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Modelling the thermo-mechanical behavior of a redesigned tool holder to reduce the component geometrical deviations in cryogenic machining

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Abstract

In recent years cryogenic cooling based on Liquid Nitrogen has been adopted to improve the titanium alloys machinability mainly in rough operations. However, when applied to semi-finishing machining, the very low temperatures may significantly affect the component final geometry. To this aim, the paper presents the thermal-mechanical modeling of a new tool holder properly designed to reduce the component geometrical deviations from its nominal geometry during cryogenic machining. The model was calibrated and validated through turning trials on wrought Ti6Al4V samples, proving a reliable prediction of the tool holder behavior during cryogenic machining.

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Keywords: Ti6Al4V, cryogenic machining, geometrical distortion, thermal model.

1. Introduction

Nowadays, the significant costs associated to the components cleaning and disposal of conventional cutting fluids based on mineral or synthetic oils are driving machining companies towards more sustainable alternatives.

One of the emerging and most promising strategies, which has been widely tested in recent years by several researchers, foresees the use of low-temperature coolants, such as Liquid Nitrogen (LN2), Carbon Dioxide or air cooled at high pressure, to be applied directly to the cutting zone, thus reducing the temperature arisen during the cutting process. These technologies, in addition to be safe, non-toxic and suitable to leave the machined surface clean, are also advantageous in terms of process outcomes and machined product quality. The highest performances were found using LN2 when machining difficult-to-cut alloys: in fact, the extremely low temperature (-196°C) allows improving their machinability in terms of both tool wear and surface integrity.

As example, in a previous work carried out by the authors [1], a significant reduction of the tool crater wear compared to dry and conventional lubricating strategies was found in semi-finishing turning biomedical Additive Manufactured Ti6Al4V alloys. When using LN2, Bermingham et al. [2] showed improvements in terms of energy consumption, tool life and chip morphology. In addition, the machined surface integrity can be improved in terms of surface roughness, residual stresses, surface defects and surface hardened layer as demonstrated by Iturbe and al. [3] when machining nickel alloys and by the authors [4] in turning titanium alloys. Moreover, Pusavec and al. [5] demonstrated that the cryogenic machining reduced the overall productions costs with respect to the conventional case up to 30% making it economically sustainable.

Despite the several advantages highlighted hitherto, the industrial application of this technology is limited due to the cryogenic coolant extremely low temperatures that could damage the mechanical parts of the CNC machine and cause thermal distortions that cannot be offset, with consequent loss of dimensional accuracy of the machined components, especially when finishing and semi-finishing operations are addressed.

To overcome the aforementioned drawback, in this work, the thermal field of the tool holder during cryogenic turning

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of the Ti6Al4V titanium alloy was measured; afterwards, in order to reduce the thermal distortion, safeguard the lathe revolver and stabilize its thermal field, the tool holder was re-designed using an embedded cartridge heater.

A thermo-mechanical model of the newly redesigned apparatus was developed and calibrated using the experimental outcomes from cartridge heater-free cryogenic turning tests, with particular attention to the identification of the heat exchange coefficients of the LN2 flowing inside the feeder channel of the tool holder. The model was then validated by applying it to turning tests carried out using the cartridge heater with two heat power levels, comparing both the temperature evolution along the tool holder and the thermal distortions the tool holder underwent.

The achieved final target was then a reliable thermo-mechanical numerical model of the tool holder behavior during cryogenic machining that will be further applied to improve the tool holder redesign.

2. Material

The workpiece material used in this study was the Ti6Al4V ELI alloy supplied by Sandvik™ in bars with a diameter of 40 mm. This alloy, obtained through hot working followed by annealing, presents a microstructure composed by alpha equiaxed grains with 8% of beta phase at the grains boundaries. The mechanical properties are listed in Table 1: the high values of the ultimate tensile stress and hardness determine a low machinability that makes it a difficult-to-cut alloy.

Table 1. Ti6Al4V mechanical properties in the as-received conditions [6]

E [GPa]	UTS [MPa]	Ys [MPa]	Elongation [%]	Hardness [HRC]
114	940	870	16.0	31.0

3. Turning tests

Semi-finishing turning tests were carried out on a Mori Seiki™ 1500 NL CNC lathe. A carbide insert coated by TiAlN supplied by Sandvik™ (CNMG 120404-SM GC1105), with rake angle 6°, clearance angle 0° and cutting edge radius of 0.4 mm, was clamped to the PCLNR 2525 M12-CHP tool holder produced by Tungaloy™.

The cutting parameters were chosen according to the cutting tool manufacturer's recommendations and on the basis of previous works carried out by the Authors [7]. The experimental plan is shown in Table 2; a fresh cutting edge was used for each trial, thus avoiding the tool wear effects on the component final dimensional accuracy.

The turning tests were carried out under wet conditions and with the use of LN2 supplied at a pressure of 15 bar simultaneously to the tool flank and rake faces using the internal lubricating channels of the tool holder. A nozzle of 0.8 mm diameter was used to deliver the LN2, smaller than the one used in previous works: in this way the total cryogenic coolant flow rate was reduced minimizing its costs.

Hypothesizing that the sample geometrical deviations were mainly caused by the thermal contraction of the tool holder induced by the low temperatures, it was mandatory to monitor the temperature variations during the cutting operation. To acquire the temperature field generated during the turning tests, 4 k-type thermocouples (Chromel-Alumel) were positioned at different locations along the tool holder. The first one was inserted into a hole produced by electro-discharge machining at 1 mm from the tool rake face and 2 mm from the cutting edge, while the others were spot-welded on the tool holder at 40, 50, 60 mm from the tool tip, respectively, as highlighted in Fig. 1. To process the thermocouple signals into temperature measurements, a LabVIEW™ based software was used.

In order to prevent the tool holder thermal contraction and therefore preserve the lathe turret by overcooling that might cause further distortions, the tool holder itself was modified inserting a cartridge heater with diameter of 6.5 mm, length of 50 mm and electrical power of 75 W and 150 W.

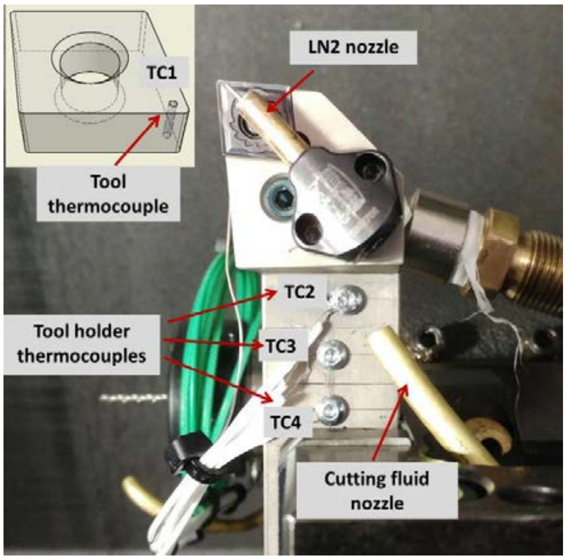

Figure 1. Tool holder setup.

Table 2. Experimental plan for the turning tests.

Depth of cut [mm]	0.25
Cutting speed [m/min]	80
Bar initial diameter [mm]	40
Bar final diameter [mm]	38
Feed rate [mm/rev]	0.2
Cooling strategies	Wet, LN2
Cartridge electrical power [W]	75, 150

Lastly, the geometry of the machined samples was measured using a Zeiss™ Prisma 7 Vast Coordinate Measuring Machine (CMM). A single stylus with a 3 mm diameter rubidium tip was used. The measurements were carried out in a temperature-controlled room at 20°C; the results are reported in Table 3, each one being the average of three measurements. The difference between the actual final diameter compared to that attained in wet conditions can be regarded as a quantitative index of the temperature-induced tooling distortions. The re-designed setup reduced the sample geometrical deviation compared to the original tool holder: the best result was highlighted using a cartridge of 150 W with which the improvement was about 38%.

Table 3. Diameters of the cryogenic machined samples and relative differences with the ones machined under wet conditions.

	Sample dia. [mm]	Standard deviation [µm]	Difference [mm]
Wet	38.13543	0.38	-
Original tool holder	38.34356	0.86	+0.208
Re-designed tool holder (75 W)	38.28970	0.47	+0.154
Re-designed tool holder (150 W)	38.26397	0.60	+0.129

4. Numerical modeling of the tool holder

The numerical model of the tool holder was developed in order to simulate the temperature field during cryogenic machining and the consequent thermal shrinking of the tool holder itself.

The model was developed using the ANSYS™ software with an implicit solution scheme applied to a coupled transient thermo-mechanical material model. As the steel thermal diffusivity in cryogenic conditions was proved to be almost constant down to -210°C[9], the thermo-mechanical characteristics of the tool holder material were assumed from steel standard values at 0°C (see Table 4).

Table 4. Thermo-mechanical characteristics of the tool holder material at 0°C.

Material parameter	Value
Density [kg/m^3]	7850
Young modulus [MPa]	210000
Poisson ratio [-]	0.3
Thermal conductivity [W/mK]	60
Specific heat [J/kgK]	435
Coefficient of thermal expansion [1/K]	1.1 10^{-5}

The 3D model of the entire lathe turret assembly was implemented, composed by:

- tool insert;
- tool holder (comprising the LN2 feeding system and the cartridge heater housing drilled in the holder body);
- tool holder fastening system (comprising plates, wedges and bolts);
- lathe turret.

The lathe turret was discretized with a coarse mesh size of 1.5 mm, while the rest of the tooling with a finer one of 0.7 mm. Figure 2 highlights the main features of the model.

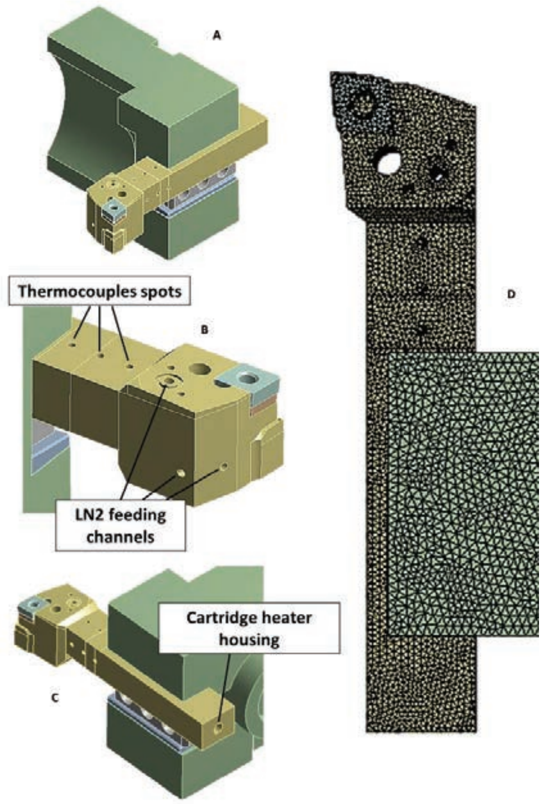

Figure 2. FEM model: A) general overview, B) detail of the tool holder, C) position of the cartridge heater housing, D) adopted meshes.

The main effort in the numerical model calibration consisted in the proper setting of the heat transfer boundary conditions, namely the Heat Transfer Coefficients (HTCs) at the various interfaces. Since the target was the accurate prediction of the temperature distribution along the tool holder, in order to predict its thermal distortions, the first assumption was to neglect the heat generated by the cutting process. This is reasonable since the heating generated by cutting is very localized at the tool tip where a strong cooling condition is imposed by the LN2 adduction, also confirmed by the experimental temperature evolution at the tool tip shown in purple in Figure 4. It is worth to note that the temperature evolution at the tool tip highlights two peaks corresponding to two cutting cycles, but no effect is propagated to the tool holder thermocouples.

Therefore, the most critical heat transfer conditions to be calibrated were those between the LN2 and tooling both in the feeding channels and on the external surfaces. The evaluation of the LN2 HTC has been rarely addressed in literature and usually just in the modelling of the LN2 external flow (i.e. between the cooling fluid and cutting tool). In [8], Hong and Ding evaluated different cooling systems both numerically and experimentally and an HTC value in the range between 20000-40000 W/m^{2}K was found. Also in the works of Kheirredine et al. [9] and Rotella and Umbrello [10], an HTC value of 20000 W/m^{2}K was used. In the work of Jin et al. [11], on the other hand, lower values were found, in the range between 0-3500 W/m^{2}K, as reported also by Pusavec et al. [12]. This was in agreement with the fact that in [11] the HTC was evaluated in still bath conditions and not in external turbulent ones, as in the other cited works.

In the present numerical model, the HTC was assumed to be 20000 W/m^{2}K on the external surface of the cutting tool, while for the internal feeding channels (which are supposedly the most important concerning the cooling of the tool holder), an optimal value was searched by inverse analysis in the range between 0 and 3500 W/m^{2}K.

To this regard it was observed that the HTC in the LN2 feeding channels cannot be constant during the whole turning test because the flow passes through transient states; in particular the following regimes can be observed:

- A N2 → LN2 transient regime in the first part of the test; in this stage the LN2 enters the feeding channel, which is still at room temperature, partially evaporating and reaching the nozzles in a mixed gaseous-liquid state.
- A LN2 steady state regime; in this stage there is a stable liquid flow through the device and the nozzles. It is reasonable to assume that the HTC is higher than in the previous stage, due to the higher thermal conductivity of the LN2 [12].
- A final stage in which the LN2 flow is interrupted; after the cutting operation is finished, the flow is interrupted, the feeding channels remain still full of LN2, which does not move anymore. In this case, a lower HTC value can be expected, due to its reduced convective effect.

The occurrence of the aforementioned regimes is evident from the temperatures recorded by the four thermocouples during the cartridge heater-free test shown in Figure 3.

Even if the second LN2 regime is the most important for the temperature evolution, a reliable numerical model must be correctly calibrated for all the heat exchange conditions, to eventually take into account the repeated start-and-stops and tool changes of the cutting cycles.

The inverse analysis was carried out using a factorial plan of simulations testing different HTC sets searching the best fitting with the experimental temperature evolution. The optimal HTCs values found through inverse analysis are shown in Figure 3.

The optimal values of the HTCs are reported in Table 5, together with the other thermal parameters used in the model. Figure 4 presents the comparison of the experimental and numerical temperature evolutions during the cryogenic turning test using the original tool holder: a good agreement is shown with a maximum error of 9°C during the turning operation.

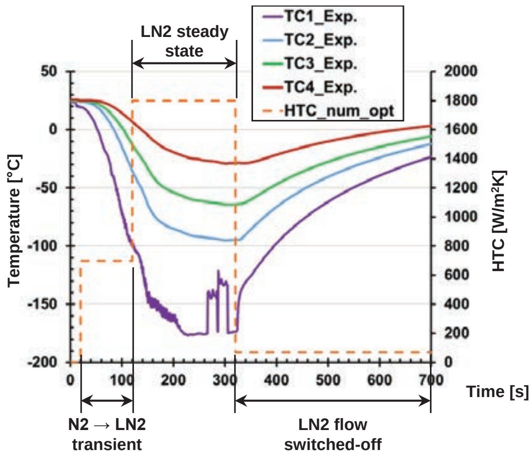

Figure 3. Temperature evolutions (continuous lines) recorded by the thermocouples in the cartridge heater-free test together with the optimal HTC values (dashed lines) found by inverse numerical analysis corresponding to the three LN2 flow regimes.

The coupled thermo-mechanical simulation allows also predicting the thermal shrinking of the tool assembly, as shown in Figure 5, in which the tool holder temperature distribution and horizontal displacement are reported.

Table 5. Thermal parameters implemented in the numerical model.

Parameter	Value
HTC feeding channel [W/m^{2}K] N2 → LN2 trans	700
HTC feeding channel [W/m^{2}K] LN2 steady state	1800
HTC feeding channel [W/m^{2}K] LN2 not moving	70
HTC cutting tool [W/m^{2}K]	20000
HTC with air [W/m^{2}K]	10
Room temperature [°C]	25
LN2 temperature [°C]	-196

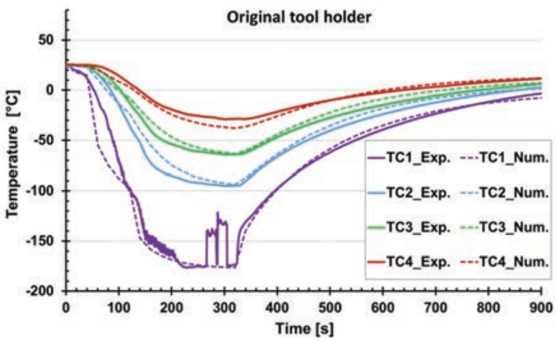

Figure 4. Numerical and experimental temperature evolutions for the cryogenic turning test with the original tool holder.

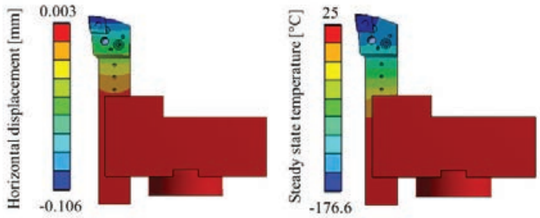

Figure 5. Numerical prediction of the horizontal displacement and temperature distribution during the turning operation for the cryogenic turning test with the original tool holder.

5. Validation of the numerical model

The calibrated numerical model was then applied to the other two experimental cases, namely the ones with the cartridge heater working at 75 W and 150 W, respectively.

Except for the additional heat flow condition, namely the heat flow provided by the cartridge heater at the contact surface in the cartridge housing, the other thermal parameters were left unchanged, as from the previous optimization. The resulting temperature evolution comparison is shown in Figure 6. Excluding the cooling ramp slope, which has no significant effect on the temperature distribution during the turning operation, the values are in good agreement with a maximum temperature error of 11°C for the farthest thermocouple in the 150 W heating case, see also Table 6.

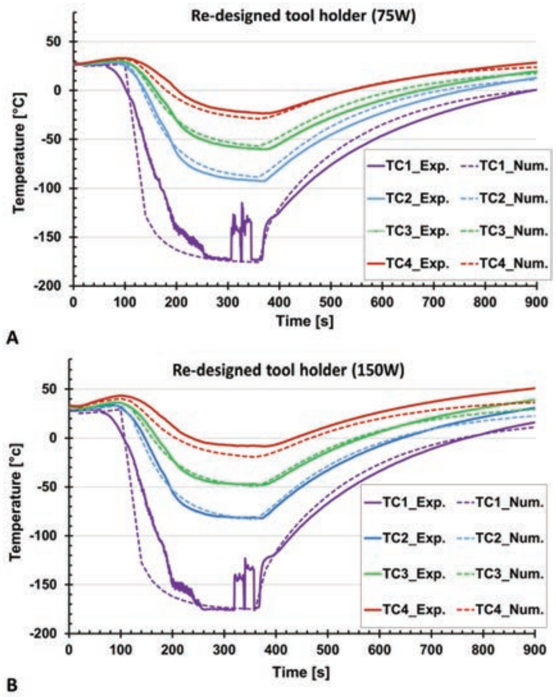

Figure 6. Numerical and experimental temperature evolutions for the cryogenic turning test with: a) the re-designed tool holder with cartridge heater at 75 W, and b) the re-designed tool holder with cartridge heater at 150 W.

Table 6. Experimental and numerical temperature values (measurement uncertainty equal to 0.1°C)

	TC1 [°C]	TC2 [°C]	TC3 [°C]	TC4 [°C]
Original tool holder_exp.	-176.7	-95.2	-64.4	-29.2
Original tool holder_num.	-176.5	-93.6	-63.6	-38.1
Re-designed tool holder (75W)_exp.	-173.6	-92.7	-60.4	-23.6
Re-designed tool holder (75W)_num.	-175.8	-88.6	-56.7	-29.0
Re-designed tool holder (150W)_exp.	-176.1	-82.1	-48.1	-8.5
Re-designed tool holder (150W)_num.	-174.8	-83.0	-49.3	-19.4

The validation was then further carried on assessing the geometrical distortion predicted by the numerical model and comparing it with the experimental outcomes. In order to do this, the maximum displacement of the tool tip during the turning operation resulting from the simulations was compared with the final part dimensions derived from experiments and already listed in Table 3.

Taking the wet cutting condition as baseline, the difference in the machined samples diameters resulting from the CMM measurements can be regarded as a reliable estimation of the total tooling shrinkage. To compare the experimental and numerical data, Eq. (1) was used on the basis that a tool tip certain displacement caused a double amount of diameter variation on the turned sample:

$$\Delta\phi_{num} = 2\Delta x_{num} \qquad (1)$$

where
$\Delta\phi_{num}$ is the sample numerical diameter change
Δx_{num} is the numerical horizontal displacement of the tool tip

The comparison between the experimental and numerical diameter deviations are presented in Figure 7, showing a maximum error of 6% when using the 75 W cartridge heater.

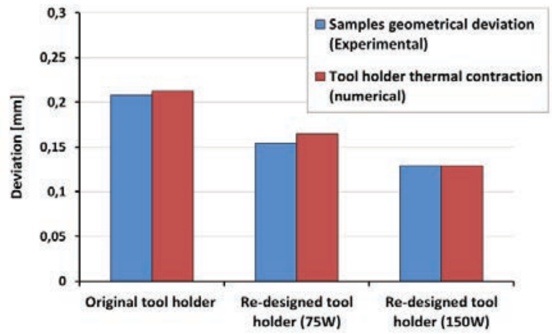

Figure 7. Comparison between the tool holder contraction determined through numerical simulation and the real dimensional deviations of the machined samples using the wet condition as baseline.

6. Conclusions

The paper presented a feasibility study aimed at reducing the part geometrical deviations caused by the use of LN2 cooling during semi-finishing turning.

The adopted strategy consisted in the tool holder re-design by embedding in the tool assembly a cartridge heater to provide a heat flow compensating the cooling action of the LN2. This device has also the beneficial effect of protecting the tool holder and the lathe turret structure from possible overcooling due to heavy-duty LN2 turning working cycles.

Based on the main findings, the following conclusions can be drawn:

- The sample that was cryogenic machined using the original tool holder presented a dimensional deviation of +0.208 mm with respect to the wet condition sample used as baseline; this deviation cannot be consider acceptable in industrial applications.
- The use of cartridge heaters with electrical power of 150 W guaranteed a reduction of about 38% the geometrical deviations compared to the cryogenic turning test with the original tool holder; a further increase of the heating power should allow having a further compensation of the geometrical deviation.
- A thermo-mechanical model of the tool holder was developed in order to effectively predict the sample geometrical distortion as a consequence of the LN2 use.
- The numerical predictions were in good agreement with the experimental observations: the temperature percentage differences did not exceed 6% while the geometrical deviation showed a maximum error of around 7%.
- The proposed thermal-mechanical model can give reliable predictions of the tool holder behavior and can be useful both for further improvements of the experimental apparatus in terms of cartridge heaters power and position and, more generally, for cryogenic machining process design.

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