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Coupling machining and heat treatment to enhance the wear behaviour of an Additive Manufactured Ti6Al4V titanium alloy

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ABSTRACT

The effect of coupling machining with a subsequent heat treatment on the wear behaviour of the Ti6Al4V alloy produced by Electron Beam Melting (EBM) was investigated. Reciprocating sliding wear tests in saline solution and temperature-controlled environment were performed. Results showed that the heat-treated cylinders presented a lower coefficient of friction, less wear rate and higher degree of adhesive wear compared to the not heat-treated ones. It was then demonstrated that coupling machining and heat treatment had a synergistic effect that can be used as an efficient strategy in order to improve the EBM Ti6Al4V wear resistance.

1. Introduction

Titanium alloys are engineering materials interesting for several applications thanks to their high strength-to-weight ratio combined with an excellent corrosion resistance [1,2]. Despite these excellent properties, the main concern for further developments of titanium alloys for biomedical applications is the low wear resistance, whereas, during their service life inside the human body, they are subjected to the significant action of sliding between the articulating surfaces [3,4].

Many research efforts have been devoted to improve the wear resistance of the titanium alloys, as their susceptibility to wear is the main disadvantage that shortens the durability of the implant. The scientific literature reports several records proving that the tribological properties of the titanium alloys are highly dependent on their microstructural characteristics: different treatments resulting in various microstructural features can, indeed, produce tailored mechanical and tribological properties.

Guo et al. [5] studied the effect of alloying the surface of the Ti-5Zr-3Sn-5Mo-15Nb alloy with molybdenum by using a double plasma alloying technique. The obtained microstructure was a dense layer with molybdenum, which extended for several microns below the surface, and was formed replacing the β phase characteristics of the untreated alloy. Such microstructural alteration led to improved tribological properties in terms of lower coefficient of friction and lower wear rate due to the fact that molybdenum layers were harder than the β phase.

Luo et al. [6] applied a thermal oxidation treatment to improve the wear resistance of a titanium alloy devoted to biomedical applications. It was found that a rutile film was formed on the surface of the titanium alloy and a nanohardness improvement was achieved. Tests in bovine serum environment revealed that the treated alloy presented a lower friction coefficient and higher wear resistance than the untreated alloy.

Kao et al. [7] applied a double step technique, composed by a nitriding stage followed by the deposition of a Ti-C:H coating, in order to enhance the tribological properties of the Ti6Al4V alloy subjected to a reciprocating sliding wear regime. The nitriding treatment provoked the Ti6Al4V hardness increase, and, as a consequence, a significant reduction of the friction coefficient and wear rate.

Abdulwahab [8] studied the wear response of the Ti6Al4V alloy subjected to an isothermal treatment, consisting in a solution heat treatment at 960 °C followed by an aging at 480 °C for different soaking times. The obtained results showed that the heat treated alloy subjected to the longest soaking time presented the best resistance to abrasive wear failure.

Celik et al. [9] applied a multiple-step surface treatment as a strategy to enhance the tribological properties of pure titanium used for dental applications. The titanium surfaces were first coated by plasma nitriding and then CrN-coated thanks to a duplex surface treatment. It was found that the coated surface exhibited better wear properties than the uncoated ones thanks to the increased hardness obtained with the surface treatment.

The processing route to which the material is subjected is another issue that substantially influences the material microstructure and, as a consequence, affects the wear resistance. In the framework of Additive Manufacturing (AM), the Electron Beam Melting (EBM) process appears

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as an innovative technology to quickly produce Ti6Al4V human implants, which can be customized to the specific patient. The EBM process is classified as a near-net-shape manufacturing process, although semi-finishing and/or finishing machining operations may be needed on functional surfaces [10,11], may have a significant influence on the surface integrity of a workpiece and, as a consequence, on the wear resistance of the Ti6Al4V alloy.

Bruschi et al. [12] studied the influence of the machining parameters and cooling strategies on the AM Ti6Al4V, founding that cryogenic machining affected the machined surface properties in terms of hardness and residual stresses and, therefore, enhanced the wear properties of the titanium alloy. Bertolini et al. [13] investigated the fretting corrosion response of a dry and a cryogenic machined EBM Ti6Al4V. Besides an improved corrosion resistance, they found that the cryogenic machined samples were characterized by an improved wear resistance in terms of coefficient of friction and lower amount of wear rate than the dry ones.

However, in none of the mentioned reports, the effect of a possible heat treatment after semi-finishing machining as a method to influence the wear behavior was evaluated.

To this regard, in this paper, reciprocating sliding wear experiments were conducted on Ti6Al4V samples obtained by EBM, then semi-finishing machined, and finally heat-treated in order to prove if a post-machining heat treatment in the (α+β) domain might have a positive effect on the EBM alloy wear behavior. The EBM Ti6Al4V samples were machined at different cutting speed and feed rate. Then, they were subjected to an (α+β) annealing treatment followed by a 20 °C/s cooling stage. Tribological tests in a saline solution and temperature-controlled environment adopting a cylinder-on-plate configuration were performed using the CoCrMo cobalt alloy for the plates and replicating the human body conditions as closely as possible. The obtained results showed that the applied heat treatment was an efficient method to improve the wear resistance of the EBM Ti6Al4V alloy.

2. Experimental

2.1. Material

In the present work, the EBM Ti6Al4V alloy was considered for the tribological tests. The Ti6Al4V samples were obtained from cylindrical billets manufactured through the EBM process 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 EBM Ti6Al4V chemical composition and main mechanical properties are reported in Table 1.

Table 1
Chemical composition and mechanical properties of the EBM Ti6Al4V in the as-received condition.

Ti6Al4V chemical composition (wt%)							
Al	V	C	Fe	O	N	H	Ti
6	4	0.03	0.1	0.15	0.01	0.003	Bal
Mechanical properties							
E [GPa]		UTS [MPa]		Y [MPa]		HV 0.05	
120		1020		950		335	

The microstructure of the EBM Ti6Al4V in the as-received condition is given in Fig. 1: it consists in a α/β dual phase in which the α-phase is composed of fine lamellae, organized in a basket-weave morphology [14].

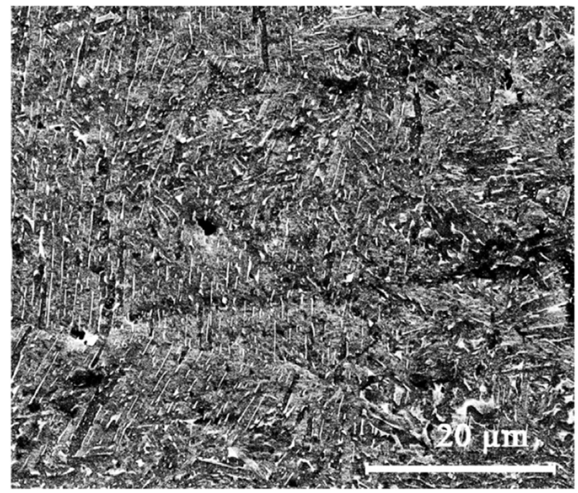

Fig. 1. Microstructure of the EBM Ti6Al4V alloy in the as-received condition.

These features are the result of the EBM process, namely a rapid solidification and a subsequent annealing due to the temperature of the working zone [15].

2.2. Sample preparation and characterization

The machining experimental campaign was conducted on a Mori Seiki™ CNC lathe. The utilized cutting tool insert was a semi-finishing coated tungsten carbide insert DNMG150604SMH13A with a radius of 0.4 mm, mounted on a PDJNR2020K15 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. Two values of the cutting speed (Vc) and feed rate (f) were chosen, namely 80 and 110 m/min, and 0.1 and 0.2 mm/rev, respectively. The depth of cut (d) was maintained constant and equal to 0.25 mm in order to achieve a semi-finishing cutting condition. The machining operations were carried out in a regime of full lubrication. Six samples were machined for each condition and three of them was subsequently subjected to the heat treatment.

The heat treatment was conducted for 2 h in an inert gas atmosphere to prevent the alloy oxidation.

The machined Ti6Al4V samples were placed in a furnace that was evacuated and then backfilled with argon before being heated at the treatment temperature of 980 °C, in order to be still in the (α+β) domain. The samples were then cooled to room temperature at a cooling rate of 20 °C/s.

The summary of the experimental campaign for the sample preparation is reported in Table 2.

Optical microscopy was used for the microstructural analysis, using the Kroll's reagent to etch the polished samples (10 vol% HF and 5 vol% HNO_3 in water). In order to quantify the extent of the globular layer obtained thanks to the heat treatment the following procedure was adopted: the layer thickness was measured from the optical microscopy images recorded at 500× of magnification every 20 µm; the measures were repeated in two different zones of the sample and then the average value was calculated. The same experimental procedure was adopted for the measurement of the extent of the obtained transformed layer below the globular one recording optical microscopy images at 200× of

Table 2
Experimental plan for the sample preparation.

Vc (m/min)	f (mm/rev)	Heat treatment
80	0.1	/
80	0.1	✓
110	0.1	/
110	0.1	✓
80	0.2	/
80	0.2	✓
110	0.2	/
110	0.2	✓