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A machining strategy to fulfil geometrical quality requirements in cryogenic turning of acetabular cups made of Additive Manufactured Ti6Al4V

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Abstract

Additive Manufacturing (AM) techniques are more and more employed in the biomedical industry to produce surgical implants made of Ti6Al4V alloy. After the AM process, some finishing machining operations are still required to obtain the final product geometry. In recent years, cryogenic cooling has been adopted to improve the Ti6Al4V poor machinability, but mainly in rough machining operations. The adoption of cryogenic cooling can cut down the cleaning and sterilizing costs of biomedical components due to the drastic reduction of residual pollutants on the parts. This paper investigates the feasibility of cryogenic cooling using LN_2 when finishing turning AM acetabular cups made of Electron Beam Melted (EBM) Ti6Al4V, focusing on geometrical accuracy. A preliminary study conducted on a test specimen, showed that the most critical thermal induced dimensional errors are caused by the progressive tool holder contraction and that they can be limited by acting on the cutting length. On the basis of these findings a temperature-dependent correction of the tool trajectory can be implemented to achieve the required dimensional accuracy of the acetabular cup when machined under cryogenic cooling.

Ti6Al4V, Additive Manufacturing, Acetabular Cups, Cryogenic Machining

1. Introduction

Cryogenic cooling is under the spotlight as one of the most efficient cooling strategies to enhance the machinability of Difficult-To-Cut (DTC) materials, such as nickel, titanium and cobalt-based alloys [1]. Reduction of tool wear and improvement of machined surface integrity are the proved beneficial effects of this cooling strategy in comparison with the standard methods [2]. Although many interesting works have being developed to width spread this cooling strategy to an industrial scale, most of them are focused on rough machining conditions to respond at the growing demand of improving the productivity in manufacturing aeronautical and aerospace machined components made of nickel and titanium [3].

Furthermore, in some specific applications, such as machining of surgical implants, the adoption of the cryogenic cooling might also cut down the cleaning and sterilizing costs due to the drastic reduction of residual pollutants on the parts surfaces, especially if they are porous as is the case of parts made of Additive Manufacturing (AM) technologies. By taking into account this industrial application where the prostheses are mainly made of Ti6Al4V, cryogenic machining might find its ideal application carrying all the above mentioned beneficial effects. Nonetheless its application must be validated also in terms of dimensional accuracy of the components being machined adopting such technique. On this basis, the paper aims to investigate the feasibility of using cryogenic cooling in the finishing internal turning of acetabular cups made of Ti6Al4V realized by the AM technology called Electron Beam Melting (EBM).

In a previous work [4] it was highlighted that the main contribution to the geometrical distortions of the workpiece are induced by the thermal contraction of the tool-holder, whose thermal evolution induces a low repeatability of the machining process. In this paper, five acetabular cups were machined under cryogenic cooling using a conventional machining strategy. Variations in their geometry with respect to the nominal one were analyzed to highlight the need of a temperature-dependent correction of the machining process.

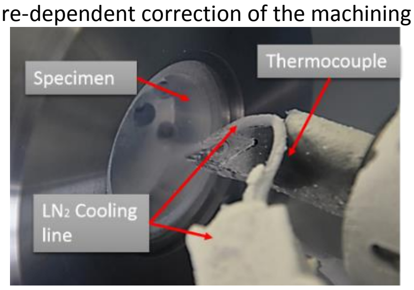

Figure 1. Experimental set-up for cryogenic machining.

2. Experimental approach

The experimental set-up is shown in detail in fig. 1. A Mori Seiki® NL 1500 CNC lathe was used for the turning tests. The machine tool was provided with a specially designed cooling apparatus to supply the LN2 in the cutting zone, as described in detail in [5]. A Sandvik Coromant® A20M-SDXCR 11-R boring bar with a DCGT 11 T3 08-UM GC1105 coated carbide insert supplied by the same manufacturer was used as cutting tool.

Turning the internal profile of an acetabular cup can be considered a quite simple operation; nonetheless the lubrication, tool geometry, and cutting length are factors that have a combined effect on the geometrical deviations. In a previous work all these factors were separately studied using a simplified test specimen made of EBM Ti6Al4V alloy and

comparing the obtained geometry with the one from traditional machining strategies and lubrication [4].
The cutting parameters chosen for this work are: cutting speed equal to 60m/min, feed rate equal to 0.1mm/rev, and depth of cut equal to 0.25 mm. A new cutting edge was used to carry out each turning operation, thus minimising the tool wear effect on dimensional accuracy.
The geometry of the machined parts was measured using a Zeiss® Prismo 7 VAST coordinate measuring machine (Maximum permissible error 2.2+L/300 µm, L in mm). A single stylus with a 3 mm diameter rubidium tip was used. The measurements were carried out in a temperature-controlled room at a nominal temperature of 20°C. Moreover, the workpiece temperature stability was ensured by laying it in the measuring room for 24 hours before measuring. To investigate the relation between geometrical distortions on the acetabular cups and thermal effects in cryogenic cooling conditions, it was decided to evaluate the following geometrical elements (see fig. 2): a top plane (machined exclusively for fine alignment), a cylinder and a sphere. For these elements the following characteristics were selected (see fig. 2): the diameter of three different circles on the cylinder, the cylinder diameter, and the sphere diameter.

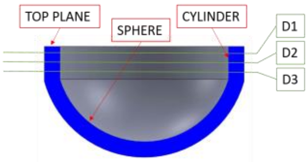

Figure 2. Nominal geometry of the acetabular cup.

The temperature of the tool holder was monitored embedding a type k thermocouple into the lubricating hole inside the tool stem at a distance of 35 mm from the tool tip as showed in fig. 1. A LabVIEW® based software procedure was used to acquire the temperature from the thermocouple signal. The following machining strategy was chosen: switch on of the cooling system, wait until the LN2 reached the liquid phase, machining (150±4 s), switch off of the cooling system, change of the tool and the workpiece and start again the machining (130±13 s). This strategy was repeated five times to machine the five acetabular cups.

3. Results

The nominal diameters were fixed in the CN part program being equal to 43.07 mm and to 44.36 mm for the cylinder and the sphere, respectively. Fig. 3 shows the temperature evolution acquired inside the tool holder when turning consecutively the five acetabular cups.

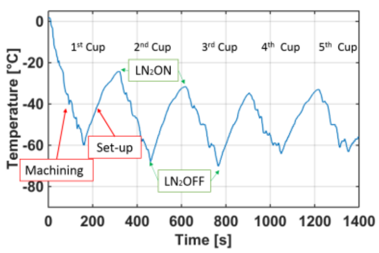

Figure 3. Temperature evolution inside the tool-holder.

A saw tooth shape trend is observable, where the decreasing portions correspond to the machining phase, while the ascending portions correspond to the set up time, hence the tool holder heated up because no LN2 was supplied to the cutting zone. Just for the first turned acetabular cup, a temperature above zero was measured at the beginning of the cutting operation and then a steep lowering trend was recorded up to a minimum temperature of – 60 °C. Due to this first drop of the temperature, the tool holder suffered a significant contraction. Proceeding with the cutting process, a repeatable saw tooth trend of the temperature was found. By considering that the cutting tool zero set-up was made at room temperature, geometrical deviations might have occurred due to the contraction of the tool older. A decreasing trend is noticeable in fig. 4 for the measured diameters during the sequential turning process.

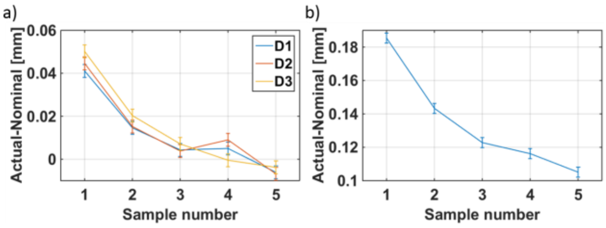

Figure 4. Geometrical deviations with respect to the nominal value after turning: a) cylinder diameter; b) sphere diameter.

This trend is due to the aforementioned contraction of the tool holder due to the cryogenic cooling condition. Moreover, a discrepancy of up to 0.05 mm is reached between the first and the fifth machined cup for the cylinder diameter, and up to 0.0 8mm for the sphere diameter. Nevertheless, the nominal diameter equal to 43.07 mm was closely achieved by the third machined cup. For the sphere diameter a decreasing trend starting from the first turned cup towards the last one is present: for this case diameters are generally greater than the nominal fixed value equal to 44.46 mm as can be observed in fig. 4. For the cylinder diameters a geometrical stability is reached after the second sample, so for this geometry it's necessary to develop and apply a temperature- and time-dependent correction to reduce the deviations for the first and second parts. In the case of the sphere the combination of two working axis causes an unstable situation: there's no clear stability situation after five samples. Therefore, further investigations are planned to characterise the machining of the spherical surface.

4. Conclusions

This work shows that a temperature-dependant correction has to be developed and applied in the machining strategy to improve dimensional accuracy in machining a typical biomedical component under cryogenic cooling.
When machining a batch of five acetabular cups, the measured sphere diameters were decreasing starting from the first turned cup towards the last one and generally greater than the nominal values. After two machined cups, deviations from the nominal geometry were smaller than 0.01 mm for the cylindrical feature and a satisfactory repeatability was reached. On the sphere a satisfactory repeatability was not reached however the deviation from the nominal geometry was reduced from 0.183 mm of the first sample to 0.105 mm of the fifth sample.

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