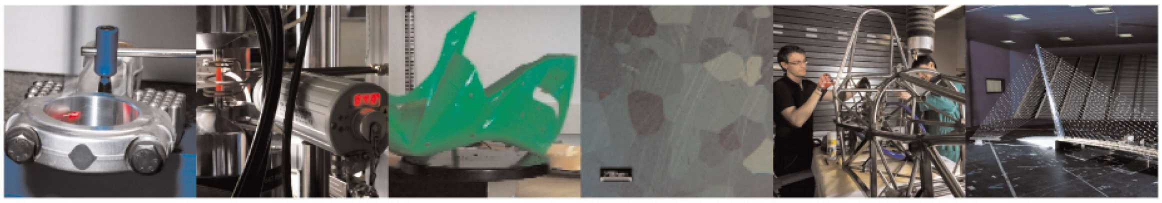

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Estimation of cutting and friction coefficients in dry and cryogenic milling through experiments and simulations

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Abstract. Cryogenic milling with internal delivery of liquid nitrogen is an effective way for improving the cutting performance and the environmental impact in machining of titanium. Physical experiments of down-milling of aerospace titanium have been conducted and a numerical model of the process has been developed, in order to model and predict the cutting forces. Combining the results of the numerical model and of a mechanistic cutting force model, it can be concluded that internal cryogenic cooling significantly changes the mechanics of the machining process, with respect to the dry conditions.

INTRODUCTION

Titanium alloys are frequently used in many applications, including aerospace. Machining of Ti6Al4V is especially inefficient, because of large buy-to-fly ratios [1] and rapid tool wear due to chipping and early tool failure [2]. The low thermal conductivity of titanium further reduces the tool life. The implementation of advanced cooling strategies can increase the productivity and reduce the machining costs [3]. In this context, the use of a cryogenic fluid (typically a jet of liquid nitrogen LN), locally directed towards the tool-chip interface [4] is an effective way of enhancing the cutting performances [5] and improving the environmental sustainability of machining [6]. Despite its potential advantages, cryogenic milling has not been successfully adopted in machining industry yet. This is partly due to the problematic need for internal delivery of the fluid through the spindle. The research on cryogenic milling operations has been mostly focused on using external jets [7], but internal delivery of LN allows a targeted cooling of the cutting edges. Very few papers have presented experimental results of cryogenic milling of Ti6Al4V with internal cooling. Park et al. [8] studied the effect of internal and external spray methods on cryogenic machining, by evaluating tool wear and cutting force at cutting conditions. Wang et al. [9] focused on the effect of diffusion wear behaviour of WC-Co tool in operations. A second problem is that a deep comprehension of the effects of the cryogenic cooling on the chip formation is far from being accomplished. Some finite element models FEM of cryogenic machining process have been developed, but mostly on orthogonal cutting [10] and without properly considering the contribution of the cryogenic fluid in terms of capability of removing heat from the cutting region [11], which is required for accurate simulation [12]. Only few researches started dealing with these issues, e.g. [13] and [14]. Imbrogno et al. [15] performed 3d FEM simulation of semi-finishing turning of Ti6Al4V in dry and cryogenic conditions. To the author's knowledge, no scientific paper has ever been published including an FEM model of milling with internal cryogenic cooling. In this paper the development of a 3D FEM model of cryogenic milling of titanium is presented. The model helps explaining the mechanics of down-milling of aerospace titanium with internal cooling. The numerical and experimental results are discussed in terms of cutting forces, material cutting coefficients and coefficient of friction.

EXPERIMENTAL AND NUMERICAL SETUP

Experimental set up and cutting tests definition

A 4-axis machine with a horizontal spindle (FIGURE 1, (A)) was used for straight shoulder milling tests both in dry and cryogenic conditions. The machine was equipped with an electro-spindle with the maximum available torque of 160 Nm and it can achieve up to Ω=8000 rev/min. The liquid nitrogen, in the cryogenic tests, was delivered to the cutting zone through the inner channels of a commercial indexable cutter, FIGURE 1 (B). A specific delivery system and a cryogenic head were adequately developed and designed. The cutting forces were measured through the Kistler dynamometer 9255B with the charge amplifier type 5070A. Preliminary dynamic tests on the dynamometer/piece system were performed in order to estimate the available bandwidth for the force measurements (70Hz along X, 75Hz along Z and 300Hz along Y). The tool used for the test was an indexable (Z=2) commercial cutter (R390-020B20-11L) designed and manufactured by Sandvik Coromant. The tool, for what concerns the inner channel, had been adapted to the cryogenic application. The tool is particularly suitable both for contouring and for slotting due to the lead angle χ=90°. The utilized inserts, the R390-11 T3 08M-MM S30T type is featured with a physical vapor deposition PVD TiAlN coating developed by Sandvik Coromant that, according to the industrial state-of-art, it is an effective solution for processing Ti6Al4V or other HRAs. With respect to LN consumption estimation, the overall mass flow rate $\dot{m}$ was roughly measured through differential measurements of the weight of the dewar. Setting the LN pressure inside the dewar equal to 3.5bar, the mass flow rate was $\dot{m}\cong$60kg/h. The cutting tests were performed with the following parameters: feed per tooth f_z=0.15 mm/tooth, axial depth of cut a_p=3 mm, radial depth a_e=5 mm, cutting velocity v_c=50 m/min.

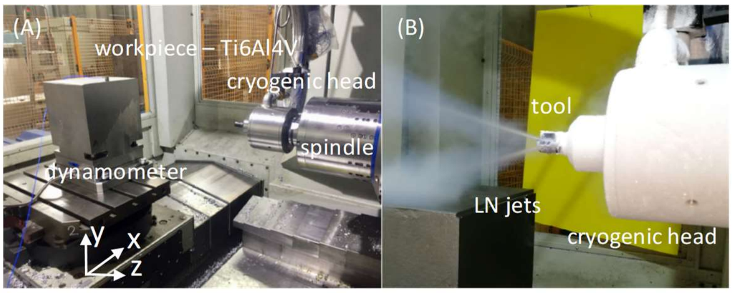

FIGURE 1. Experimental set-up (Kistler dynamometer) and details of the cryogenic milling set-up (A), LN jets (B)

FEM model setup

A FEM model has been developed with the commercial software Forge NxT, using solid 5-nodes tethraedral elements with quadratic shape functions and automatic remeshing [16]. The nonlinear mechanics is solved with a lagrangian geometrical update of the mesh [17]. The non-linearity is solved with implicit time integration. The tool is also meshed with volume elements in order to model the heat conduction, but it is a rigid body, with the geometry of one insert of the face mill used in the down-milling tests (FIGURE 2 (B)). The insert was meshed with a constant target mesh size of 0.05 mm. To model the movement of the insert, its translation speed was set equal to the relative speed of tool axis and workpiece of the experimental case (i.e. the table feed rate): its rotation speed around the tool axis was set equal to the one of the spindle during the experimental tests. To have a complete engagement a_e, with the typical cutting parameters used in titanium alloy milling, a process with a duration in the order of seconds should be implemented. In straight shoulder milling, when the tool is engaged at the nominal value a_e, the tool creates two surfaces in the workpiece: the base and the wall. The wall surface can be seen as the sum of a plane surface and a tapered wall created by the movement of cutting edge of the mill. This movement is a cycloid given by the combination of the tool rotation and the tool feed rate. The equation of the insert trajectory is described by (the x axis is the one parallel and oriented along the feed direction of the tool): where r_{tool} is the tool radius, n is the tool rotating speed in RPM, v_{feed}, is the tool feed rate, t is the time. In order to have a realistic initial workpiece geometry suitable for the simulations (FIGURE 2 (A)), the cycloid trajectory was generated with a Matlab® script and imported into a CAD as a spline. In this way the tool can cut a realistic chip thickness during the simulations, where the chip size is maximum at the start of the insert engagement and decreases as the simulation proceeds.

$$x = x_{rot} + x_{trasl} = Re\left(r_{tool} \cdot e^{i\frac{n}{60}\pi t}\right) + v_{feed} \cdot t$$
$$y = y_{rot} + y_{trasl} = Im\left(r_{tool} \cdot e^{i\frac{n}{60}\pi t}\right) \quad (1)$$

The obtained 3D CAD solid of the workpiece was than imported in FORGE NxT along with the insert model. The tool was than positioned against the workpiece, in the position that it would reach just before the engagement of the cut. The workpiece was meshed with the built-in automatic mesh refinement algorithm, using two mesh windows where a finer mesh size is prescribed than the rest of the workpiece. The windows were cylindrical rings (FIGURE 2 (C)), with a prescribed target mesh size of 0.08 mm set for the inner ring (the green one) and a size of 0.25 mm for the outer one (the red one). In the rest of the body a target size of 1 mm was selected.

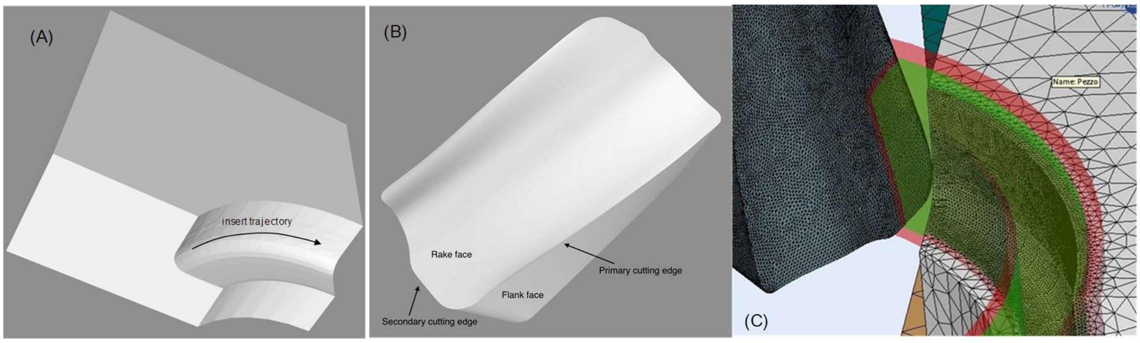

FIGURE 2. Workpiece to be machined (A) – insert geometry (B) – Developed model and meshing (C)

To model the frictional contact between the insert and the workpiece, three different models have been tested: a constant Tresca shear friction (with friction factor m); a constant Coulomb friction (with coefficient of friction f), and a mixed Tresca-Coulomb model, where τ is the shear friction stress and σ is the flow stress of the material:

$$\tau = \mu \cdot \sigma_n; \qquad \tau < \sigma$$
$$\tau = m \cdot \sigma; \qquad \tau \geq \sigma \quad (2)$$

The correct selection of the friction model is important not only to predict the cutting forces, but also to predict the thermal fields [19]. These three models were calibrated, by iteratively changing the values of the coefficients, as in [15]. The response variable considered in order to obtain the best match between the simulation and the experiments was the main cutting force F_y. The best prediction for F_y was obtained with a mixed friction model using μ = 0.6 and m = 0.35 for the dry case and μ = 0.2, m = 0.2 for cryogenic cutting.

Material properties and heat transfer conditions

A Johnson-Cook isotropic hardening model with 5 parameters has been used:

$$\sigma = B\epsilon_p^n\left(1 + C\, ln\frac{\dot{\epsilon}_p}{\dot{\epsilon}_0}\right)\left[1 - \left(\frac{T-T_0}{T_m-T_0}\right)^m\right] \quad (3)$$

where ϵ_p is the equivalent plastic strain, $\dot{\epsilon}_p$ is the strain rate, T_m and T_0 are the melting temperature and a reference ambient temperature used in the test. The 5 parameters are B equal to 1508 MPa, the strain sensitivity index n equal to 0.049, C equal to 0.067, $\dot{\epsilon}_0$ which is a reference strain rate for milling (assumed equal to 1000 s-1), the temperature sensitivity m equal to 0.71. The parameters had been obtained in a previous experimental work with face milling tests of aerospace titanium [20]. The Cockroft-Latham damage model has been used. It is the most frequently used model for the simulation of machining [21]. Damage modelling is uncoupled with the flow stress, i.e. it does not determine softening, but an element deletion strategy is implemented. A damaged element is deleted whenever its damage function reaches the critical threshold D:

$$D = \int_0^{\epsilon_p} \sigma_I \, d\epsilon_p \quad (4)$$

According to the specific literature, D-value equal to 245 MPa was set for the simulations of both dry and cryogenic conditions. A global convection coefficient h_{air} =20 Wm^{-2} K^{-1} was set for the workpiece. This is the typical value reported in the scientific literature for heat exchange through of a metallic surface with calm air. Anyway, the results are not sensitive to this value, since a very short processing time is considered. In agreement with a standard practice in the scientific literature [15] [22], an overestimated value of the heat exchange coefficient (10 kWm^{-2} K^{-1}) has been assigned at the contact interface. With this value a thermal steady state is reached in nearly 0.5 ms. The tool is modelled as a rigid body with the density of tungsten carbide, an assigned thermal conductivity k=44.03 W m^{-1} K^{-1} and an assigned specific heat capacity c_p=188 J kg^{-1} K^{-1}. In order to simulate the cryogenic cooling with liquid nitrogen, a heat exchange windows with a temperature of −187°C, with the same convective coefficient of 20 kW m^{-2} K^{-1}. The cryogenic cooling window was modelled as a hollow cylinder, similarly to the meshing window shown in FIGURE 2 (C). This window has no tangible cooling effect onto the workpiece surface, because of the short processing time, its large mass and high thermal inertia. On the contrary, it has a clear cooling effect on the tool.

RESULTS AND DISCUSSION

The validation of the numerical model was performed comparing the experimental and the simulated cutting forces, FIGURE 3. The measured cutting force Fy acquired both during the execution of cryogenic and dry tests were adequately averaged in order to remove the run-out effect. The corresponding confidence intervals (ULC upper confidence level and LCL and lower confidence level, eq. 5) were reported in FIGURE 3. More in details, several cutting force profiles $F_{y_r}(t)$ were synchronized and averaged $F_y(t)$ using equation 5. r is the index for the cutting force profile and q=24 is the total number of profiles used for the averaging process and $\sigma_{F_y}(t)$ the standard deviation.

$$F_y(t) = \frac{1}{m}\sum_{r=1}^{r=q} F_{y_r}(t);\ \ \sigma_{F_y}(t) = \sqrt{\frac{\sum_{r=1}^{r=q}\left(F_{y_r}(t)-F_y(t)\right)^2}{m-1}}\ ;UCL(t) = F_y(t) + 3\sigma_{F_y}(t);\ \ LCL(t) = F_y(t) - 3\sigma_{F_y}(t);\ (5)$$

It is worth of noting that cryogenic cooling exhibited a relevant effect on the cutting forces and specifically, it made the cutting forces reducing, FIGURE 3. As can be observed, this effect was properly reproduced by the developed FEM model. Since the computational time (AMD Opteron6282SE 2.6GHz, 16 Core (24 parallel processing) close to 200 hours) is very relevant, only a portion of the whole tooth passage was simulated. This does not affect the validation of the numerical modelling since the simulations reached the thermal regime. Focusing on the simulation models, it was observed that the coefficients of the friction model for cryogenic milling were set significantly lower than the values used for simulating dry cutting. This was confirmed by the experimental data. More specifically, a linear regression on the average cutting forces measured in different cutting conditions was used to identify the parameters of a mechanistic model, Altintas [23] and Gonzalo et al. in [24]. Three levels for the feed (0.1, 0.15 and 0.2 mm/tooth) and two different cutting velocities (50 and 70 m/min) were adopted in the experimental campaign. Some of the identified cutting coefficients (K_{tc} and K_{te}) together with their 95% confidence intervals are reported in Table 1. It was reported the identified values both for dry and cryogenic cutting. K_{tc} represents the specific cutting pressure typically used for computing the tangential force contribution proportional to the chip section while K_{te} allows computing a force supplement proportional to the axial engagement (a_p). Since this last force contribution is proportional to the length of the engaged cutting edge, it takes into account frictional effects. As can be observed in Table 1, the edge contribution identified in dry cutting is significantly higher than the respective value in cryogenic milling.

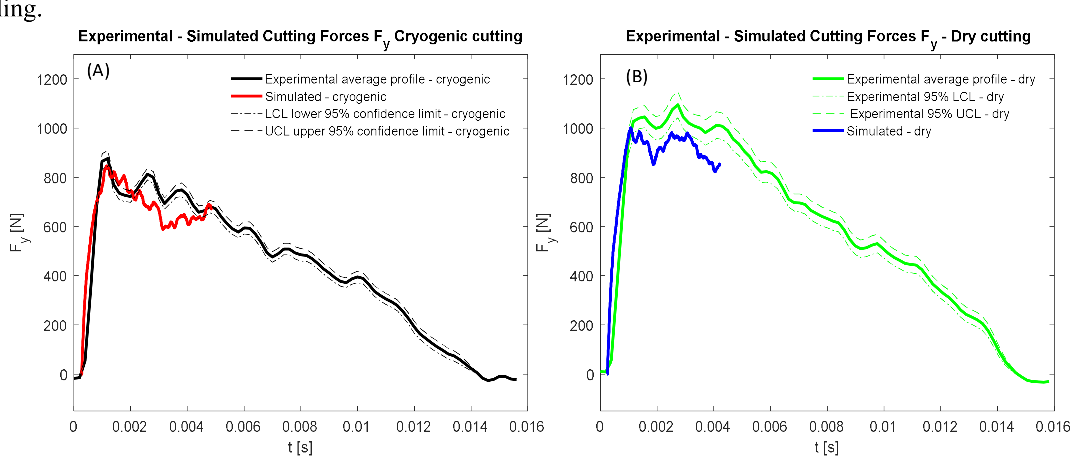

FIGURE 3. (A) Cutting force Fy in cryogenic condition – (B) cryogenic and dry cutting force comparison (average profiles)

This effect was already observed in other scientific contributions but mainly in orthogonal cutting or in turning, Jawahir et al. [7] Sharma et al. [3], Venugopal et al. [25] and Strano et al. [26]. The most accredited hypothesis is that a cushion of gas between the chip and the tool face functions as a lubricant.

TABLE 1. Identified tangential cutting coefficients and their confidence intervals 95% CI – cryogenic

Lubrication condition	cutting coefficients	LCI	$\widehat{K_{t_j}}$	UCL
dry	K_{tc} [MPa]	1710,2	1868,3	2026,4
dry	K_{te} [N/mm]	32,8	44,4	55,98
cryogenic	K_{tc} [MPa]	1350,7	1623,1	1895,3
cryogenic	K_{te} [N/mm]	-7,08	12,9	32,9

The performed simulations were used for carrying out some considerations about the thermal behavior. It was observed from simulations that the temperature difference was roughly 100 °C. Indeed, the temperature reduction makes the chip less ductile and it is more rapidly damaged. This observation, combined with a reduced tool-chip friction agrees with the observed cutting force reduction.

CONCLUSIONS

The experimental down-milling tests have shown that cryogenic cooling with internal delivery of the liquid nitrogen is able to reduce the cutting forces down by about 20% in the peak values, with respect to dry conditions. An FEM simulation model has been developed, which convincingly reproduces the cutting forces. The coefficient of friction of the cryogenic simulation has been reduced in order to match the results, and this reduced friction largely explains the results. This was also confirmed by the analysis carried out exploiting a mechanistic cutting force model. The results achieved in the thermal simulation agree with the observed behavior. The work has demonstrated that milling of Ti-6Al-4V titanium with internal cryogenic cooling through the tool can be performed with reduced cutting forces with respect to dry machining.

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