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SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

Executive Summary of the Thesis

Simulations of Ti6Al4V milling for assessing different cooling lubrication strategies.

Laurea Magistrale in Mechanical Engineering - Ingegneria Meccanica

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1. Introduction

The aim of this thesis work is the investigation, through finite element analyses, of the causes that determine a different duration of the tools while milling Ti6Al4V with different cooling lubrication strategies (cryogenic vs wet machining) or different machining approaches (high feed vs square shoulder milling).

Cryogenically assisted machining is emerging as an environment/health friendly alternative to the more dangerous and pollutant conventional wet machining. In practice, a cryogenic liquid (mainly LN2) is delivered in the cutting zone in order to limit the temperature build up between tool and workpiece, which is detrimental for tool life. A reduction of the cutting temperature is crucial during the machining of an hard to cut material as Ti6Al4V, since its low thermal conductivity tends to concentrate the heat generated during the cut in a small area around the tool-workpiece contact interface.

In literature the superiority of cryogenic machining is assessed for turning, but passing to milling the results are not univocal.

Experimental tests showed how the application of cryogenic coolant in case of square shoulder milling drastically reduces the life of the tools if compared with flood cooling. On the contrary, the application of cryogenic coolant (with the same delivery system) in case of high feed milling can increase the life of the tools if compared with flood cooling, especially at high cutting speeds.

In this scenario finite element analyses are crucial in order to deeply understand which are the reasons of such different performances, with the possibility of visualizing stresses, strains, temperatures, thermal/mechanical power exchange mechanisms, wear indexes and other meaningful quantities near the cutting zone.

Previous thesis works by A.Elefanti and L.Losa aimed at the finite element modelling of square shoulder milling in dry and cryogenic conditions, this work demonstrates that similar models can be developed for different approaches as high feed milling and different cooling lubrication strategies as wet machining obtaining reliable results and allowing interesting comparisons.

2. Experimental tests

A system for the delivery of cryogenic fluid in the cutting zone was installed on a 5-axes machine tool (Flexi model by Sigma, FFG group). A flexigas (pressurized liquid nitrogen reservoir) was placed on the back of the machine. In the figure below are reported also the associated piloting electro-valve, a vacuum jacket flexible pipe, and a phase separator that is used to purge the evaporated nitrogen in the feeding line due to both heat transfer and cavitation phenomena [2].

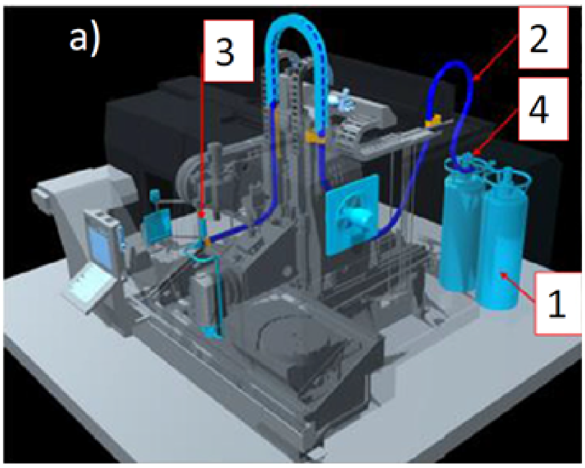

Figure 1: Representation of the machine tool equipped with cryogenic system

where the main parts of the feeding line are: 1 = flexigas liquid nitrogen reservoir, 2 = insulated pipe, 3 = phase separator, 4 = electro valve.
The mass flow rate of LN2 in cryogenic cutting was estimated exploiting subsequent weight measurements of the flexigas. It was observed that averagely the mass flow rate, at a pressure of 3.2 bar was about $\dot{m}_{LN} = 45$ kg/h. For the tests performed with the conventional coolant, a pressure of 40 bar was set for the pump and the observed flow rate was equal to $\dot{m}_{\text{coolant}} = 2770$ kg/h (measured using a flow sensor). A Kistler force dynamometer (9255B) with the corresponding amplifier (5070A) were used for acquiring and real-time monitoring the tool and the process conditions during the tests. The tool body is AJX06R203SA20S from Mitsubishi characterized by nominal diameter D = 20 mm and three cutting inserts JOMT06T216ZZER-JL MP9140. They are formed by a carbide substrate and PVD coating characterized by an Al-rich (Al,Ti)N single layer.

Figure 2: Cutting insert.

The forces were measured at three different cutting speeds 50 - 70 - 125 m/min, both in wet and cryogenic environment so it is possible to reproduce on the finite element software six different cases and compare the simulated forces with the measured ones to validate the model and to infer about the process condition.

2.1. Finite element set up

The finite element software used in this work is Forge Nx T 3.0. It is basically conceived for forging and more in general for metal deformation procedures. All the bodies in the simulations are addressed as dies and they can be rigid or deformable.
According to the available license, the software allows the computation on multiple cores. The simulations were run with 16 cores on a 60 core - 4 processors workstation with 2.5 GHz base clock speed and 356 GB DDR3 RAM.
Once generated the geometry of tool and workpiece on Inventor (CAD software), it is imported in Forge.
The material model adopted is a Johnson-Cook

$$\sigma = (\mathrm{A} + \mathrm{B}\varepsilon^{\mathrm{n}})\,(1 + \mathrm{C}\ln\dot{\varepsilon}^{*})\,(1 - \mathrm{T}^{*m})$$

A = yield strength sensitivity of the material, B = strain sensitivity of the material, C = strain rate sensitivity of the material, $\dot{\varepsilon}^*$ = normalized strain rate = $\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} = \frac{\text{effective platic strain rate}}{\text{reference plastic strain rate}}$, $T^* =$ normalized temperature = $\frac{T-T_0}{T_m-T_0}$, T_m = melting temperature of the material, T_0 = reference temperature of the quasi static test used to determine the material constants.
In this case takes the coefficients
$[A, B, C, n, m, \dot{\varepsilon_0}] =$
$= \left[782.7, 498.4, 0.028, 1.0, 10^{-5}\right]$ have been determined by Lee and Lin in the article [3].
To better reproduce the chip morphology also a

simple Latham-Cockcroft damage model is used in the form:

$$\int_0^{\varepsilon_f} \sigma_1 * d\varepsilon = D$$

The contact/friction model adopted is the Coulomb-Tresca.
For the thermal problem is necessary to define the conductance at tool-workpiece interface=10000 W/m^2K, the tool effusivity =

$$= e = \sqrt{\rho * K * c_p} = 1111\frac{W}{K} * \sqrt{\frac{s}{m}}$$

, and the heat transfer coefficients with the ambient media. In wet environment the system exchanges thermal power with one single medium (conventional coolant) characterized by $h_{coolant} = 5000W/m^2K$, while in cryogenic environment the system exchanges thermal power with the evaporated nitrogen that surrounds the cutting zone $h_{N2vap} = 1500W/m^2K$ and with a window of enhanced heat exchange in the zone where it is likely to find the nitrogen in liquid form, with an heat transfer coefficient function of the temperature of the cooled surface as suggested in an important study [5].
Here below a preview of the process on Forge.

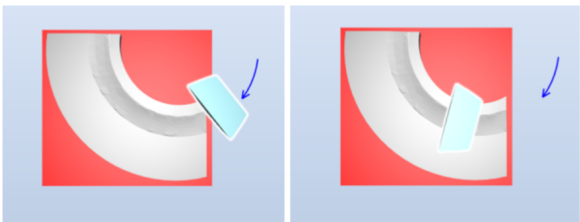

Figure 3: Preview of the process.

3. Model Validation

Unfortunately not all the acquired forces are comparable with the simulated ones. In particular the values of F_y (forces perpendicular to feed direction) are affected by the dynamics of the machine tool + dynamometric table. Strong oscillations are evident and they are not replicable by the finite element simulations.

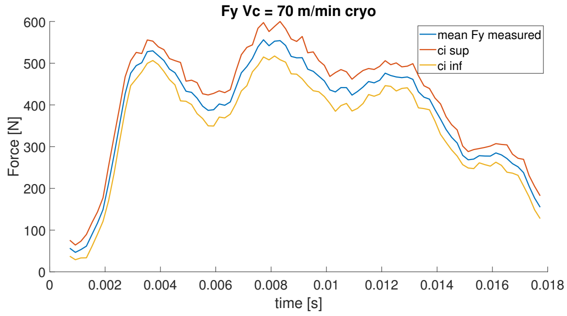

Figure 4: Fy oscillations.

The forces in vertical direction are compromised by the weight force of the workpiece. So a reliable comparison between experimental forces and simulated ones is possible only for F_x, the forces in feed direction. Here, calibrating the friction coeffcients m and μ of the Coulomb-Tresca model it is possible to tune the model and bring the simulated values closer to the measured ones. The best results are obtained at low cutting speeds where the measured forces are more stable and the strain rates are more similar to the ones at which the material model has been determined.

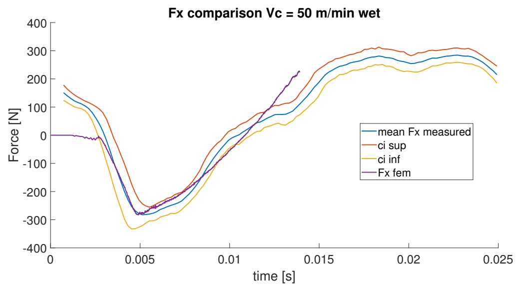

Figure 5: Fx comparison between experimental and FEM forces at Vc=50 m/min, ap=0.4mm, ae=13mm, fz=0.7mm/rev*tooth in wet environment

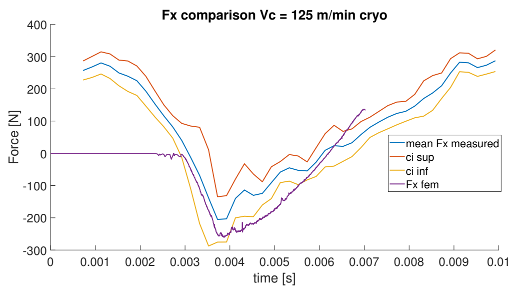

Figure 6: Fx comparison between experimental and FEM forces at Vc=125 m/min, ap=0.4mm, ae=13mm, fz=0.7mm/rev*tooth in cryogenic environment.

In every simulated condition (six in total) the agreement between experimental and FE results is good, this is the basis for considering valid the developed models, giving reliability to their results and it is also a demonstration of robustness of the models.
The chip morphology is correctly reproduced in a macroscopic way (continous and curled chip), but for a microscopic reproduction (precise shear bands' prediction) a smaller mesh size is necessary.

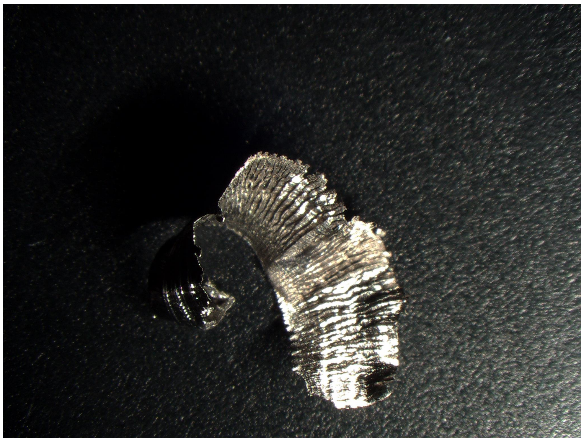

Figure 7: Real chip from operation at 125 m/min in cryogenic conditions.

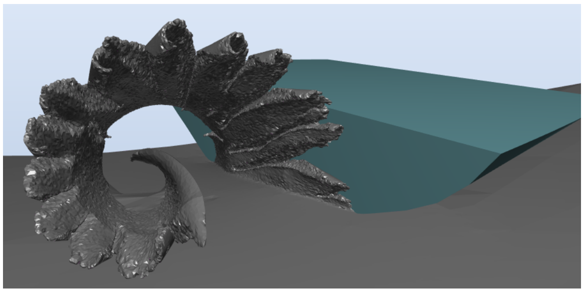

Figure 8: Simulated chip from operation at 125 m/min in cryogenic conditions.

4. Results

4.1. Differences between high feed and square shoulder milling

As said before high feed mills perform better than square shoulder mills when applying a cryogenic coolant in the cutting zone.
First of all using square shoulder inserts with small or null recline angles in wall milling the whole cutting edge is engaged at once, the engagement is sudden, not gradual thus square shoulder concentrates immediately the load on a thin rake area. The action of the cryogenic fluid can overharden the workpiece and (with this geometry) reduce the toughness of the cutter drastically decreasing its life. In high feed the engagement phase is much more gradual and the value of depth of cut is generally higher than the feed per tooth adopted with square shoulder, thus the stresses are distributed in a wider area. Significative is the comparison of two Fy force profiles between two simulations at Vc=50 m/min one in square shoulder and the other one in high feed configuration. The first part of the plot is explicative on how sudden (and dangerous) is the engagement phase in case of square shoulder.

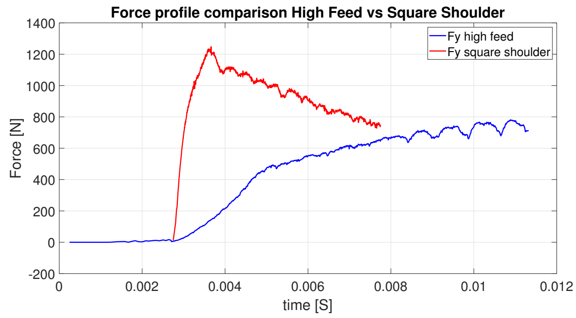

Figure 9: Force profiles (Fy) comparison Square shoulder vs High feed.

One crucial result coming from the simulations is that in case of sqaure shoulder the zone of maximum temperature and maximum stress on the tool are concident since they are both located on the edge at the maximum distance from the centre of the tool. In high feed the maximum temperature spot and the most stressed one on the tool are not coincident anymore, the latter in fact is shifted towards the centre of the tool where the relative tangential speed between tool and chips is lower than on the external profile, thus lower temperatures are developed. And also comparing the maximum temperature of two operations at same cutting speed 50 m/min, both in cryogenic environment, the maximum temperature developed in square shoulder configuration is higher and more "sudden" than the one of high feed.

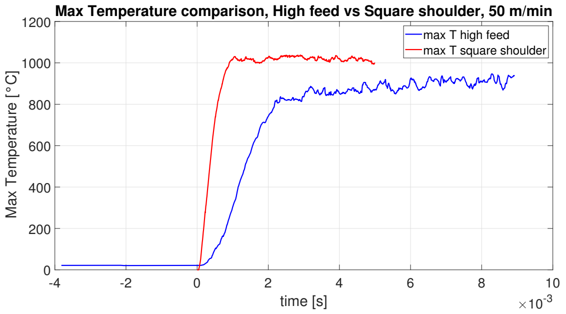

Figure 10: Difference in Max temperature between High Feed and Square Shoulder at 50 m/min.

These considerations are made on operations with same cutting speed but the other cutting parameters are different: high feed is featured by fz = 0.7 mm/rev*tooth, ap = 0.4 mm, ae = 13 mm, square shoulder by fz = 0.2 mm/rev*tooth, ap = 3 mm, ae = 5 mm.
Activating the computation on the tool it is also possible to extract the Abrasion index that is the integral in time of the product of pressure and relative speed between workpiece and tool. For the same contact time this value is always bigger in case of square shoulder approach.
All these evidences suggest that the high feed approach is more adapt to the application of cryogenic cooling and it is worth further investigating its full potentialities with new experimental trials.

4.2. Different wear depending on cooling lubrication strategies

The results of the simulations indicate that different cooling lubrication strategies modify the mechanics of cut justifying different behaviour under the tool wear point of view.
First of all the cryogenic coolant, if compared with conventional metal cutting fluid, is able to reduce the maximum temperature in the tool-WP interface for every tested cutting speed.

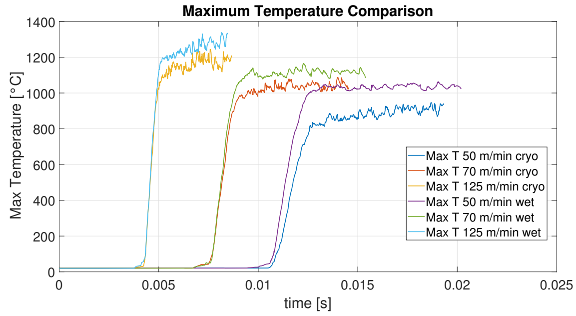

Figure 11: Overall maximum temperatures comparison (high feed).

The reduction of this temperature is able to contrast some common wear causes as atomic diffusion, oxidation and plastic deformation.
For the abrasion this tendency is reversed, the cryogenic coolant reduces the contact area for every tested cutting speed, localizing the stresses on a thinner area on the tool's rake. The pressure on the tool increases and as consequence also the abrasion index. Anyway with FEA it is not possile to quantify the possible enhancement of abrasion resistance of a cooled tool.

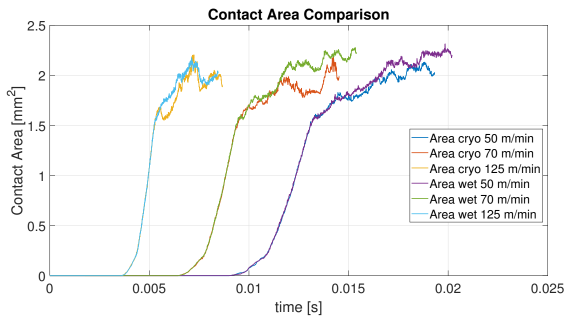

Figure 12: Overall comparison of tool workpiece contact areas (high feed).

Another wear cause to consider is the thermo-mechanical fatigue. The cryogenic coolant increses the pressure on the cutter but not so much to justify a different fatigue behaviour. More important is the effect played by the cooling of the tool during the idle phase, here an excessive reduction of the tool's temperature can embrittle it (exposing the edge to chipping), can damage the coating layer and also induce thermal fatigue due to the higher difference between maximum and minimum temperature if compared with the case of conventional coolant.
As said before in high feed the advantages of cryogenic cooling against conventional flood cooling are more evident at high cutting speeds.

At low/medium cutting speeds (50 - 70 m/min) the performances of cryogenic machining are lowered by the presence of a sort of built up edge (BUE) / adhesion like phenomenon [2], not experienced in wet tests. This phenomenon usually does not affect Ti6Al4V, it is typical of ductile materials machined at sub-optimal cutting speeds. Actually the most mechanically stressed zone of the cutter moves with a small tangential speed, since it is not on the external edge but it shifted towards the centre of the tool, where the tangential speed is reduced by the 40% (Point B) if compared to the one on the external diameter (Point A).
For nominal cutting speeds of 50 - 70 - 125 m/min the tangential speeds in point B are respectively 30 - 42 - 75 m/min.

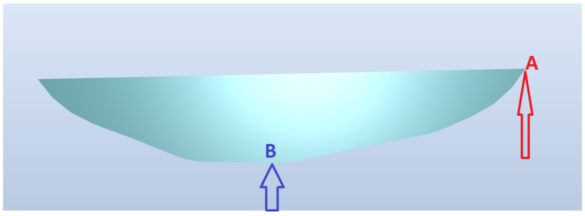

Figure 13: Detail on external edge (A) and actual engagement point (B) in high feed.

It is reasonable to asses that in the tests the cryogenic coolant applied at low/medium cutting speeds has made the engagement phase more difficult promoting rubbing between tool and workpiece instead of pure cutting, leading to adhesion phenomena. Anyway from the simulations it is not possible to deeply understand the causes of this phenomenon and why in wet environment it is not verified.
Another important result of the simulations is the fact that the total mechanical power requested by the cut is reduced for every cutting speed when passing from wet to cryogenic machining. The two main contributions to this result are the reduction of plastic and friction power with the application of LN2. These results confirms that, at shop floor level, cryogenic machining reduces energy consumption and net carbon emission as underlined in [1].

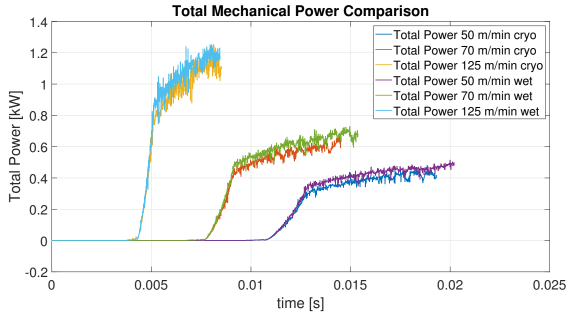

Figure 14: Overall comparison of total mechanical power.

5. Conclusions

This thesis work demonstrates how finite element simulations can be precious in order to better understand macro and microscopic phenomena occurring during milling operations, difficult to appreciate from the analysis of experimental results only. The superiority of high feed approach over square shoulder in case of cryogenic milling has been assessed, encouraging new studies on this promising technology. Comparing wet and cryogenic machining important results coming from experimental campaigns are confirmed with FE results. Cryogenic machining has always been considered an environment friendly technology able to reduce the energy consumption of the machines avoiding the use of suction and recirculating pumps for conventional metal cutting fluids, and for the potential enhancement of tools' life, but also a reduction of the mechanical power requested for cutting itself has been assessed. The next industrial revolution will be the environment/health conscious one, the hope is the possibility of substituting wet machining with cryogenic one where dry cutting is not applicable. Many efforts are still necessary in this sense, the materials and geometries of the tools should be optimized for keeping high performances also at cryogenic temperatures, avoiding embrittlement or thermal fatigue. Moreover, less pollutant processes for the liquefaction of nitrogen should be found.
This work also demonstrates how material, damage and contact models that guarantee good results in the simulation of less complicated processes [4] can give good results also with more complicated processes as high feed milling (no similar works are availbale in

literature).
For a more robust validation of the model more accurate experimental forces' values and the availability of chips from a wide range of operations are necessary. Another factor to be considered is the impossibility of exactly separating the effect of material model and contact/friction model. To exploit all the potentialities of the material model (in the chip morphology reproduction for example) finer mesh elements and more frequent remeshings are necessary, but when applied to complex kinematics they exponentially increase the computational time. So in this case more powerful hardware resources would be required. Anyway the results exposed can be considered reliable and give the basis for future FE investigations. Next goals are the completion of one or more cutting arcs in a reasonable time and the activation of deeper analysis tools on the cutter, but also here more powerful hardware resources are necessary. Also the prediction of surface properties/characteristics of the machined parts through FE simulations would be an interesting achievement.

References

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