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Tribological behavior of PVD hard coated cutting tools under cryogenic cooling conditions

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Abstract

Cryogenic assistance is used to improve machining performance and to enhance tool life under extreme contact conditions (pressure and temperature). This paper focuses on the influence of cryogenic cooling conditions using liquid nitrogen within the context of machining Ti6Al4V with CrN-coated carbide cutting tools. Friction behavior of both CrN-coated and uncoated pins with and without cryogenic cooling were evaluated using a home-made laboratory tribometer. The adhesive and plastic friction coefficients were evaluated using a finite element model of the pin-Ti6Al4V system through an inverse methodology. Finally, the contribution of the CrN coatings was evaluated under both cryogenic cooling and dry conditions.

Keywords: Cryogenic cooling; machining; friction; PVD coatings

1. Introduction

Titanium and its alloys are common materials employed in aerospace industry. This is due to their low density coupled with a very good mechanical behavior [1]. Nevertheless, titanium alloys are considered as hard cutting materials because of their low thermal conductivity and chemical affinity with cutting tools [2]. Those materials require low cutting velocities, which increases the machining costs [2].

Nomenclature

LN_2	Liquid Nitrogen
FE	Finite Element
COF	Coefficient of friction
PVD	Physical Vapor Deposition
CNC	Computer Numerically Controlled

The interest of Cryogenic assistance machining is now more and more studied in comparison to traditional machining.

Indeed, Hong et al [3] dealt with the cutting temperature using different lubrication conditions and with cryogenic assistance on titanium alloy Ti6Al4V machining. Temperature measurements and finite element (FE) simulation showed a decrease of the cutting temperature of about 500 °C (from 900 °C to 400 °C) for cryogenic assistance machining in comparison to traditional machining. Nevertheless, cutting forces trended to increase with this process.

Venugopal et al [4] studied the influence of cryogenic assistance on the tool wear during Ti6Al4V machining. He compared the cryogenic assistance with dry and classic lubrication. The obtained results showed that cryogenic assistance enhanced considerably the carbide’s tool life: two times in comparison to classic lubrication machining, and by three times in comparison to dry machining. However, this tool life improvement is only observed for low cutting velocities. This means that LN_2 cryogenic assistance can be used for both lubrication and cooling of the cutting area.

On the other hand cutting fluid removal can generate a main financial interest, due to fluid costs (16% of total costs),

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and can reduce health problems (skin and respiratory diseases) [5].

Until now, in the case of cryogenic machining, the most common operation is turning with tungsten carbide tools; very few studies have been found about cryogenics machining with coated tools [6,7]. Usually titanium based alloys are machined with uncoated carbide tools because of their chemical affinity with some of the coatings that are titanium-based [8].

Hence, CrN coating can be a good candidate for titanium alloys cryogenic machining because of its tribological and wear properties [9] and to avoid the titanium chemical affinity phenomena.

In this work, we studied the influence of CrN coatings on cryogenic machining (in turning) of Ti6Al4V. The friction coefficient of CrN-coated and uncoated pins behavior is considered here to check its influences on the tool and machining efficiency; besides, the assistance of cryogenic cooling is compared using a self-made laboratory tribometer. The adhesive and plastic friction coefficients and contact temperatures are evaluated using a finite element model of the pin-Ti6Al4V system through an inverse methodology.

2. Experimental procedure

2.1. CrN deposition

CrN coating were deposited using a reactive DC magnetron sputtering system (KENOSISTEC KV40). After a process optimization, which enabled to obtain the adequate adhesion and tribological properties, the chosen process parameters are shown in Table 1.

Table 1. CrN deposition parameters

Process parameters	
Residual pressure (mbar)	5.0×10^{-5}
N_2 flow (sccm)	35
Ar flow (sccm)	68
Cr bias voltage (-V)	378
Substrate bias voltage (V)	500
Substrate holder rotation (Yes/No)	No
Deposition time (min)	50
Heating temperature (°C)	300

CrN coatings were applied on Wolfram Carbide pins at two roughness levels, measured using an optical profilometer (Alicona), ~1.1 µm (new pin) and ~0.8 µm (worn pin) respectively. Tips' 3D aspects of new and worn coated pins is shown in Fig. 1.

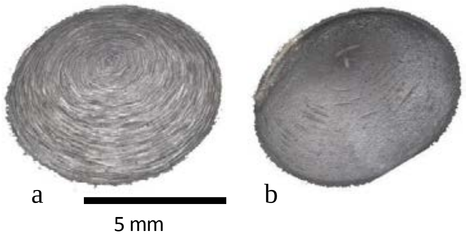

Fig. 1. 3D topography of (a) a new pin (R_a~1.1 µm) and (b) a worn pin (R_a~0.8 µm).

2.2. Tribological tests under cryogenic environment

For tribological tests, the device consisted of a Computer Numerically Controlled (CNC) machining lathe, a self-designed tribometer and a LN_2 nozzle as decribed in Fig. 2.

The Ti6Al4V part was previously polished to R_a ~ 0.15µm in order to neglect its roughness effect. Then it has been positioned on the CNC lathe. The pin is inserted in the home-made tribometer holder which consists of a hydraulic cylinder coupled to a Kistler type 9121 three-component piezoelectric dynamometer designed to measure cutting forces. The hydraulic pressure in the cylinder is set in order to obtain a contact force between the pin and the part of 1000 N, which is similar to the one used by Courbon et al [7,8] for subsequent comparison. The CNC lathe is programmed to operate helical trajectory (spiral) - facing operation- with a cutting velocity of 60 m/min and a feed of 1.5 mm/rev.

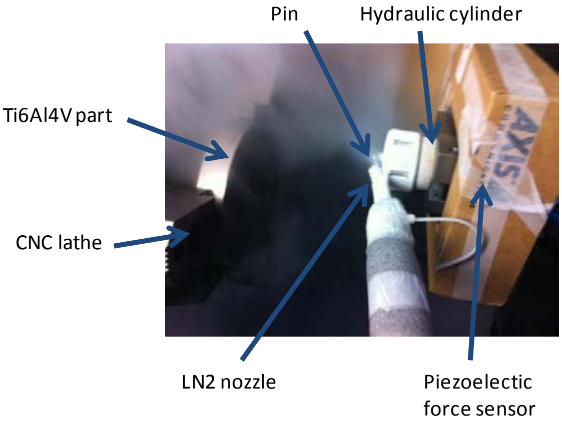

Fig. 2. Tribological tests tests setup, the piezoelectric dynamometer is protected from LN2 splash to avoid thermal drift Four types of pins were used for six configurations (Table 2) of tribological tests (see Fig. 3):

Table 2. Tribological test configurations

Coating (Yes/No)	Ra (µm)	Environment
No	0.8	Dry
No	1.1	Dry
No	0.8	Cryogenic
No	1.1	Cryogenic
Yes	0.8	Cryogenic
Yes	1.1	Cryogenic

Fig. 3. (a) coated pin (Ra~1.1 µm); (b) uncoated pin (Ra~1.1 µm); (c) coated pin (Ra~0.8 µm); (d) uncoated pin (Ra~0.8 µm).

Through tribological tests, both tangential (F_t) and normal force (F_n) are measured with the previously mentioneddynamometer; forces used to compute the apparent coefficient of friction according to the following equation (1):

$$COF_{app} = \frac{F_t}{F_n} \quad (1)$$

3. Numerical model

A 2D Lagrangian Finite Elements (FE) model was developed to evaluate physical properties of the contact between the pin and the part, such as the temperature and the adhesive coefficient of friction. The principle of this model is similar to the one described by Zemzemi et al [10], but improved with the cryogenic flow implementation, like in Rotella and Umbrello's model [11].

The input data of the simulation are similar to the experiment with a sliding velocity of 1000 mm/s and a normal pressure set to obtain a normal reaction force of ~1000 N. The cryogenic flow is applied on both the external face of the pin and the near area of the part (see Fig. 4). For Ti-based part the LN_2 cryogenic flow is applied at different part zones following the pin locations. Thus, a Python program has been developed to couple the nodes on which are applied the cryogenic flow and the pin motion. The heat convection flow was set to 100 000 W/m^2.K, which is close to the one used by Hong et al [3] (87500 W/m^2.K).

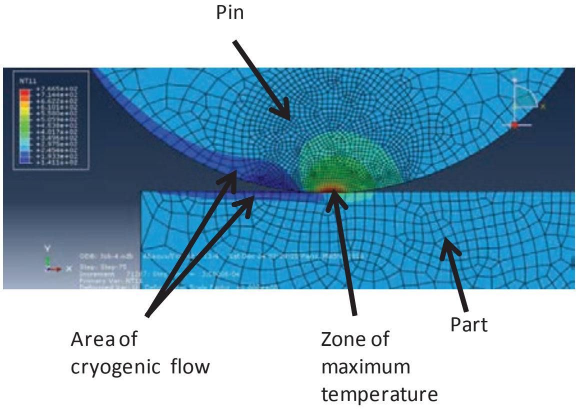

Fig. 4. Simulated contact zone under cryogenic environment

The pin and part base material properties are close to the WC and Ti6Al4V ones , respectively. In order to simplify the model and to reduce the calculations duration, we did not take into account the CrN properties in the model as the thickness of the coating was thin (~ 2 µm).

To obtain the adhesive component of coefficient of friction, the following formula was used (2):

$$COF_{app} = COF_{adh} + COF_{plas} \quad (2)$$

where COF_{app} is the apparent coefficient of friction (the experimental one), COF_{adh} is the adhesive coefficient of friction and COF_{plas} is the coefficient of friction due to plastic deformation. Numerically, to evaluate COF_{adh}, an inverse methodology is applied. COF_{adh} is used as an input data to obtain COF_{app} as output data.

4. Results

4.1. Optical observations

After tribological tests, an adhesion zone is observed at the same area of the contact zone for all the pins (both coated and uncoated ones). Fig. 5 shows the optical image of the cross section of a coated pin after tribological test.

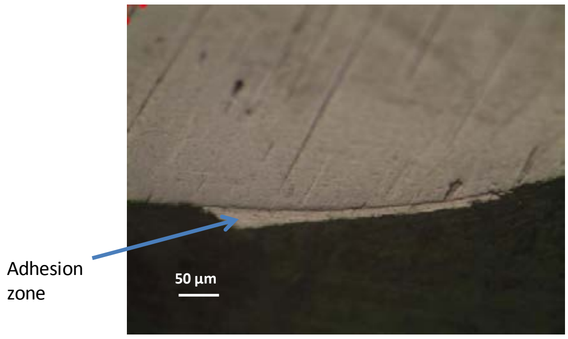

Fig. 5. Optical image of the cross section of a coated pin after tribological test (objective magnification of x20)

To ensure that the adhesive material is Ti6Al4V from the part, an EDS (Energy Dispersive Detector) microanalysis using a Scanning Electron Microscope (Jeol-JSM 5900LV) is undertaken on the adhesion zone. It showed the presence of Ti, Al, V elements that compose the Ti6Al4V alloy (see Fig. 6). This result confirmed that a transfer of Ti6Al4V to the pin material occurred during the tribological test. This clue highlights the partt’s material adhesion on both WC and CrN material under extreme contact conditions (high contact stresses and high temperatures). Therefore CrN coating does not seem to be efficient enough to avoid the adhesion phenomena with Ti6Al4V, as in the case of uncoated carbide pin.

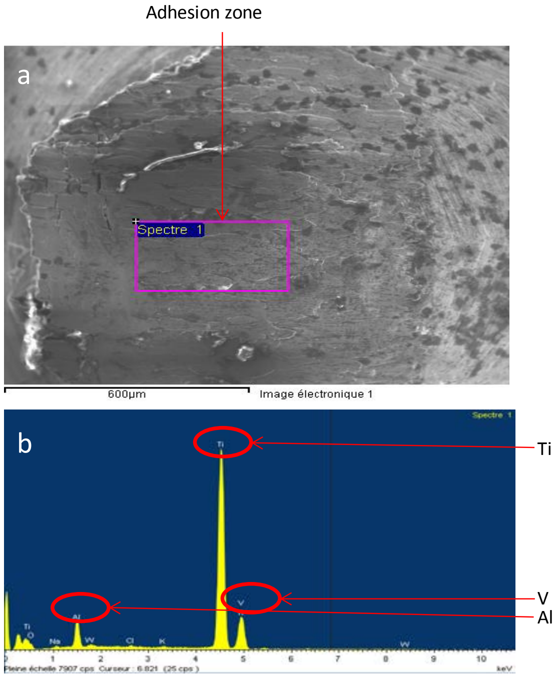

Fig. 6. a) SEM image and b) EDS microanalysis of the adhesion zone (magnification x100)

4.2. Tribological results

Fig. 7 shows the values of COF_{adh} for each tribological test configurations.

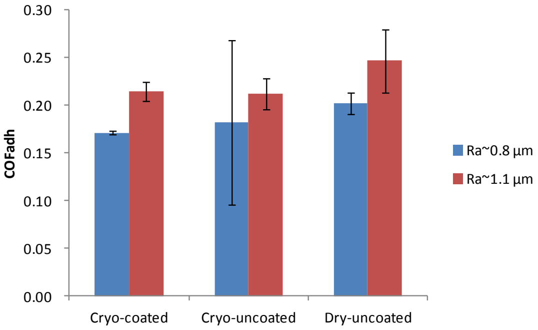

Fig. 7. COF_{adh} for each test configuration

First, COF values are at the same magnitude as to the one arising from the literature for this type of contact [7,8,12]. The influence of roughness on COF_{adh} (COF increases with R_a) is obvious here. Then, cryogenic assistance influenced on COF reduction too, which is noticed by Courbon et al [7,8]. Concerning the CrN coating influence, the COF reduction is very sensitive but obvious for a R_a of 0.8 µm. Indeed, lower the roughness is, better the influence of the 2 µm thick CrN coating is.

Fig. 8 shows the maximum temperature at the contact zone for each tribological test configurations.

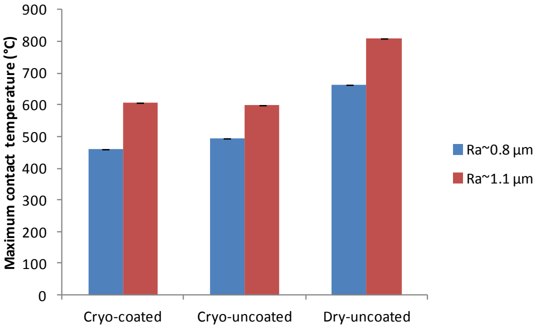

Fig. 8. Maximum temperatures at contact zone for each test configuration

The influence input parameters (cryogenics, roughness and coating) is similar to the previous ones obtained for the COF. The temperature can be reduced to ~ 400 °C with cryogenic assistance, which is similar to Hong et al [3] results (500 °C). Besides, the CrN coating allowed to obtain the lower temperature when the roughness is 0.8 µm. Its efficiency is again not obvious for R_a of 1.1 µm.

Fig. 9 shows the correlation of input parameters (cryogenics, roughness and coating) on COF_{adh} using a linear correlation coefficient (when the coefficient is positive, COF_{adh} increases with the parameters influence).

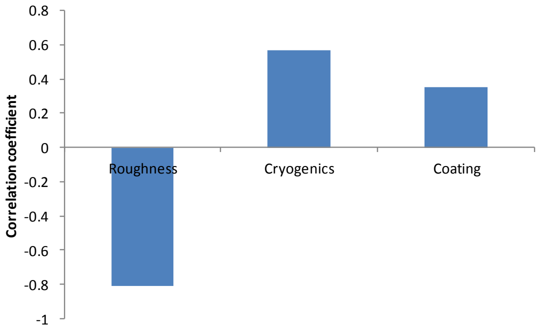

Fig. 9. Correlation coefficient of each input parameter on the adhesion friction coefficient COF_{adh}

As expected, roughness is the most impactful parameter on the coefficient of friction variation, whereas the coating contribution is the lowest as it directly depends on the roughness.

Conclusion

This study deals with the contribution of cryogenic assistance during turning operation compared to other parameters such as the roughness and the presence of a PVD coating or not.

Therefore some results can be highlighted:

- An adhesion phenomenon between both uncoated and coated pin and Ti6Al4V material occurred. In order to prevent it, the CrN coating should be optimized. A thicker coating or another coating with a very low Ti-alloys affinity has to be tested.
- The contribution of cryogenic environment on friction reduction is satisfactory and the temperature reduction is up to 400 °C, which showed the relevance of the numerical model.
- Roughness is showing the most influent parameter on the friction variation compared to other parameters.
- The CrN coatings were efficient (lower COF_{adh} and contact temperature) only for the smallest R_a (0.8 µm) because it is only 2 µm thick. It would be interesting to test thicker coatings.

This study is helpful to understand (through experiment and numerical modeling) and improves different aspects of TiAl4V machining conditions (tool coating and roughness choices). Moreover, it highlights the benefits of cryogenic machining compared to traditional machining.

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