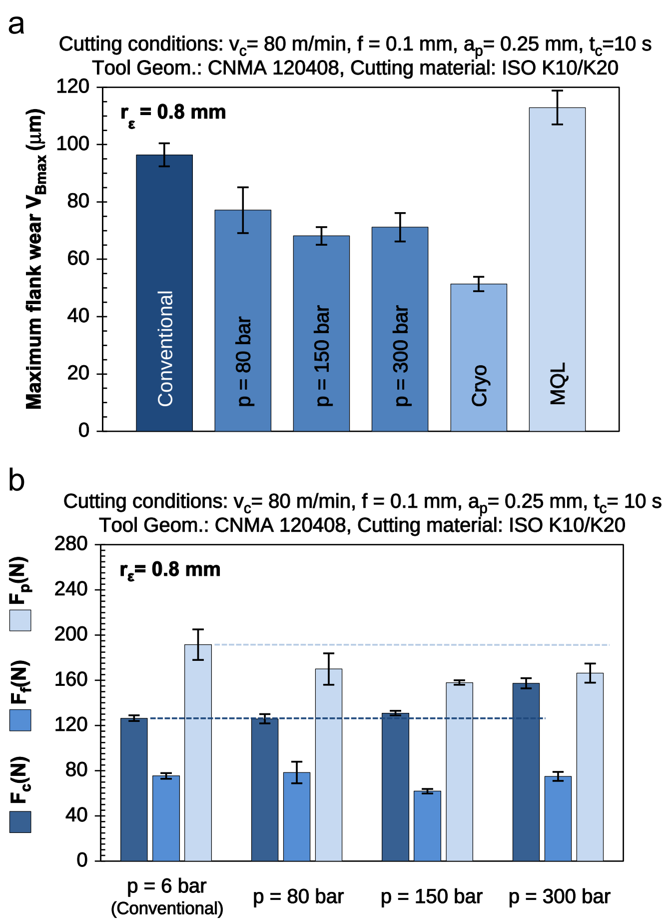

Fig. 15. Influence of the reduction of tool corner radius to 0.8 mm on tool wear (a) and cutting forces (b).

whilst chip obtained with cryogenic lubricoolant shows an increase in length and in chip curvature radius, in comparison with conventional flood cooling. The chip breaking due to the high pressure lubricoolant supply was detected [20], and this phenomenon rises with the increase of the supply pressure.

3.6. Effects of tool corner radius

The same testing approach was also applied for cemented carbide inserts (K10/K20 ISO grade) with CNMA 120408 geometry (tool corner radius $r_\varepsilon = 0.8$ mm). Fig. 15 shows the results of tool wear and cutting forces measurements, after the cutting time $t_c = 10$ s. Experimental evidences highlight that the findings previously discussed are confirmed even for the different tool geometry. The cryogenic cooling was the best lubrication condition to reduce tool wear. In addition, for the CNMA 120408 cutting inserts, the transition of lubricoolant supply pressure from 150 to 300 bars does not imply benefits in terms of tool wear reduction, and MQL performs slightly worse than with conventional flood cooling. A comparison between Figs. 5 and 6 (concerning CNMA 120424 inserts) and Fig. 15 (CNMA 120408) indicates that the size of the corner radius of the main cutting edge has a significant impact on tool wear behaviour and on cutting forces. With the smaller corner radius the wear progression in higher and the cutting forces are lower, according to Meyer et al. [24]. More in detail, the tool corner radius has a major influence on the passive force F_p, which is the dominant force component, and a perceivable effect on the cutting force F_c, whilst the impact on the feed force F_f is negligible. The decrease of tool corner radius leads to the increase of surface roughness indices R_a and R_t, as expected [8].

4. Conclusions

To open new markets and to increase the usage for titanium-aluminides in aircraft engines, a broad approach is necessary, including a scientific consideration of the machined workpiece surface due to safety reasons, focusing on tool and process design as well as the development of adapted high performance cutting strategies and cutting tools. When finish turning a 45-2-2 XD gamma titanium aluminide, experimental observations detailed in this study evidenced a meaningful influence of lubrication and cooling conditions on the alloy's machinability. As far as tool wear is concerned, the application of a high pressure lubricoolant supply reduces tool flank wear, but the specific mechanical tool load is increased and the risk of breakouts on the cutting edge rises.

Cryogenic cooling with liquid nitrogen was identified as a promising way to lower tool wear and furthermore to limit surface and sub-surface defects. In particular, surface roughness is reduced in comparison with all the other lubrication conditions, and also a reduction of sub-surface microstructural alterations is expected. Overall, cryogenic cooling can be identified as a lubricoolant strategy to potentially enhance cutting performances through tool wear reduction and surface quality enhancement.

Acknowledgements

The authors would like to thank the European Union for funding the research activities in the EFRE (Europäischer Fonds für regionale Entwicklung) programme. Furthermore, the authors would like to thank the federal state of NRW for the financial support in the programme "Regionale Wettbewerbsfähigkeit und Beschäftigung for Europe – Investition in unsere Zukunft." The authors also acknowledge ACCESS e. V. Techcenter (Aachen, Germany) for the contributions in the evaluation of surface integrity.

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Please cite this article as: F. Klocke, et al., High performance cutting of gamma titanium aluminides: Influence of lubricoolant strategy on tool wear and surface integrity, Wear (2013), http://dx.doi.org/10.1016/j.wear.2012.12.035