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The influence of material properties on the tool crater wear when machining Ti6Al4V produced by Additive Manufacturing technologies

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Abstract

In the biomedical field the Additive Manufacturing (AM) technologies are increasingly being adopted for the production of near-net-shape products made in titanium alloys, however finishing machining operations can be necessary to obtain the required geometrical tolerances and surface characteristics. This paper aims at investigating the effects of the workpiece properties on the tool crater wear behavior in semi-finishing turning of Ti6Al4V produced by Electron Beam Melting (EBM) and Direct Metal Laser Sintering (DMLS) AM technologies in comparison with the one of the wrought commercial alloy. Liquid nitrogen was used as a coolant to reduce the crater wear and its performances compared with dry turning. A correlation is proved between the mechanical and thermal properties of the investigated alloys and the crater wear occurrence.

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Keywords: Machinability, Cryogenic machining, Ti6Al4V alloy, Microstructure, Wear

1. Introduction

Titanium alloys have received considerable interest thanks to their wide range of application in the biomedical, chemical and aerospace fields. The excellent corrosion resistance, high strength to weight ratio and the well-documented biocompatibility have promoted their use for the manufacturing of surgical implants, such as knee joints, bone plates and acetabular cups [1]. For the production of near-net-shape components of complex shape in small batches, Additive Manufacturing (AM) technologies, such as Direct Metal Laser Sintering (DMLS) and Electron Beam Melting (EBM), can be effectively used. The main difference between products realized by different AM technologies lies in the obtainable microstructure: a small variation in the percentage of the phases or in the grain size may determine a significant variation in the alloy mechanical and thermal properties. Despite one of the main advantages of the AM technologies is the reduction of the manufacturing steps, in many cases finishing machining operations can be necessary to obtain the required specific surface properties and geometrical tolerances. The low machinability of the titanium alloys due to their high thermal reactivity, low thermal conductivity and high hardness is usually overcome by using conventional cutting fluids composed by pollutant mineral oil solutions. Whereas, in the biomedical field, the machined product should be as clean as possible in order to reduce the expensive and time-consuming cleaning steps. The solution currently adopted is based on the compromise to work without coolants, thus minimizing the surface pollution but accepting a large reduction of the tool life. The use of alternative coolants, such as the Liquid Nitrogen (LN_2), is proposed in literature [2,3], being proved to reduce the temperature in the cutting zone and thus determining a reduction of the adhesive and diffusive wear phenomena. The latter are responsible of the crater formation on the tool rake face while the abrasive wear influence depends on the mechanical properties of the machined materials. The aim of the present study is to

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investigate the influence of different microstructures of the Ti6Al4V titanium alloy produced by different AM technologies on the crater tool wear resulting by the use of different lubricant strategies in semi-finishing turning. The paper proves that there is a correlation between the mechanical and thermal properties of the machined alloys and the crater wear occurrence.

2. Materials

The object of investigation is the Ti6Al4V titanium alloy produced by Electron Beam Melting (EBM) and Direct Metal Laser Sintering (DMLS) additive manufacturing technologies whereas the commercial wrought Ti6Al4V was used as reference. Fig. 1 shows the different microstructures of the analysed materials. The EBM Ti6Al4V in the as-built condition presents a fine acicular microstructure constituted of α phase fine lamellae with 7% of β phase at the grain boundaries (Fig.1.a) [4]. The DMLS process instead produces a martensitic microstructure composed only by acicular α'-phase with lattice parameters very similar to the hcp pattern (Fig1.b). This metastable structure presents high mechanical properties but low ductility and, therefore, it is not suitable for the production of biomedical implants, consequently a heat treatment is necessary to transform it into a α+β lamellar structure (Fig.1c). The new α and β grains nucleate and grow along the martensitic grain boundaries maintaining the previous orientations, this phenomenon representing a clear memory effect of the martensite to the α transformation. The dimensions of the α plate, β grain size and even morphology depend on the temperature, soaking time, and cooling rate of the heat treatment [5]. Finally, the wrought Ti6Al4V was supplied in the annealed condition with a microstructure composed by equiaxed α grains with 8% of β phase (Fig.1d).

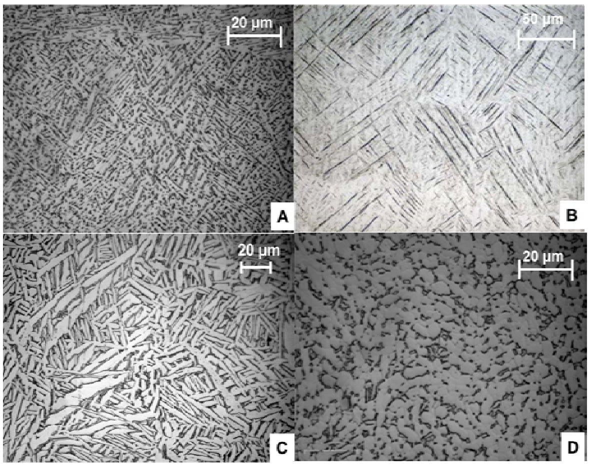

Fig. 1. Ti6Al4V microstructures: (a) EBM, (b) DMLS, (c) heat treated DMLS, (d) wrought.

The EBM material was produced by means of an Arcam™ Q10 machine in cylindrical bars with a diameter of 50 mm and length of 230 mm while for the realization of the DMLS material an EOS™ EOSINT M270 machine was used. In the latter case the samples had a diameter of 40 mm and length of 150 mm. The wrought material was supplied by Sandvik™ in bars with a diameter of 50 mm. In all the AM samples no microstructural defect as cavities or cracks were detected.

3. Turning experiments

Semi-finishing turning tests were conducted on a Mori Seiki™ NL 1500 CNC lathe by adopting inserts supplied by Sandvik™ in WC coated TiAlN (CNMG120404-SM1105). The lathe was implemented with a system for the management of the liquid nitrogen that consists in a control unit including solenoid valves and safety systems and a distribution system made of plates mounted on the lathe turret. According to the literature findings, the cutting zone was cooled using two nozzles directed onto the insert rake and flank faces. The liquid nitrogen was delivered to the distribution system at the pressure of 10±0.5 bar directly Dewar through a high vacuum insulated pipe. The cutting parameters were kept fixed: a cutting speed of 80 m/min, feed rate of 0.2 mm/rev, and depth of cut of 0.25 mm were adopted with a fixed time length of 15 minutes for each test.

4. Characterization of the investigated materials

The cratering phenomenon depends on diffusive and abrasive wear. The mechanical properties of the material to be machined, such as hardness and yield stress, influence the abrasive wear, while the thermal properties mainly influence the diffusive wear. In both cases, the resulting cutting temperature represents the most important process parameter as it influences the workpiece material properties. To roughly estimate the cutting temperature, an orthogonal cutting test on the heat treated DMLS alloy was carried out adopting a cutting speed of 80 m/min and feed rate of 0.2 mm/rev. The thermal field acquired by means of an infrared camera showed an average temperature in the cutting zone around 450°C. Therefore, in order to analyse the crater wear and correlate it to the different material microstructures, both the mechanical and thermal properties of the different microstructures were measured in a range of temperature between the room temperature and the maximum estimated one.

4.1. Mechanical properties

The mechanical properties of the investigated alloys are listed in Table 1. Their yield strength values are distributed nearly between 835 and 995 MPa while there are no substantial differences in the elastic modulus.

Table 1. Mechanical properties of Ti6Al4V alloys, *[6], ** source: datasheet Sandvik bioline Ti6Al4V ELI.

Material	E [GPa]	UTS [MPa]	Yield Stress [MPa]	Elongation [%]
EBM*	118±5	915±10	830±5	13.1±0.4
DMLS*	110±5	1095±10	990±5	8.1±0.3
Heat treated DMLS*	117±1	915±5	835±5	10.6±0.6
Wrought**	114	940	870	15.0

The DMLS alloy presents the highest values of the ultimate tensile and yield strengths, and the lowest value of the elongation: these characteristics are due to the martensitic microstructure and the presence of residual stresses caused by the structure rapid cooling during the DMLS process [7]. The high temperatures generated during the cutting process may cause a thermal softening of the material since the yield stress and hardness values decrease with the temperature increase. As in this work the hardness is considered the main mechanical property responsible for the crater formation on the tool rake, its evolution at increasing temperature for the Ti6Al4V different microstructures is shown in Fig. 2. The measurements were carried out using an Instron™ Wilson Wolpert series 2000 hardness tester following the ISO 6508 standard.

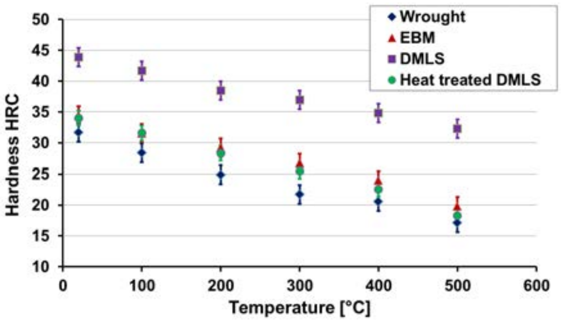

Fig. 2. Hardness of the Ti6Al4V different microstructures as a function of the temperature.

The wrought, EBM and heat treated DMLS alloys present very similar hardness values regardless the temperature, with a hardness reduction at the maximum tested temperature of about 45% compared to the room temperature value. On the contrary, the DMLS material always shows the highest hardness values with a reduction of 23% at 500°C.

4.2. Thermal properties

The most significant factors that characterize the diffusive wear are the temperature and degree of chemical affinity between the chip and the tool. The temperature effect has been described in terms of solid state diffusion mechanism across the chip-tool interface, and becomes important when the relative solubility of the two sliding materials is relevant. The value of temperature also depends on the thermal conductivity of the workpiece material, whose value may be affected by a microstructural variation. Therefore, experimental tests for the determination of the thermal conductivity were carried out on Ti6Al4V samples of different microstructures by means of the transient plane source technique (TPS) using Hot Disk equipment. Two different types of sensors were used: the first covered with Kapton and radius of 9.719 mm for the lower temperatures, the second coated with Mica and radius of 6.631 mm for the higher ones. Fig. 3 shows the evolution of the thermal conductivity for the different microstructures as a function of the temperature. The DMLS and EBM alloys show the most significant difference (about 16%) in their thermal conductivity values at 500°C, meaning that the EBM sample conducts heat better than the other Ti6Al4V alloys. The heat treated DMLS and wrought Ti6Al4V present almost the same thermal conductivity values, with a reduction of 11.7% at 500°C compared to the one of the EBM alloy.

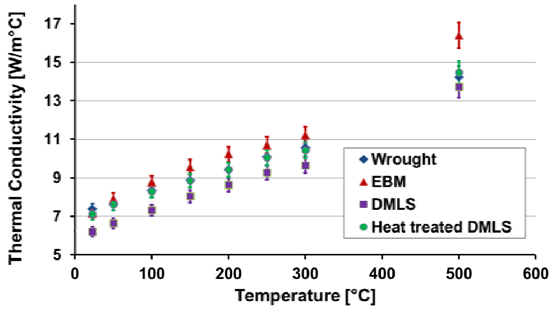

Fig. 3. Thermal conductivity of the Ti6Al4V different microstructures as a function of the temperature.

5. Crater wear analysis

The crater wear mechanism was evaluated by means of a FEI QUANTA 450^{TM} Scanning Electron Microscope (SEM) equipped with BSED and ETD detectors. A Sensofar ^{TM} Plu-Neox^{TM} optical 3D profiler was used for the 3D scanning of the rake face of the cutting tools, allowing the quantification of the crater depth in a fixed central position. As example, in Fig. 4 the SEM and profiler images of the tool rake surface after machining the heat treated DMLS titanium alloy under dry and cryogenic cutting conditions are shown.

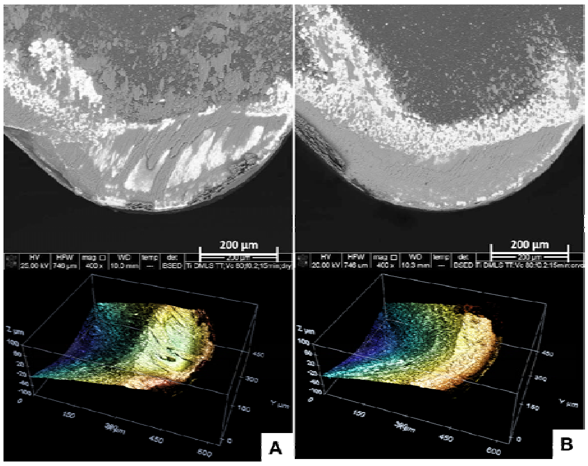

Fig. 4. SEM and profiler analyses of the tool rake face after machining a heat treated DMLS sample under a) dry, and b) cryogenic cutting conditions.

Regardless the Ti6Al4V microstructure, adhered material and welded chips are present on the tool cutting edge and rake face for both dry and cryogenic cooling conditions. In Fig. 5 the blue profile represents the unworn insert, whereas the red, green, purple and orange ones are the profiles of the worn tool rake faces after machining the EBM, the DMLS, the heat treated DMLS and the wrought alloys, respectively.

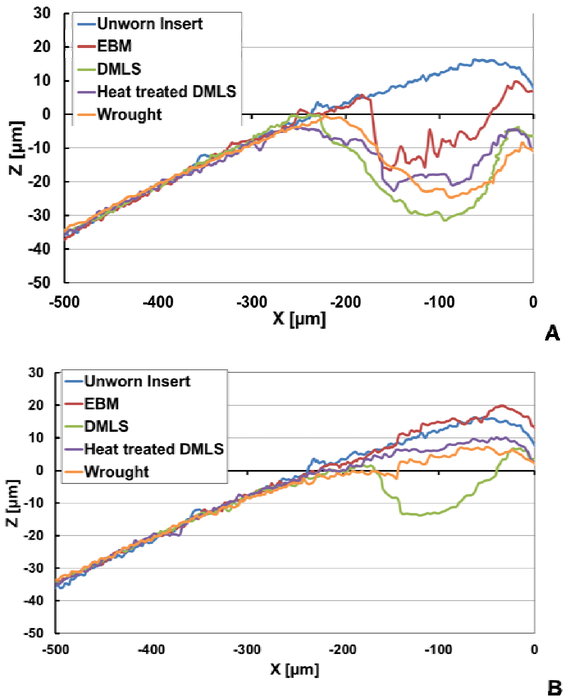

Fig.5. Tool rake face profiles under a) dry condition, and b) cryogenic cooling.

In dry conditions the crater wear is always present and the maximum depth results to be 52.3 µm for the DMLS alloy, whereas the cryogenic cooling significantly reduces it for all the analysed samples (Fig. 5b). The percentage reduction in the crater wear depth when applying the Liquid Nitrogen overtakes 58% for the DMLS material reaching the value of 80% for the heat treated DMLS and wrought cases, whereas in case of the EBM alloy the cratering phenomenon is completely eliminated (see Table 2).

Table 2. Crater wear depth as a function of the Ti6Al4V microstructures and cutting conditions.

Material	Dry Max Depth Z [µm]	Cryogenic Max Depth Z [µm]
EBM	-23.52	0
DMLS	-52.3	-21.6
Heat treated DMLS	-42.2	-6.7
Wrought	-44.1	-7.4

In this work the hardness and thermal conductivity are considered as the material properties mainly responsible of the crater wear. In dry conditions the Ti6Al4V low thermal conductivity determines a higher surface temperature and consequently more diffusive exchange of the chemical species (Co, Ti and V) between the adhered material on the tool surface and the tool rake face. This phenomenon determines an embrittlement of the tool and the subsequent creation of the crater as a result of the hardened chip sliding. In dry turning the deepest crater was found for the tool that worked the DMLS sample, and it is the direct consequence of its lowest thermal conductivity and highest hardness at high temperature (see Fig. 2 and Fig. 3). Since the other alloys present similar hardness values, the corresponding crater depth differences may be attributed to their thermal properties: in fact, the heat treated DMLS and wrought alloys exhibit a thermal conductivity significantly lower than the EBM alloy. Under cryogenic cooling, the application of LN2 reduces the temperature in the cutting zone, the adhesive and diffusive wear are inhibited, and consequently the crater wear depends only on the alloys mechanical properties. The crater was found only on the tool rake face that machined the DMLS material. The heat treated DMLS and wrought alloys present a uniform abrasion of the notch whereas in case of machining the EBM alloy only adhesive wear is found. In the alloys that present similar hardness values the differences in the tool rake faces profiles are minimal.

6. Conclusions

In order to define how the properties of the material to be machined affects the tool wear in dry and cryogenic cutting several analyses were conducted on the Ti6Al4V alloy produced by different AM and conventional technologies. In this work the hardness and the thermal conductivity are considered to be the material properties mainly responsible of the formation of the crater wear. Based on the obtained results, the following conclusions may be drawn:

- The main differences are found between the DMLS and EBM alloys. The DMLS presents the highest value of hardness and the lowest thermal conductivity at the estimated cutting temperature.
- In dry conditions the deepest crater is found when machining the DMLS alloy, this due to both its mechanical and thermal properties, whereas for the EBM, heat treated DMLS and wrought alloys the differences are exclusively caused by the thermal conductivity since their hardness is very similar.
- In cryogenic conditions the crater is present only in the DMLS material. The low temperature inhibits the diffusive wear and the material property that causes the cratering phenomenon is the hardness.

References

[1] ASTM F1472-08e1, Standard Specification for Wrought Titanium-6Alluminion-4Vanadium Alloy for Surgical Implant Application (UNSR56400), ASTM International West Conshohoken, PA, 2008.
[2] Yakup Yildiz, Muammer Nalbant. A review of cryogenic cooling in machining processes. International Journal of Machine Tools and Manufacture 48 (2008) p 947-964.
[3] Z.Y. Wang, K.P. Rajurkar. Cryogenic machining of hard-to-cut materials. Wear 239 (2)(2000) 168-175.
[4] Facchini L, Magalini E, Robotti P, Molinari A. Microstructure and mechanical properties of Ti-6Al-4V produced by electron beam melting of pre-alloyed powders. Rapid Prototyping Journal 15(3)(2009)171-178
[5] Bey Vrancken, Lore Thijs, Jean-Pierre Kruth, Jan Van Humbeeck. Heat treatments of Ti6Al4V produced by Selective Laser Melting: Microstructure and mechanical properties. Journal of Alloys and Compounds, 541 (2012) 177-185.
[6] Facchini L, Magalini E, Robotti P, Molinari, Höges S, Wissenbach K. Ductility of a Ti-6Al-4V alloy produced by selective laser melting pf prealloyed powders. Rapid Prototyping Journal 16(6)(2010)450.