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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.

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

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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.

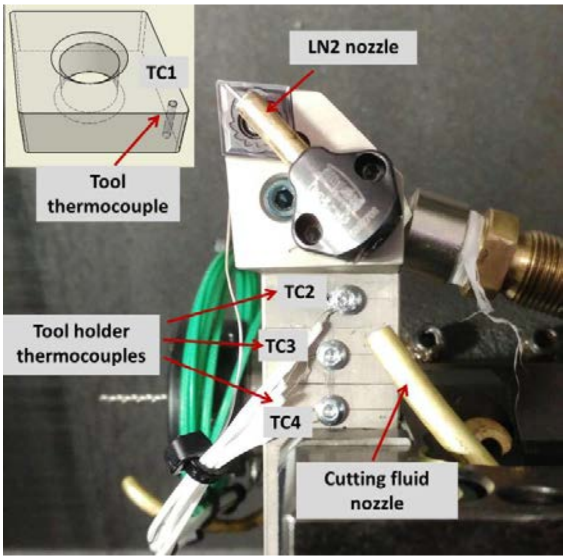

Figure 1. Tool holder setup.

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