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Influence of the machining parameters and cooling strategies on the wear behavior of wrought and additive manufactured Ti6Al4V for biomedical applications

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ABSTRACT

The paper presents the effect of the machining parameters and cooling strategies on the wear behavior of the wrought and Additive Manufactured Ti6Al4V used for biomedical applications. Wear tests were performed using a cylinder-on-plate configuration in a wet and temperature-controlled environment in order to investigate the reciprocating sliding wear behavior under human body conditions. The obtained results showed that the adoption of the cryogenic cooling during machining significantly affected the Ti6Al4V surface properties improving its wear performances, in terms of lower friction coefficient and less release of metal debris due to abrasive wear compared to dry cutting conditions, regardless the alloy as-delivered condition.

1. Introduction

Titanium alloys are nowadays the most attractive metal alloys for biomedical applications thanks to their chemical (i.e. corrosion resistance, biocompatibility) and mechanical properties (i.e. stiffness, density) [1–3]. However, they usually present a low wear resistance to the combined action of body fluids and micromotions [4,5], which usually accelerates the release of metal debris and reduces the implants lifetime due to adverse tissue reactions.

The wrought Ti6Al4V is widely used for manufacturing biomedical implants but in recent years Additive Manufacturing (AM) techniques have gained significant interest as they can produce in a single step complex-geometry parts with tailored porosities that help reducing the stiffness mismatch with the human bones [6,7], obtaining the prosthesis fixation through complete bone ingrowth [2], as well as help improving the cells adhesion, viability, differentiation and growth [8]. However, regardless the AM technique, finishing or semi-finishing machining operations may be still required on functional surfaces. Several studies indicate that the machining operations carried out on both the wrought and AM Ti6Al4V not only change the part surface topography, but also induce residual stresses and alteration of microstructure, grain size and hardness as a function of the machining parameters and cooling strategies. In [9] the influence of the cutting tool geometry, coating type and cutting condition on the wrought Ti6Al4V was studied, finding that the machined surface characteristics in terms of micro-hardness and microstructure were strongly affected by the cutting conditions. The relevance of the cooling strategy in machining AM Ti6Al4V was recently pointed out in [10], where it was proved that the application of liquid nitrogen led to an improvement of the machined surface integrity by reducing the microstructural alterations. In [11] the effects of the cutting conditions on the surface integrity in machining wrought Ti6Al4V were evaluated, showing that the cryogenic cooling led to a lower degree of dynamic recrystallization and, therefore, higher surface micro-hardness.

However, very few studies can be found in literature that are devoted to explore the effect the machining conditions have on the product performances, especially in case of biomedical applications.

Therefore, the present work is aimed at investigating the influence of the machining parameters and cooling strategies on the sliding wear behavior of a Ti6Al4V alloy of biomedical interest delivered in two conditions, namely wrought and additive manufactured by Electron Beam Melting (EBM). The study is divided into two parts, the first dedicated to analyze the influence of the cutting parameters on the machined surface integrity, and the second to the influence of the machined surface integrity on the wear behavior under conditions replicating the ones characteristic of the human body.

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EBM and wrought Ti6Al4V cylinders were machined adopting different machining parameters and cooling strategies and then tested by using a reciprocating sliding wear testing set-up specifically developed to carry out in-vitro temperature-controlled wear tests. Different techniques were adopted to characterize the sliding wear behavior in order to evaluate and possibly quantify the main wear mechanisms arising as a function of the tested conditions.

2. Experimental procedure

2.1. Materials

The wear performances of the machined EBM and wrought Ti6Al4V samples were investigated under reciprocating sliding wear conditions adopting a cylinder-on-plate configuration. The wrought ASTM F1537 CoCrMo cobalt alloy was used for the flat plates and the Ti6Al4V in two as-delivered conditions for the cylinders. The EBM Ti6Al4V pins were obtained from cylindrical billets manufactured by using an ARCAM™ Q10 machine. Each billet was manufactured with the symmetry axis parallel to the growing direction, with a diameter of 14 mm and a height of 180 mm. The wrought Ti6Al4V cylinders were obtained from an annealed bar of 14 mm diameter and 200 mm height.

Table 1 reports the main mechanical characteristics of the Ti6Al4V in the as-delivered conditions.

Table 1
Ti6Al4V mechanical characteristics in the as-delivered conditions.

Material	*E* [GPa]	UTS [MPa]	*Y* [MPa]	Elongation (%)	HRC	$HV_{0.05}$
EBM Ti6Al4V	120	1020	950	14	33	335
Wrought Ti6Al4V	118	872	790	16	31	330

2.2. Machining tests

The EBM and wrought Ti6Al4V cylinders were semi-finished turned on a Mori Seiki™ CNC lathe under dry cutting and cryogenic cooling conditions. For the latter, the lathe was equipped with a special designed line, which uses as cryogenic fluid Liquid Nitrogen (LN2) supplied at a pressure of 6 (±0.5) bars through two copper nozzles with an internal diameter of 0.9 mm directed towards the flank and rake faces of the tool [12].

The adopted cutting tool was a semi-finishing coated tungsten carbide insert DNMG 150604 SM H13A with a radius of 0.4 mm, mounted on a PDJNR 2020K15 tool holder with an approach angle of 93°, both supplied by Sandvik Coromant™. The rake and clearance angles were equal to 7° and 3°, respectively. Both the insert grade and micro-geometry were chosen on the basis of the tool manufacturer's guidelines for machining titanium alloys. In order to avoid the influence of the tool wear on the surface topography of the machined cylinders, a fresh cutting edge was adopted for each turning test. Two values of the cutting speed (vc) and feed rate (*f*) were chosen, namely 50 and 80 m/min, and 0.1 and 0.2 mm/rev, respectively, which are values typically used for machining biomedical implants; the depth of cut (*d*) was maintained constant and equal to 0.25 mm in order to achieve a semi-finishing cutting condition (Table 2). Three cylinders were realised for each of the tested conditions to assure the repeatability of the experimental results. The cylinders were turned clamping the bars only at the spindle: as a consequence, the unsupported machined length was limited to a maximum value of 30 mm to reduce machining vibrations. After semi-finishing turning, the bars were cut-off to obtain 5 mm long cylinders.

Table 2
Experimental plan for the machining tests.

f [mm/rev]	vc [m/min]	*d* [mm]	Cutting condition
0.1	50	0.25	Dry
0.1	80	0.25	Dry
0.2	50	0.25	Dry
0.2	80	0.25	Dry
0.1	50	0.25	Cryogenic
0.1	80	0.25	Cryogenic
0.2	50	0.25	Cryogenic
0.2	80	0.25	Cryogenic

2.3. Characterization after machining

The surface roughness of the Ti6Al4V cylinders after machining was measured through a Sensofar Plu-Neox™ optical 3D profiler with a resolution of less than 20 nm on the optical *Z*-axis. The average roughness Ra and the mean roughness depth Rz of the turned cylinders were evaluated along the perpendicular direction with respect to the turning feed marks.

Vickers micro-hardness measurements were performed using a Leitz Durimet™ micro-hardness tester with a load of 50 (±0.5) gr for 30 s; five values were recorded for each cylinder and then the average value calculated.

The residual stresses on the cylindrical machined surfaces were measured by means of the X-Ray Diffraction (XRD) technique using the $\sin^2\psi$ method [13]. The XRD analysis was carried out on an Enixè™ TNX diffractometer, using CuKα radiation at 85 μA and employing 9 tilt angles (ψ). The residual stresses along the axial and circumferential directions with respect to the cylinder axis were measured on the surface and at a depth of 25 μm below the surface, by removing the material layers through an electro-polishing process to avoid modifications of the machining-induced stresses.

2.4. Reciprocating sliding wear tests

The reciprocating sliding wear tests were carried out on a Bruker-UMT-3™ tribometer using a cylinder-on-plate configuration. With the purpose of investigating the wear behavior of cylindrical shapes obtained by turning, the Ti6Al4V cylinders were made to slide against the CoCrMo plates parallel to their axis, in a linearly reciprocating path. Ti6Al4V and CoCrMo alloys were used for the wear tests as they are frequently used as neck-head materials pair in hip joint replacements because of their excellent biocompatibility. The same materials pair as well as the same type of configuration were studied in [14], in which a wear fatigue analysis on a Ti6Al4V/CoCrMo arrangement, was carried out both experimentally and numerically.

The wear tests were performed in a temperature-controlled environment (testing temperature of 37(±2 °C) monitored through a thermometer immersed in the water basin) using a saline solution (0.9% NaCl in distilled water). A nominal normal load of 7 N was applied, imposing a displacement amplitude of 500 μm for 10^5 cycles at a frequency of 10 Hz, in order to have an average normal pressure of 90 MPa. The wear test parameters are summarized in Table 3.

Fig. 1B shows schematically the testing set-up. The Ti6Al4V cylinder, with a diameter of 10 (±0.02) mm and a length of 5 (±0.02) mm, is clamped to the cylinder holder, which is mounted to a motion plate that allows vertical and horizontal translations and the measurement of the tangential and normal forces during