Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 45 (2016) 123 – 126

www.elsevier.com/locate/procedia

3rd CIRP Conference on Surface Integrity (CIRP CSI)

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

Stefano Sartori[a*], Alberto Bordin[a], Andrea Ghiotti[a] and Stefania Bruschi[a]

[a]*Dept. of Industrial Engineering, University of Padova, Padova, Italy*

* Corresponding author. Tel.:+39 049 8276819; fax: +39 049 8276816. *E-mail address: stefano.sartori@dii.unipd.it*

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

doi:10.1016/j.procir.2016.02.328

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].

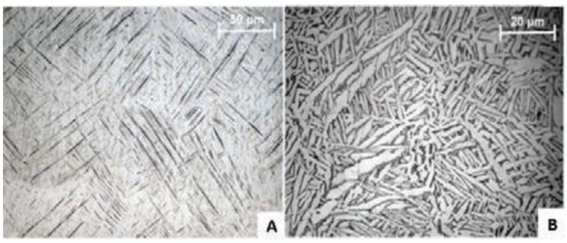

Fig. 1. Ti6Al4V microstructures: a) as-built DMLS, b) heat treated DMLS.

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^{TM} NL 1500 CNC lathe adopting inserts supplied by Sandvik^{TM} 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^{TM} portable roughness tester while the surface topography scanning was performed using a Sensofar Plu-Neox^{TM} optical 3D profiler. The surface defects were analyzed by means of a FEI QUANTA 450^{TM} 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^{TM} 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