Experimental comparison between traditional and cryogenic cooling conditions in rough turning of Ti-6Al-4V

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Abstract. Titanium alloys, mainly because of their poor thermal conductivity, need to be cut at relatively low cutting speeds to avoid a severe diffusion wear, with obvious negative consequences on the profitability of machining. An important amount of research activities has been done in order to increase productivity in titanium machining operations and one of the most promising solutions is represented by the use of liquid nitrogen as a coolant during the machining operation.

The aim of this paper is to compare traditional and cryogenic turning of Ti6Al4V in a region of cutting parameters particularly relevant to the aerospace industry where no previous data are available. The cutting parameters are those typical of titanium alloys rough machining which is considered, cost-wise, the most important operation because, for aerospace components, the so-called Buy-To-Fly ratio can reach values up to 20:1.

The experiments have been performed using a full factorial design in order to statistically evaluate, using ANOVA and regression analyses, the significance of the input factors on the process most interesting outputs. The considered input factors are: type of cooling method, cutting speed and feed rate. The main analysed responses are: tool wear, surface roughness, cutting forces, coefficient of friction and chip morphology.

The results show the significance of the cooling method on the tool life and that cryogenic machining is able to increase the tool life with respect to wet cutting. On the other hand, the beneficial effect of the liquid nitrogen cooling is reduced at high cutting speed and feed rate. Besides, the results showed that a small but significant reduction can be achieved for both the repulsion force and the coefficient of friction at the tool-workpiece interface.

Introduction and state of the art

Titanium alloys present many interesting mechanical properties (such as very high strength to weight ratio, high toughness, biocompatibility and good corrosion resistance) that promote the use of these materials not only in the aerospace industry, but also for bio-medical applications and for the chemical and oil & gas industries. Conversely, titanium alloys are classified as "difficult to machine" materials especially due to their low thermal conductivity, which is one of the most important material characteristics when considering machinability [1]. Furthermore, titanium shows low elastic modulus and high chemical reactivity [2]. Among several problems encountered in titanium machining, the quick tool failure due to an excessive wear represents one of the most critical issues.

High cutting performance is strongly needed in aerospace manufacturing, where generally rough machining removes about 90% of the material from the blank, even in small parts production. This manufacturing approach is typically adopted due to the high costs of titanium forgings and to the fact that dedicated dies are not economically feasible, because of small production batches. So far, a lot of research has been done to study and to improve the performance of carbide tools in titanium

machining. The use of cryogenic cooling in metal cutting has received renewed recent attention because liquid nitrogen (LN_2) is a safe, clean, non-toxic coolant that requires no expensive disposal and can substantially improve tool life.

Uehara and Kumagai [3] have pioneered works on cryogenics in machining. A relatively recent review of cryogenics in machining has been written by Yildiz and Nalbant [4]. Cryogenic cooling approaches in machining can be classified into several types according to the delivery method [5]: pre-cooling of the workpiece, tool back cooling, tool flank cooling, tool rake cooling and simultaneous rake and flank cooling. The most effective cooling approaches are the last two: rake only cooling or flank and rake cooling. All studies agree that these cooling techniques reduce the tool temperature and prolong its life, with respect to dry cutting and to conventional emulsion lubrication. Recent studies by Bermingham and co-workers demonstrate that using high pressure emulsion lubrication outperforms cryogenic cooling with respect to tool life [6]; in both cases the nozzle design is critical for a successful operation. It is reasonable to expect that the advantage of cryogenic cooling vs. water based oil emulsion lubrication with respect to tool life enhancement should depend on the selected levels for the process parameters (feed rate, depth of cut, cutting speed). The role of cutting speed and other parameters in cryogenic cutting of titanium alloys is not yet unanimously assessed. Some authors observed that the greatest improvement in tool life using cryogenic coolant occurs for high feed rate and low depth of cut combinations [7], with constant cutting speed and approximately constant MRR. The authors also proved that these conditions do not represent the optimal operating parameters with respect to economic efficiency nor they allow to maximize the tool life. Some authors have proved that, in machining of AISI 304 stainless steel [8] or of titanium [9], the percentage tool life advantage and the economic convenience of cooling by liquid nitrogen, with respect to conventional emulsion lubrication, increases as the cutting speed increases. According to other studies, the advantage of cryogenics is nearly independent on the process parameters, at least for stainless steel [10]. On the contrary, some claim that with the increase in cutting speed to very high levels (up to 100 m/min and above), the differences tend to decrease, in terms of wear on the rake face of the tool [11].

Similar contrasting results emerge from the literature when forces and friction coefficient are analysed. Results of cutting force measurements often indicate that the cold strengthening of titanium material might increase the cutting force in cryogenic machining, but lower friction allows to reduce the feed force, compared to dry cutting [12]. Although many authors compare the performance of liquid nitrogen vs. dry cutting condition [13][14], a more meaningful comparison of forces and friction should be done with respect to conventional emulsion lubrication. As anticipated, not all studies in the literature agree. Some works demonstrate that no change in the cutting forces [15] occurs. Other studies report a decrease in both main cutting and feed forces for cryogenic vs. wet conditions, regardless of cutting speed [16]. As for the tool life, it is reasonable to expect that the advantage of cryogenic cooling compared to the more widespread emulsion lubrication with respect to forces (cutting, feed and repulsion forces) depends on process parameters values. In fact, recent research works prove that force reduction is greatest when using high feed rate and low depth of cut combinations [7], if keeping constant the cutting speed. An increase in cutting speed, according to most previous works, causes also a decrement of the coefficient of friction for dry, water-oil emulsion based cooling and cryogenic cooling [17][18].

The differences between conventional and cryogenic machining may be due to several causes: both tool and workpiece can be hardened by the low working temperatures, the tribological conditions are altered, etc. As a consequence, cryogenic machining changes the mechanics of the chip formation, generating a thinner [7] and more discontinuous [19] chip and also a limited amount of built up edge [17] if compared to dry machining.

A recent work by Rotella et al. [20] showed the capability of cryogenic cooling to improve the product surface finishing, in terms of surface roughness, microhardness and grain size, with respect to dry and MQL turning of Ti6Al4V alloy.

In conclusion, all authors agree that cryogenic cooling allows a significant improvement of the tool life over dry machining. When compared to traditional flood cooling, less results are available, but

all results agree that cryogenics has a great potential of improving the process performance. However, especially when the process is compared to standard industrial cutting conditions, different researchers have obtained conflicting results. One possible explanation for these differences is that the design of the injection system strongly influences the process, as it determines the localization of the nitrogen flow on the workpiece-tool interface surfaces and the flow rate guaranteed by the overall cryogenic injection systems. It is worth observing that, due to inherent difficulties in measuring the actual flow rate of the coolant, it is very difficult if not impossible to find data about this supposedly important parameter. Another source of variation among different results is that the investigated range of process parameters varies from paper to paper. In order for the coolant to have time enough to subtract heat from the working area, it seems reasonable that the influence of nitrogen, which is injected through small nozzles, is larger for smaller values of MRR. On the other hand, it also seems reasonable that the advantage of cryogenics in terms of tool life becomes evident only at larger cutting speeds, i.e. when the tool is more stressed by higher cutting forces and higher heat generation. The expected outcome of the process is therefore not so trivial and the results can easily be influenced by the cutting conditions. There is a need for additional experimental evidence with respect to different issues, such as the three components of force (cutting, feed and thrust), the coefficient of friction, the rate of tool wear at different values of the process parameters.

Rough turning is economically more relevant to the machining industry, especially in the aerospace field where the so-called buy-to-fly ratio can be as large as 10:1 and above [21]. Because of their poor machinability, titanium alloys are industrially cut with moderate cutting parameters. In rough turning, in order to avoid premature tool failure, cutting speed vc and feed rate f are never set respectively above 60 m/min and 0.4 mm/rev.

Besides, in order for the industry to evaluate the actual advantage of cryogenic coolants, the performance must be compared to conventional flood emulsion cooling, not to dry conditions, which are never used industrially. No paper in this literature review investigates the cutting forces at low speed and high feed and only two papers [15][16] report force comparisons with respect to emulsion cooling. In this paper, some new experimental observations are presented, in order to fill this gap, providing cutting force measurements with emulsion and cryogenic cooling, at a relatively low cutting speed (50 m/min) and a relatively high feed rate (0.3 mm/rev).

The main goal of this paper is to fill some gaps that have been identified in the scientific literature and underlined above and to compare the effect of emulsion cooling and liquid nitrogen cooling, within an industrially relevant range of working parameters, on tool life and other important process parameters.

The paper is organised as follows: the detailed description of tool, inserts, cryogenic adduction scheme, experimental setup and procedure is presented in Section 2. The results and discussion of the experimentations are proposed in Section 3, focusing on tool flank wear progression, cutting forces and tribological aspects. Finally, in Section 4 some conclusions are drawn.

Lathe Turning Tests

Experimental setup. The workpiece consisted in Ti6Al4V bars with 55 mm as initial diameter. The certificate of the adopted material, provided by the seller, reports a tensile strength of 934 MPa and a yield strength of 867 MPa. The effect of the microstructure of titanium alloys on their machinability is relevant, as demonstrated by several authors [22][23]. The material microstructure has been analysed along the bar diameter and it can be considered quite homogeneous, according to a micrographic that shows a substantially uniform granularity across the cross section of the bars.

All machining trials have been conducted using a CNC Somab Unimab 400 lathe with a maximum spindle speed of 2560 rev/min and a drive motor rated up to 11 kW.

The machining trials were aimed at comparing the difference in terms of tool life between traditional and cryogenic cooling method. Traditional fluid is a water-oil emulsion (Hocut 795/I) at a concentration of 5% and a flow rate of 2 l/min. The cryogenic system consisted in a dewar (courtesy of SIAD, Fig.°1) at a pressure of 160 kPa with a capacity of 240 l and a thermally

insulated metal pipe that delivers the fluid to a commercial tool holder MIRCONA PCLNL 2525 EB, Fig.°2). The tool holder has two injection nozzles for both rake and flank cooling.

The insert type used during the turning test is a commercial Sandvik CNMG 120408 SMR 1115, well suited for rough turning of titanium alloys. The insert is a coated carbide tool with coating layers TiAlN (2 μm) + AlCrO (0.7 μm). Hardness measurements of the insert have been performed with a pressing load of 0.5 kg, selected in order to characterize the hardness of the entire tool: WC + coating layers. Each hardness value has been computed considering six repeated hardness measurements on the tool flank. The insert presented a mean surface hardness of 1878 HV.
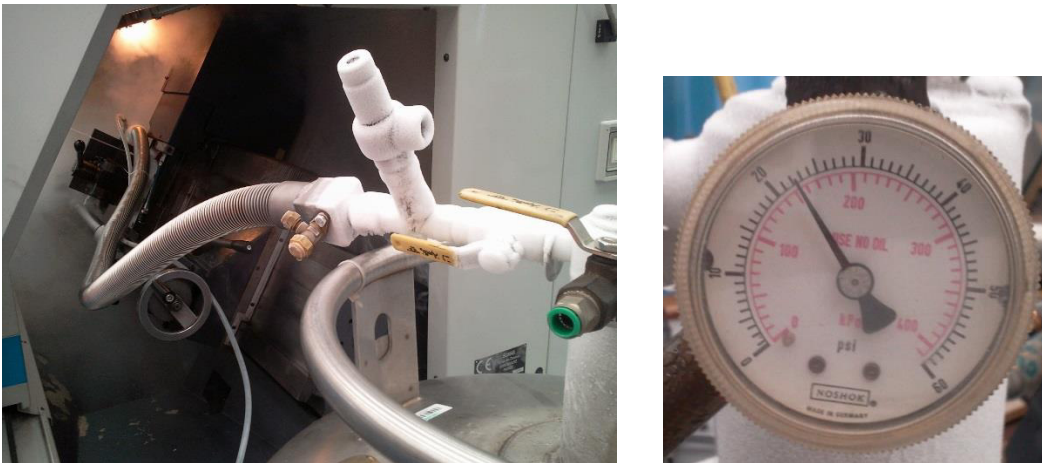

Fig.°1: view of the piping connecting the dewar to the lathe; manometer.
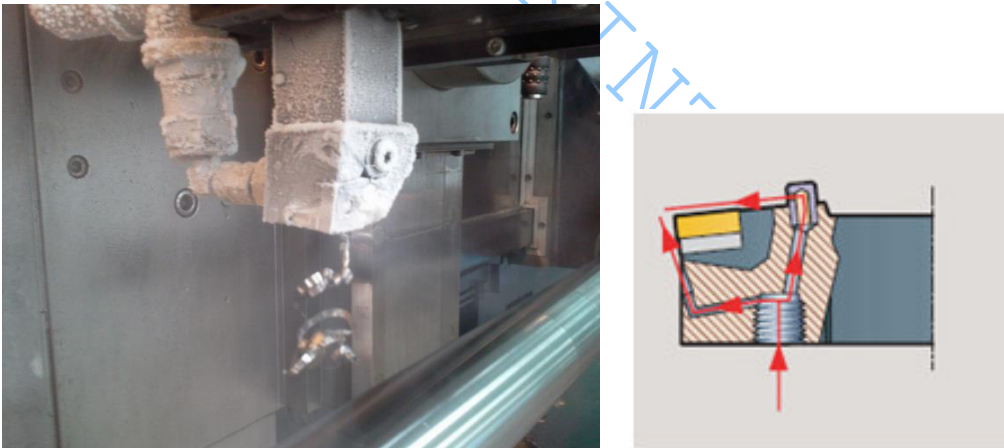

Fig.°2: view of the cooled toolholder and the titanium bar; scheme of the internal holes of the toolholder.

The cutting tests have been performed with the following parameters: entry angle κ_r=95°, top rake angle γ=-6°, side clearance angle α=5°, back rake angle λ=-6°. The process parameters are summarized in Table 1.

Experimental plan. An experimental plan has been designed in order to evaluate and compare the influence on tool life and other process parameters of two different cooling methods: water-oil emulsion and cryogenic cooling. The parameters have been selected according to a full factorial Design of Experiments (DOE) with centerpoint [24], with the following input factors: cooling method, cutting speed and feed rate. Their levels are listed in Table 1. Three replicates were performed for every cutting condition. The experimental plan consists of 5 tests (2 cutting speeds and 2 feed rates plus one centerpoint) for both cooling types for a total of 30 turning runs.

The ANOVA test has been used as the statistical method to determine if each investigated factor significantly affects the measured responses. A I-type error threshold α=0.01 has been adopted for every F-test of the ANOVA table.

Table 1. Machining parameters for turning tests

Factors	Levels
Cutting speeds (V_c)	50, 60 (center point) and 70 [m/min]
Feed rates (f)	0.2, 0.25 (center point) and 0.3 [mm/rev]
Depth of cut (b)	2 [mm]
Cutting fluid	1) Hocut 795/I at a concentration of 5% and a flow rate of 2 [l/min] 2) Liquid nitrogen cooling

Average flank wear VB_B was measured on micrographic images, taken using an Optika stereomicroscope; the positioning reproducibility of the measured insert was guaranteed by an adequately designed insert holder, fixed to the base of the microscope. Images have been analysed after being processed, as suggested in [25]. Each test has been interrupted at least five times (according to ISO9685), in order to have six points on the VB_B vs. time curves. The tool failure adopted criterion is the average flank wear of 0.3 mm.

A Kistler dynamometric table has been used to measure all three orthogonal components of the cutting force: main cutting force F_c, feed force F_f, thrust or radial force F_r.

Results and discussion

The results are now presented and discussed. ANOVA analyses were performed to determine the influence of the experimental plan parameters, with particular focus on the cooling method, on the response variables. The considered variables are: tool wear, surface roughness, cutting forces, coefficient of friction and chip morphology.

Tool life. In Table 2 the average tool life in terms of removed material and cutting time for every cutting parameters combination is reported.

Table 2. Average tool life values for every cutting condition with traditional and cryogenic cooling

vc [m/min]	f [mm/rev]	ap [mm]	MRR [mm³/sec]	V cryo [mm³]	V wet [mm³]	T cryo [sec]	T wet [sec]
50	0.2	2	333	351678	292920	1055	879
50	0.3	2	500	279163	284150	837	852
60	0.25	2	500	232158	199547	696	599
70	0.2	2	467	158892	152887	477	459
70	0.3	2	700	59258	54256	178	163

Cryogenic cooling improves tool life in about all conditions, in particular at 50 m/min and 0.2 mm/rev (about 20%) and at 60 m/min and 0.25 mm/rev (about 16%). At the other conditions there is a substantial equality of tool life between the two cooling methods.
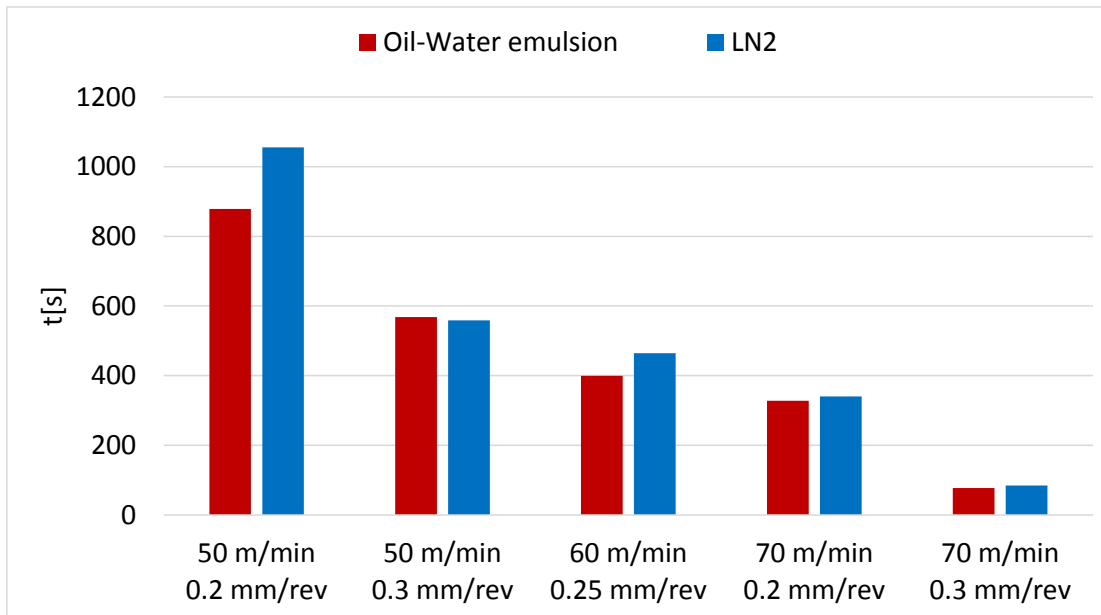
Fig.°3. Average tool life for each cutting condition

At high cutting speed or high feed rate, LN$_2$ seems to decrease its capability of reaching the cutting zone. This can be due to two main factors: 1) the larger amount of generated heat; 2) liquid nitrogen is not highly pressurized inside the dewar and the nozzle is located at about 20 mm away from the cutting edge. Thus, the LN$_2$ jet speed may not be sufficient to get to the cutting edge in its liquid phase losing a large part of its capability of heat removal.

The obtained results are according with the flooding LN$_2$ adduction tested by Hong et al. [26] which was performed in similar setup conditions with the present work.

Statistical analysis. For the two cooling conditions, two different tool wear models were obtained to predict the flank wear amount basing on cutting parameters and cumulated machining time. For this general regression analysis the progression of tool wear, V$_B$ (µm), at each stop of all the performed tests was considered as output. A Box-Cox transformation of the response was implemented in order to improve the diagnostics of the regression residuals. The suggested rounded λ for the transformation was equal to -1 hence the factors values (cutting speed 'vc', feed rate 'f', cumulated machining time 't cum') were transformed adopting the natural logarithm factor. Traditional emulsion cooling is -1 and cryogenic cooling method value is +1.

The laws obtained for the two levels of cooling method ('refr') are reported below. All factors and interaction are significant, with the exception of the interaction `ln(f)*ln(t cum)`.

```
refr
-1   VB*^-1  =  -0,0819589 + 0,0203656 ln(vc) - 0,0652192 ln(f) - 0,0127236+
                +ln(t cum) + 0,00271219 ln(vc)*ln(t cum) + 9,7848e-005 ln(f)*
                *ln(t cum) + 0,0173616 ln(vc)*ln(f) + 0,000383116 ln(t cum)^2

+1   VB*^-1  =  -0,0824804 + 0,0203656 ln(vc) - 0,0652192 ln(f) - 0,0127236+
                +ln(t cum) + 0,00271219 ln(vc)*ln(t cum) + 9,7848e-005 ln(f)*
                *ln(t cum) + 0,0173616 ln(vc)*ln(f) + 0,000383116 ln(t cum)^2
```

Analysis of Variance

Source	DF	Seq SS	Adj SS	Adj MS	F	p
Regression	8	0,0008757	0,0008757	0,0001095	62,0840	0,000000
ln(vc)	1	0,0000184	0,0000294	0,0000294	16,6825	0,000063
ln(f)	1	0,0000373	0,0000282	0,0000282	15,9684	0,000090
ln(t cum)	1	0,0006966	0,0000419	0,0000419	23,7573	0,000002
ln(vc)*ln(t cum)	1	0,0000000	0,0000371	0,0000371	21,0281	0,000008
ln(f)*ln(t cum)	1	0,0000297	0,0000001	0,0000001	0,0494	0,824262
ln(vc)*ln(f)	1	0,0000184	0,0000375	0,0000375	21,2806	0,000007
refr	1	0,0000108	0,0000144	0,0000144	8,1545	0,004740
ln(t cum)^2	1	0,0000645	0,0000645	0,0000645	36,5815	0,000000

The cooling method ('refr') is a significant factor with a p-value of about 0.005, hence there is a statistical difference between the two V_B laws obtained. The only factor that does not influence the flank wear is the interaction between feed rate and machining time.

Cutting forces and chip morphology. Average cutting forces and chip morphology were measured and statistically analysed to understand the influence of the chosen factors, in particular the cooling method, on the cutting mechanics. All the analysed cutting force data are referred to the first passes of each test when the tool wear is negligible, to ignore the typical increase in cutting forces that occurs when the insert is nearing the end of its life. Like the tool wear level, also the cutting forces and chip morphology were statistically analysed using ANOVA tests.

In Table 3 the mean cutting (Fc), feed (Ff) and repulsion (Fr) forces, obtained by averaging the measures among the three replicates, are reported.

Table 3. Mean cutting forces for every cutting condition

		50 m/min 0.2 mm/rev	50 m/min 0.3 mm/rev	60 m/min 0.25 mm/rev	70 m/min 0.2 mm/rev	70 m/min 0.3 mm/rev
Fc [N]	Emulsion	818	1045	894	752	1051
	Cryo	806	1075	884	734	1084
Ff [N]	Emulsion	434	403	372	358	460
	Cryo	381	421	357	344	487
Fr [N]	Emulsion	230	253	214	196	263
	Cryo	229	259	246	211	295

Starting from the main cutting force values the corresponding specific cutting pressure (Kc) was calculated. An ANOVA test showed that Kc is not influenced by the cooling type but the interaction between cooling method and feed rate is found to be influent. This can support the aforementioned hypothesis that at high feed rates the LN_2 jet cannot adequately penetrate into the cutting zone and efficiently remove the generated heat.

Feed force is influenced only by the feed rate level and the radial force by both the feed rate and the cooling type. The influence of cooling type on the repulsion force is probably due to the fact that having a colder workpiece causes a slight local increment of hardness thus a major force is required to the tool to penetrate in the workpiece.

In Table 4 the obtained p-values for all the ANOVA tests on the cutting forces are reported; the significant ones are printed in italic font.

Table 4. Obtained p-values for the ANOVA tests

		Variable		
		Kc	Ff	Fr
Factor	vt	*0*	0.867	0.823
	f	*0*	*0*	*0*
	refr	0.922	0.555	*0.010*
	vt*f	*0*	*0*	*0.002*
	vt*refr	0.911	0.383	0.133
	f*refr	*0.026*	0.06	0.386
	vt*f*refr	0.817	0.598	0.698
	Ct Pt	*0.001*	*0.007*	0.125

All cutting tests produced a serrated chip (Fig.°4). Chip dimensions, considering peak and valley height and peak to peak distance, were measured from chip samples collected for every cutting condition. The results are reported in Table 5. An ANOVA analysis showed the influence of feed rate on all the three chip dimensions. Peak to peak distance was also influenced by the cutting speed

factor. This analysis shows that the cryogenic cooling does not alter chip formation mechanics despite its strong cooling effect. This is also supported by the fact that the main cutting force is not influenced by the LN$_2$ cooling.

Segmentation frequency values range from about 3500 Hz to 7000 Hz, with cutting speed and feed rate being the significant factors.

Table 5. Average chip morphology for every cutting test condition

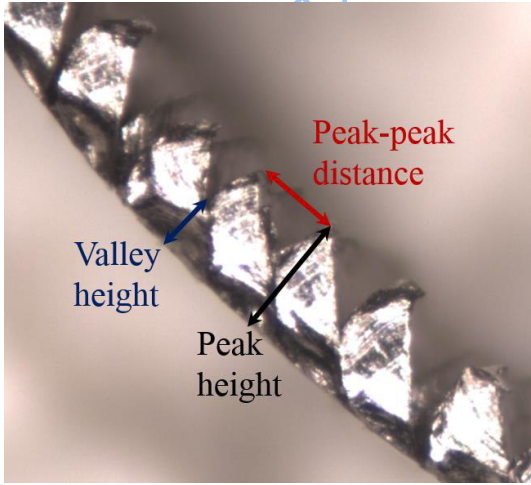|		50 m/min 0.2 mm/rev	50 m/min 0.3 mm/rev	60 m/min 0.25 mm/rev	70 m/min 0.2 mm/rev	70 m/min 0.3 mm/rev
Valley height [µm]	Emulsion	272	414	323	253	353
	Cryo	275	387	350	266	403
Peak height [µm]	Emulsion	111	241	143	139	155
	Cryo	110	206	174	122	210
Peak-peak distance [µm]	Emulsion	224	223	226	150	218
	Cryo	205	228	219	169	217

Fig.°4. Chip sample and characteristic dimensions

Tribological effects. The calculation of the coefficient of friction is performed using the measured cutting forces through Eq. (1).

$$\mu = \frac{F_n \cdot \cos(\gamma_r) + F_c \cdot sen(\gamma_r)}{F_c \cdot \cos(\gamma_r) - F_n \cdot sen(\gamma_r)}. \tag{1}$$

Where F_c is the cutting force, F_n is the normal force on the cutting plane defined by feed force (F_f) and radial force (F_r) as follows:

$$F_n = \sqrt{F_f^2 + F_r^2}. \tag{2}$$

γ_r is the true rake angle and is defined as:

$$\gamma_r = \arcsin(\sin^2(\lambda) + \cos^2(\lambda)sin(\gamma)). \tag{3}$$

The coefficient of friction μ is influenced by feed rate (p-val. 0.000) and the interaction between feed rate and cutting speed (p-val. 0.010). Cooling method is not significant on friction, hence it can be deduced that cryogenic jet has a double effect, not only heat reduction but also a lubricating action because μ is equivalent with the traditional emulsion one. μ decreases as feed rate increases,

at 0.3 mm/rev with a vc of 70 m/min the coefficient of friction is higher because the cooling fluids did not reach the tool chip interface in efficient way.

The average surface roughness (Ra) was measured three times during the cutting tests with three replicates each. In every case the Ra was measured when the tool was not significantly worn and resulted influenced only by the feed rate (p-val. 0.000), as expected, and not by the type of cooling. The measured values varies between a minimum of 1.064 µm and 2.813 µm.

Table 6. Mean friction coefficients and surface roughness values

		50 m/min 0.2 mm/rev	50 m/min 0.3 mm/rev	60 m/min 0.25 mm/rev	70 m/min 0.2 mm/rev	70 m/min 0.3 mm/rev
µ	Emul	0.48	0.35	0.37	0.43	0.39
	Cryo	0.44	0.35	0.38	0.44	0.41
Ra [µm]	Emul	1.123	2.434	1.784	1.247	2.436
	Cryo	1.448	2.212	1.640	1.509	2.014

Conclusions and future work

An experimental study on rough turning of aerospace titanium has been conducted for evaluating the difference (especially in terms of tool life and cutting forces) between conventional emulsion flood cooling and cryogenic cooling. No results were previously available in the literature in the investigated region of cutting parameters. The main findings of the present study are described as follows.

- There is a statistical difference between the two average flank wear progression laws with traditional and cryogenic cooling, with an advantage for cryogenics.
- The main cutting force and the thrust force are not influenced by the cooling method; a slight hardening effect of cryogenic jet can be noticed in radial force which is moderately higher during cryogenic cutting.
- Liquid nitrogen cooling does not affect the mean surface roughness nor chip morphology
- The coefficient of friction is not statistically influenced by the cooling method, hence cryogenic adduction presents heat reduction effect but also a lubrication effect similar to oil-water emulsion

Despite the above mentioned positive results, with the implemented experimental setup, cryogenic cooling helps improving tool life over traditional oil-water emulsion, but especially at lower material removal rates. Unfortunately, in rough turning, high MRR values are required. It must be underlined that these results have been obtained with commercial tools and tool-holders. It would be interesting to verify if, with a tooling system specifically designed and optimized for the injection of the cryogenic jet, the relative advantage of LN_2 can be increased also for large MRR-values. For this purpose, a dedicated tool-holder with LN_2 jet nozzles larger and closer to the cutting zone has been designed and built in co-operation with the Italian branch of Sandvik (Fig. 5). The tool-holder also presents a nozzle for an additional and optional adduction of a minimum quantity oil flux. Preliminary tests performed with this new tool-holder showed a substantial improvement in tool life at all the tested cutting conditions; hence, an economic comparison of the machining will be performed. The performance of this new tool-holder will be presented at Esaform 2015.
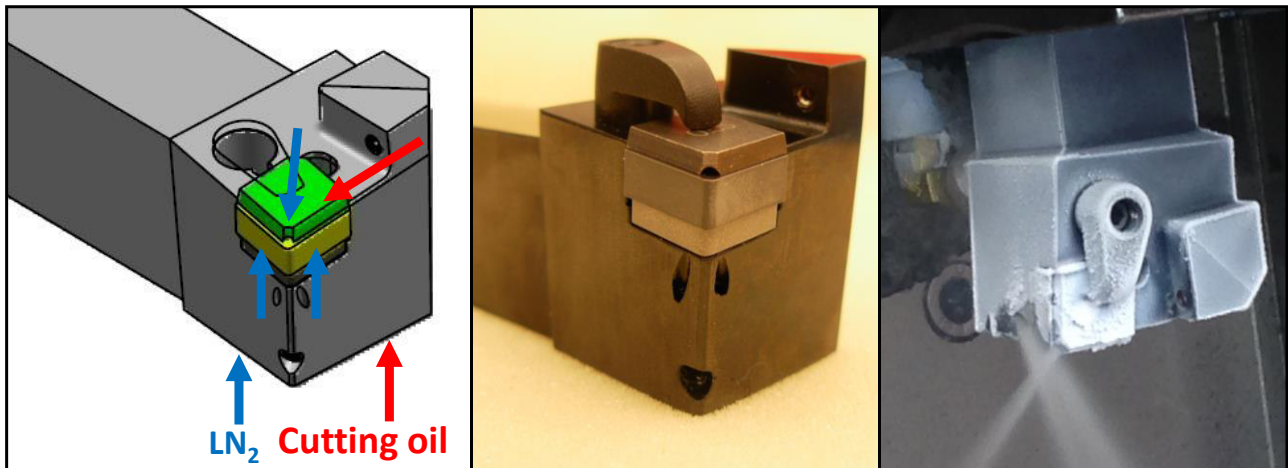
Fig.°5. Drawing and picture of the special purpose tool-holder for cryogenic cooling

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