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Analysis of the surface integrity in cryogenic turning of Ti6Al4V produced by Direct Melting Laser Sintering

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Abstract

The Ti6Al4V is widely utilized in the biomedical field thanks to its high biocompatibility, however, due to its low machinability, is classified as a difficult-to-cut material. With the goal of improving the surface quality of biomedical components made of Ti6Al4V produced by the DMLS additive manufacturing technology and later on machined, Liquid Nitrogen was tested as a coolant in semi-finishing turning. The integrity of the machined surfaces is evaluated in terms of surface defects and topography as well as residual stresses. The obtained results showed that the cryogenic machining assured a lower amount of surface defects and higher values of the residual compressive stressed compared to dry cutting, but a general worsening of the surface topography was detected.

Keywords: Ti6Al4V, Additive Manufacturing, Machinability, Liquid Nitrogen, Surface integrity

1. Introduction

The Ti6Al4V titanium alloy is today the most widely used material in the biomedical field thanks to its high mechanical properties, excellent corrosion resistance and well-documented biocompatibility. However, Ti6Al4V, due to its high thermal reactivity, low thermal conductivity and high hardness, is characterized by a reduced machinability, and, therefore, is considered a difficult-to-cut material [1]. Traditional methods to increase its machinability include the reduction of the cutting speed and feed rate, as well as the use of proper cutting fluids. The main advantages of the latter lie in the friction reduction (lubrication function), dissipation of heat (coolant function) and assistance in chip flow; however, the substances contained in them, such as chemical additives and oils, can contaminate the machined surfaces with consequences that can range from the failure of the operation or the occurrence of serious illnesses when the pollutants have toxic or mutagenic characteristics. To ensure the required cleaning specifications, expensive time-consuming cleaning steps are then necessary; therefore, currently dry machining represents the most widely accepted solution with an eye towards both the sustainability and economics of the manufacturing process, but, inevitably, a reduction of the machined surface quality and increase in the tool wear must be accepted. Many scientific works present in literature have shown the potential of the use of Liquid Nitrogen (LN2) [2,3] and Carbon Dioxide (CO_2) [4] as a coolants in machining process. The main advantage of the cryogenic cooling is the reduction of the tool wear [5,6], but the surface quality of the product has not yet been investigated in depth. The surface characteristics influence the performance of the components: the presence of cracks, cavities, microstructural alterations, phase transformations, and tensile residual stresses may cause the catastrophic failure of the product, making necessary a detailed investigation of

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the machined surface integrity as a function of the cutting parameters [7].

The aim of the present study is to investigate the effects of different cooling strategies on the surface integrity when semi-finishing turning a Ti6Al4V alloy produced by the Additive Manufacturing (AM) technology called Direct Metal Laser Sintering (DMLS). The DMLS Ti6Al4V surface integrity was evaluated in terms of surface roughness and topography, surface defects and residual stresses.

2. Material

The metal alloy used in this study was the Ti6Al4V titanium alloy produced by DMLS. The microstructures obtainable after rapid prototyping technologies are quite different from the conventional ones formed during hot working that are composed of α equiaxed grains (hpc) surrounded by β phase (bcc), since the high undercooling promotes the formation of an lamellar or acicular microstructures. The DMLS technology promotes the formation of a martensitic microstructure constituted by α’ phase with lattice parameters very similar to the hcp pattern (Fig.1.a). Since the martensite is not suitable for structural and mechanical components, post-building heat treatments are applied to transform it into a biphasic α+β microstructure (Fig.1.b). The new α lamellae nucleate along the martensitic grain boundaries maintaining the previous orientations; the dimensions of the α plate, β grain size and even the morphology depend on the temperature, soaking time, and cooling rate of the heat treatment [8].

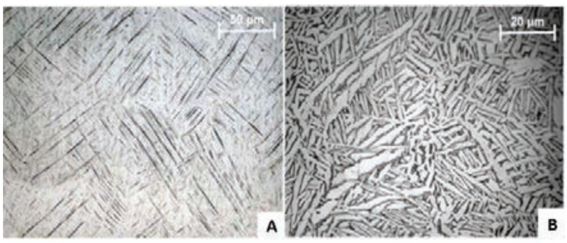

Fig. 1. Ti6Al4V microstructures: a) as-built DMLS, b) heat treated DMLS.

Table 1. Mechanical properties of the as-built and heat treated DMLS Ti6Al4V [8]

Material	E [GPa]	UTS [MPa]	Yield Stress [MPa]	Elongation [%]
As-built DMLS	110±5	1095±10	990±5	8.1±0.3
Heat treated DMLS	117±1	915±5	835±5	10.6±0.6

The mechanical properties of the two DMLS materials are shown in Table 1. The martensitic microstructure and the residual stresses caused by the rapid cooling determine higher values of the ultimate tensile and yield stress and lower value of the elongation for the as-built DMLS microstructure compared to the heat treated one. On the other hand, the heat treatment determines an increase of both the elastic modulus and elongation, leading to a reduction of brittleness.

The DMLS samples were produced using an EOS™ EOSINT M270 machine, in form of cylindrical bars with a diameter of 40 mm and length of 150 mm.

3. Experimental procedure

The semi-finishing turning tests were carried out on a Mori Seiki™ NL 1500 CNC lathe adopting inserts supplied by Sandvik™ in WC with a TiAlN coating (CNMG120404-SM1105). Dry and cryogenic turning experiments were performed with the different feed rates referenced in Table 2, while the cutting speed and depth of cut were kept fixed, respectively at 80 m/min and 0.25 mm. The turning tests were conducted at fixed time length of 15 minutes for each cutting condition on both as-built and heat treated DMLS samples. The lathe was implemented with a system for the management of the LN2, consisting in a control unit including solenoid valves and safety system and a distribution system made of plates mounted on the lathe turret designed to distribute, by means of two external copper nozzles, the cryogenic coolant onto the insert rake and flank faces. The LN2 was stored and maintained at controlled pressure and temperature in a Dewar and, through a vacuum insulated pipe, was delivered at the pressure of 10±0.5 bar to the distribution system.

The machined samples were then subjected to the analysis of the surface integrity. The surface roughness was evaluated by means of a Taylor Hobson-Subtronic 25™ portable roughness tester while the surface topography scanning was performed using a Sensofar Plu-Neox™ optical 3D profiler. The surface defects were analyzed by means of a FEI QUANTA 450™ Scanning Electron Microscope (SEM) equipped with BSED and ETD detectors. Finally, the axial residual stresses were measured by the X-ray diffraction (XRD) technique using the $\sin^2\psi$ method based on the Bragg’s law [9]. The XRD analysis was carried out on an Enixè™ TNX diffractometer following the ASTM E2860-12 standard. In order to evaluate the stress state, surface layers were repeatedly removed from the machined samples by electro-polishing to avoid the modification of the machining-induced stresses.

Table 2. Experimental plan for the machining tests.

Cutting speed [m/min]	Feed rate [mm/rev]	Depth of cut [mm]	Cooling strategy
80	0.1	0.25	Dry
80	0.1	0.25	Cryogenic
80	0.2	0.25	Dry
80	0.2	0.25	Cryogenic

4. Surface integrity analysis

In the biomedical field the surface characteristics influence the mechanical performances, life of the product, and cellular bio-adhesion process. In order to define the best cutting condition and the effects of using of the LN2 as coolant, the surface integrity of the machined samples was evaluated in terms of surface roughness and topography, surface defects and residual stresses. The residual stresses analysis was carried out only for those cutting conditions that guaranteed an acceptable required surface quality.

4.1 Surface topography and roughness

The average Ra data for all the cutting conditions are presented in Table 3. The surface roughness values are influenced by the feed rate, being the minimum values obtained at the feed rate of 0.1 mm/rev. In general, higher surface roughness values were recorded in the cryogenically cooled samples with respect to the dry machined ones: as an example, the heat treated DMLS presents a percentage increase that overtakes 20% at 0.2 mm/rev reaching 60% in the case of 0.1 mm/rev.

Table 3. Surface roughness Ra as a function of the cutting parameters and cooling strategies.

Material	**Feed rate [mm/rev]**	**Ra [µm]**	
		Dry	**Cryogenic**
As-built DMLS	0.1	0.62±0.022	0.58±0.023
	0.2	1.49±0.037	1.62±0.048
Heat treated DMLS	0.1	0.45±0.019	0.72±0.015
	0.2	1.37±0.041	1.66±0.039

Further examinations on the surface quality, conducted through 2D and 3D analysis of the surfaces topographies (Fig. 2), highlighted how the cryogenic cooling led to the formation of a more discontinuous surface and double feed marks, which may be a consequence of a drop of the material ductility due to the drastic lowering of the temperature during the turning operations.

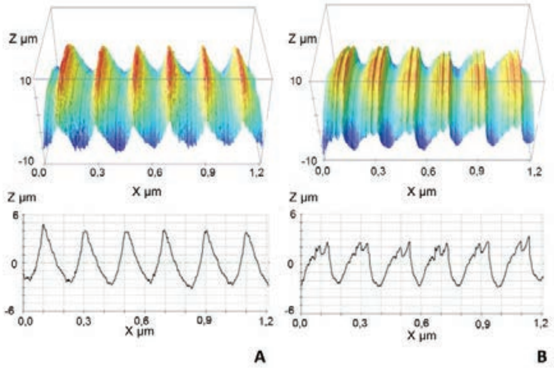

Figure 2. 3D and 2D topographies of the heat treated DMLS samples machined under a) dry, and b) cryogenic cutting conditions.

4.2 Surface Defects

The surface defects are the direct consequence of the cutting process, they cannot be eliminated but reduced by choosing properly the cutting parameters as a function of the materials properties and lubrication strategies. In this work, the typologies of surface defects and their dimensions were found to be dependent upon both the cooling strategies and the cutting parameters. In dry turning the temperatures generated at the interface between the tool and the workpiece, due to the low thermal conductivity and high mechanical properties of the Ti6Al4V alloy, can reach high values becoming the predominant cause of the onset of surface defects [10]. In all the analyzed samples adhered material (either welded chips or residuals of the build-up-edge) and side flow were found on the machined surfaces (Fig. 3). The presence of side flow is observed along the feed marks and it can be attributed to the increase of the material ductility as a consequence of the temperature increase in the cutting zone. Regardless the DMLS Ti6Al4V microstructure, a considerable increase in the density of the surface defects was observed at increasing the feed rate.

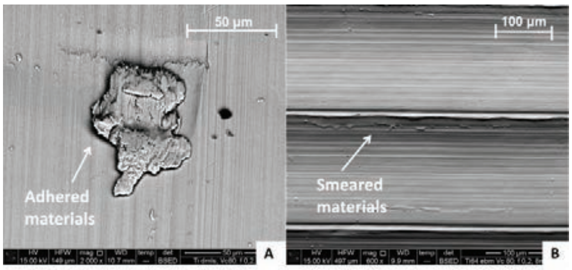

Fig. 3 Examples of surface defects in dry cutting: a) adhered material, b) smeared material.

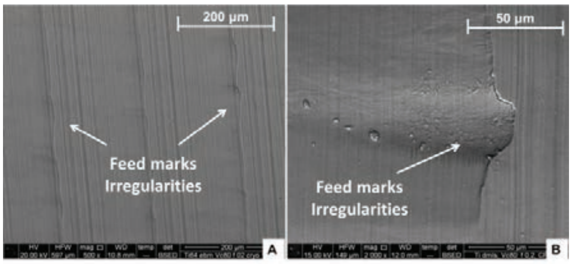

Fig. 4. Examples of surface defects in cryogenic cooling at different magnification: a) 500X, b) 100X.

When cryogenic cooling is applied, the low temperature inhibits the formation of the typical defects of the dry condition. The surfaces are almost completely free from the presence of adhered or smeared material, however strong irregularities in the feed marks are present (Fig. 4). A possible explanation lies in the drastic surface cooling induced by the use of the LN2 as coolant: a differential thermal expansion in the cutting area and an embrittlement of the material during the cutting process can be the cause of this type of defects.

The adoption of a feed rate of 0.2 mm/rev determines the onset of heavy feed marks irregularities, which are unacceptable in case of semi-finishing turning conditions (Fig. 4b). The heat treated DMLS samples exhibit only the surface defects hitherto described, instead the as-built

DMLS also presents surface tearings [11] (Fig. 5) for both the cooling strategies, even if the use of LN2 improves the surface quality since a reduction of the defects size quantifiable in an order of magnitude is observed.

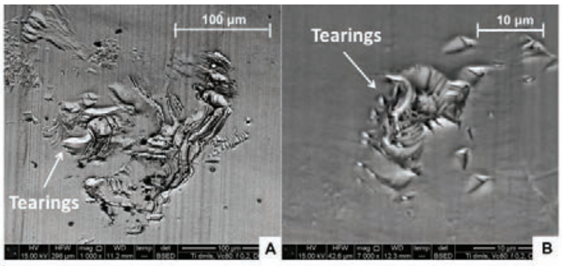

Fig. 5. Surface defects found in as-built DMLS samples machined under a) dry and b) cryogenic conditions.

4.3. Residual stresses

The surface defects analysis highlighted unacceptable surfaces irregularities for the cryogenic condition at 0.2 mm/rev of feed rate, hence the residual stresses measurements were conducted only for those samples machined at 0.1 mm/rev.

Regardless the DMLS Ti6Al4V microstructure, residual compression stress states were present for both the cooling strategies (Fig. 6), even if the highest values were found in case of cryogenic cooling.

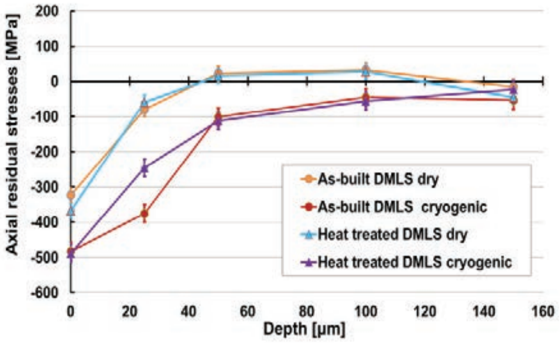

Fig.6. Residual stresses in the axial direction generated in semi-finishing turning as a function of the DMLS Ti6Al4V microstructure and cooling strategy.

The percentage increase of the surface axial compressive state when applying the LN2 with respect to the dry condition is about 33% for the heat treated DMLS material whereas overtakes 50% for the DMLS one. Moreover, the application of cryogenic cooling induced a general thickening of the compressive surface residual stress layer. A proof of that can be observed in Fig. 6, in which if a threshold value of - 200 MPa is considered for the axial stress, the corresponding abscissa is shifted towards deeper positions in the case of cryogenic machined workpieces regardless the material microstructure. For the DMLS material, this thickening increases from 15 µm to 40 µm in the cryogenic case.

5. Conclusions

The paper presented the evaluation of the surface integrity when turning the as-built and heat treated DMLS Ti6Al4V under dry cutting and cryogenic cooling; the following conclusions can be drawn:

- The use of LN2 induced more jagged and irregular surfaces with respect to the dry case.
- The cryogenic cooling drastically reduced the onset of typical defects of the dry turning (adhered and smeared materials), however it induced strong irregularities in the feed marks that were particularly evident when a feed rate of 0.2 mm/rev was adopted.
- The as-built DMLS samples presented tearings regardless the cooling strategy, even if the LN2 adoption reduced their size of an order of magnitude.
- All the machined samples presented a surface compressive stress state. However, the use of LN2 induced both the highest values of axial residual stresses and a general thickening of the compressive surface residual stress layer. The best results were found in the DMLS material where the percentage increase of the surface compressive stress with respect to the dry condition overtook the 50% and the surface layer presenting a threshold value of -200 MPa increased from 15 to 40 µm.

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