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# Numerical and Experimental Approach in Assisted Cryogenic Machining

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**Abstract.** Understanding of local mechanisms chip forming during machining by removal of material is difficult, to this end; a cutting finite element modelling is required. This study aims initially to model orthogonal cutting of Ti17 titanium alloy in dry and cryogenic machining and in a second time to study the influence of the application of cryogen during machining on temperature fields and cutting forces in numerical simulation. An experimental study was also conducted to determine the mode of tool wear and the evolution of flank wear.

**Keywords:** Ti17, cryogenic assistance, numerical simulation, flank wear, cutting forces.

## 1 Introduction

The use of titanium alloys in the field of aeronautics increases with time having regard to its compatibility with the composite reinforced with carbon fibers (CFRP), but the mechanical characteristics of the material such as its hardness machining, its low conductivity make it difficult to machine [1]. To this end, the cryogenic machining assistance is one of the solutions to reduce the temperature at the tool / chip interface [2-3].

## 2 Experimental Approach

The machining tests were carried out by a CNC turning machine LEADWELL LTC25iL (2500 rev / min and 24 kW maximum). The acquisition system is composed of a Kistler dynamometer (9257B), the forces exerted on the quartz crystals are transformed into piezoelectric signals as a result of efforts to acquire the three components of the cutting force. The analog signals derived are amplified by a charge amplifier (Kistler 5019B). Thereafter, they are passed to an analog / digital converter. The evolution of the effort over time is provided by the software (Catman Easy).

The cutting parameters for machining Ti17 are: depth of cut  $a_p=1.5\text{mm}$ , feed  $f=0.3\text{ mm/rev}$  and cutting speed is  $0.83\text{ m/s}$ .



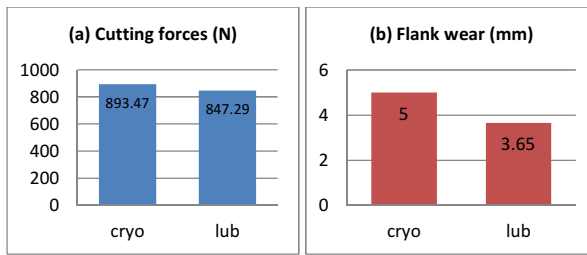
**Fig. 1** Presentation of the cryogen's flow and the cutting tool

The cutting tool used is Seco PCLNR JetStream 2525 M12 and a plate CNMG 120412-23 shade of H13A, the cutting edge  $\alpha = 7^\circ$  and the draft angle  $\beta = 6^\circ$ , the radius of curvature of  $30\ \mu\text{m}$ .

The liquid cryogen is stored in a ranger equipped with a 15 bar pressure imitator and is then injected on the rake face of the tool by two microbuses of  $1.7\text{ mm}$  of diameter.

Cutting tests were performed for both lubricated and cryogenic cutting of Ti17 to get cutting forces and flank wear.

The criterion of end of life of the tool is set at a flank wear  $VB=0.3\text{mm}$  and which was measured on constant time using a binocular microscope.



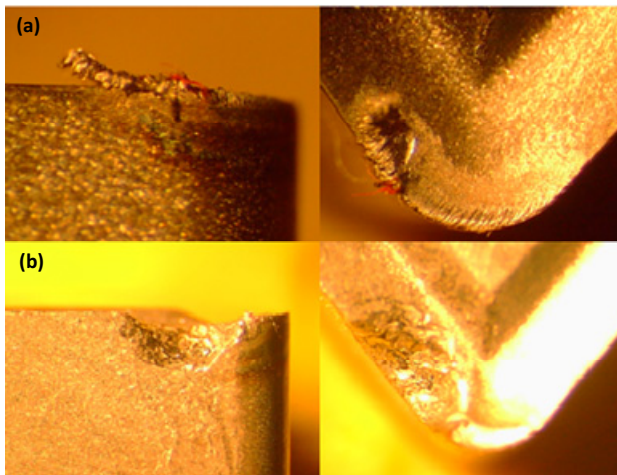
**Fig. 2** Cutting forces and flank wear in both cryogenic assistance and wet machining ( $V_c=50\text{m/min}$ ,  $f=0.3\text{mm/rev}$ ,  $a_p=1.5\text{mm}$ )

It is noted that with the cryogenic support there was no reduction in cutting forces, but, on the other hand, the life of the tool has increased 3.65min lubrication 5min which may be approximated by an increase of 27%. This may be explained by the decrease of the temperature.

A study was done to determine the mode of tool wear.

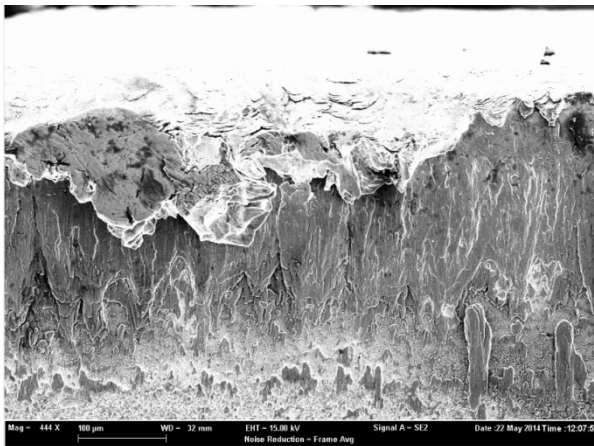
- **Degradation Mode of the Tool:**

At first sight of the flank face, we think that the material of the tool is being removed by abrasion, to determine the mode of degradation; the cutting insert was examined under scanning electron microscope (SEM) SEM views of worn tools while turning Ti17 under  $V_C = 50 \text{ m/min}$  and  $f = 0.3 \text{ mm/rev}$ .



**Fig. 3** Microscopic observation of the tool in cryogenic machining at (a) 1min and (b) 4min( $f=0.3\text{mm/rev}$ ;  $a_p=1.5$ )

We found that the percentage of titanium that is the material of the machined piece increases over the time, so we conclude that the principal degradation mode of tool wear is adhesion.



**Fig. 4** SEM views of worn tools while turning Ti17 under  $f=0.3\text{mm/rev}$  and  $VC = 50 \text{ m/min}$

It is noted that there is a deposition of titanium on the flank face, this shows, that the tool wear is by adhesion, the material accumulated on the surface of the insert is removed after that.

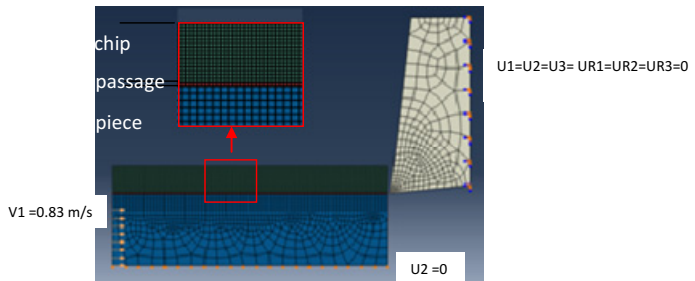
### 3 Numerical Study

#### 3.1 Model Description

2D model was developed on ABAQUS / explicit 6.11 to model orthogonal cutting. A lagrangian formalism was adopted. The boundary conditions are the embedding of the tool; the lower surface of the part has zero displacement  $U_y = 0$ , and the cutting speed is imposed on the left surface of the work piece  $V1=0.83\text{m/s}$  (Figure5).

The cutting tool is made of tungsten carbide which the parameters are presented in paragraph (2).

CPE4RT elements were used for a coupled temperature-displacement problem.



**Fig. 5** Boundary conditions

### 3.2 Law of Material Behavior

The behavior of the material was introduced by Johnson Cook constitutive law [4]. The equation generally used to describe the behaviour of the material is the BC law represents the yield stress of the material [Johnson 1983].

$$\sigma = (A+B \varepsilon^n) (1+C \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}) [1 - (\frac{T-T_r}{T_m-T_r})^m] \quad (1)$$

$\sigma$ : equivalent stress vonMises;

$\varepsilon$ : equivalent plastic strain;

$\dot{\varepsilon}$ : The equivalent plastic strain rate;

$\dot{\varepsilon}_0$ : The equivalent plastic strain reference rate;

T: work piece temperature.

$T_m$ : Melting

$T_r$ : Room temperature

A, B, C, n and m are material constants determined from tests. The main advantage of this law is the decoupling of the terms of hardening and dependence on strain rate and temperature.

**Table 1** The parameters of material behavior Law [5]

A(MPa)	B(MPa)	n	C	m	Tr (°C)	Tm (°C)
1012	399	0.22	0.035	0.85	50	1650

### 3.3 Damage Law

The use of Lagrangian formalism requires the use of a criterion of separation between the work piece and the chip which is expressed by a deterioration law Johnson and Cook [3] (Johnson et al, 1985). The damage variable is:

$$D = \sum \left( \frac{\Delta \varepsilon_{eq}^p}{\varepsilon_{eq}^p f} \right) \quad (2)$$

Where  $\varepsilon_{eq}^p$  is the increment of plastic deformation in a no integration and  $\varepsilon_{eq}^p f$  current equivalent plastic strain at break:

$$\varepsilon_{eq}^p f = [D1+D2 \exp (D3 \sigma^*)] (1+D4 \ln \dot{\varepsilon}^p) [1+D5 T^*] \quad (3)$$

D1, D2, D3, D4 and D5 are constants for the material  $\sigma^*$ : The stress triaxiality rate defined by the  $P / \sigma_{vm}$  where P is the hydrostatic pressure and  $\sigma_{vm}$  rupture is reached when the damage variable  $D = 1$ . The corresponding element is deacti-

vated. The variables and  $\epsilon p$  and  $T^* = (T - T_r) / (T_m - T_r)$  are identical to those defined in the constitutive law (1).

**Table 2** The parameters of the damage law [5]

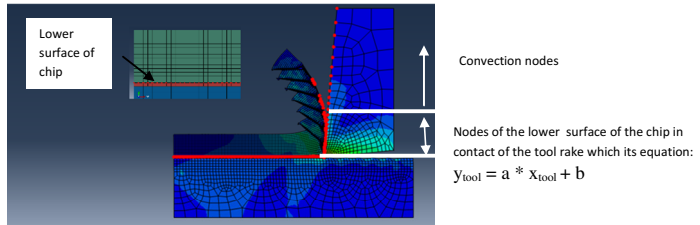
D1	D2	D3	D4	D5	$\epsilon_0$
-0.2	0.34	-0.5	-0.035	2.7	0.1

### 3.4 Modelling of Cryogenic Support

In our simulation, the elements of the damaged portion are removed after the passage of the tool, it is the lower surface of the chip which rubs on the tool. To simulate the application of the cryogenic jet on the rake face and in the lower surface of the chip detached from the tool, we use the programming software Python. The approach is as follows (fig7)

The tool rake face is a right which can determine the equation:

$$y_{\text{tool}} = a * x_{\text{tool}} + b$$

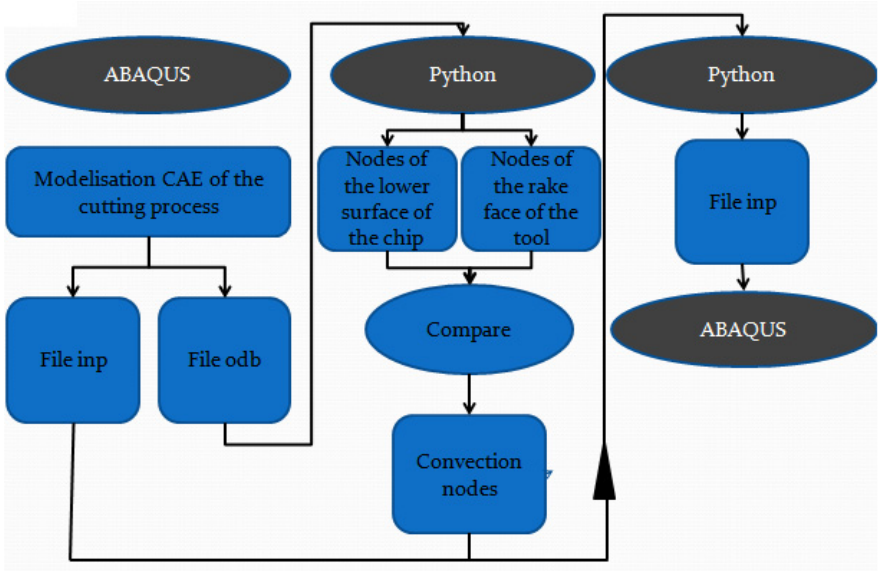


**Fig. 6** Determination of convection nodes

$dx$  is the distance of remoteness of the nodes with respect to the cutting face from which convection is applied.

The nodes of the lower surface of the chip which are more in contact with the face of the tool ie if  $[x_{\text{chip}} < ((y_{\text{chip}} - b) / a) - dx]$  then applied convection at this node.

In those nodes, convection is applied with a temperature sink of  $-196^\circ\text{C}$ . (figure2)



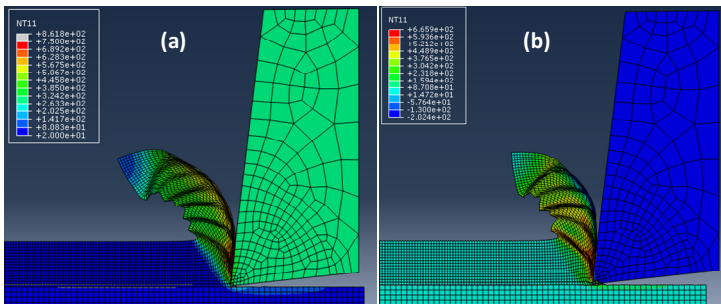
**Fig. 7** Steps of modeling the convection on the rake face

## 4 Results and Discussion

### 4.1 Temperature Fields

Ti17 titanium alloys generates segmented chip at the cutting speed of  $V_c=50\text{m/min}$  and the feed rate  $f = 0.3\text{mm / rev}$ .

The maximum temperature is  $861.4^\circ\text{C}$  in dry machining, while in cryogenic support it decreases to  $659^\circ\text{C}$  in the secondary shear zone, that's cooled the tool avoiding degradation modes at high temperatures and increases its life and provides

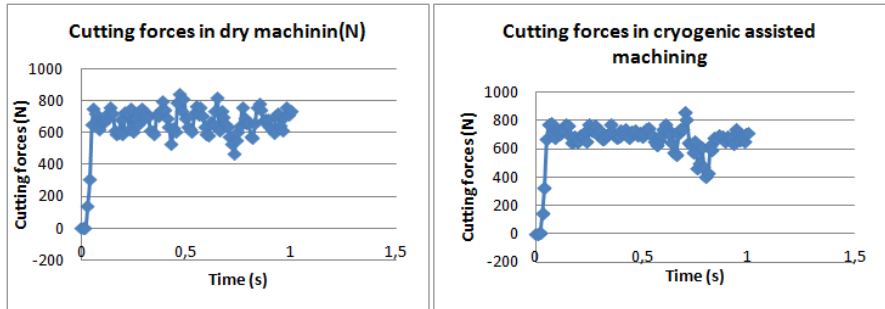


**Fig. 8** Temperature fields in (a) dry and (b) cryogenic assisted machining



## 4.2 Cutting Forces

We note that with the cryogenic assistance, the fluctuation of the effort has decreased, that's decreases tool's vibration, provides stable conditions machining and increases the tool life.



**Fig. 9** Evolution dry cutting efforts, in cryogenic assistance on the rake face

Cutting efforts in cryogenic assisted machining in numerical model is 641.95N (f0.3; ap1) while in practice 595.3 N for the same conditions.  $F_{c_{exp}} = F_{c_{num}} \pm 50N$ .

Cutting forces in cryogenic cooling are very close to dry machining efforts. This can be explained by the temperature of the primary shear zone that cryogen has not cooled.

## 5 Conclusion

- Cryogenic assistance on the rake face had no influence on the cutting forces, for against it decreases the temperature on the secondary shear zone during machining
- The wear pattern observed is the adhesive wear
- The cryogenic support decreases flank wear and preserve a longer life time. This gain was quantified at 27% for f0.3 and p1,5.

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