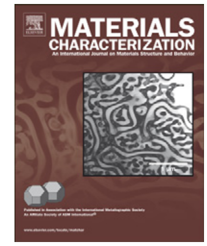
available at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/matchar



Microstructure and mechanical behaviour of Ti—6Al—7Nb alloy produced by selective laser melting

*Edward Chlebus, Bogumiła Kuźnicka**, Tomasz Kurzynowski, Bogdan Dybała*

Centre for Advanced Manufacturing Technologies, Wrocław University of Technology, 50-371, Wrocław, Poland

ARTICLE DATA

Article history:
Received 7 October 2010
Received in revised form 1 March 2011
Accepted 21 March 2011

Keywords:
Titanium alloy
Laser manufacturing
Microstructure
SEM
Mechanical properties

ABSTRACT

Selective laser melting (SLM) is an advanced manufacturing technology providing alternative method of producing complex components directly from 3D computer models. The purpose of this work is to determine the influence of the SLM manufacturing strategy on mechanical properties and microstructure of the as-built Ti—Al—Nb alloy. Specimens of Ti—6Al—7Nb were produced in three versions of the specimen axis orientation with respect to its build direction. Mechanical characteristics of the alloy were determined by tensile and compression testing, as well as hardness measurements. Microstructures were characterised utilising optical microscopy, scanning electron microscopy and X-ray diffraction analysis. It was found that the as-built Ti—6Al—7Nb alloy has microstructure of α' martensite hardened by dispersive precipitates of the second phase, which results in higher tensile and compressive strengths, but lower ductility in comparison to those of an alloy manufactured by conventional methods. The layered microstructure of the material gives it a significant anisotropy of Young's modulus, moderate anisotropy of mechanical properties, but strong anisotropy of sensitivity to the build porosity. The paper develops understanding of the relationships between the strategy of layered manufacturing of the Ti—6Al—7Nb alloy and its microstructural and mechanical characteristics. This is important for future applications of the SLM technology for producing Ti—6Al—7Nb parts, e.g. the custom medical implants.

1. Introduction

Selective laser melting (SLM) is one of the rapid manufacturing techniques that allows producing of complex 3D parts directly from CAD data by selectively melting successive layers of metal powder on top of the previous one, using thermal energy supplied by a focused and computer-controlled laser beam [1–3]. This technology could be very suitable for biomedical applications due to its ability to fabricate complex shapes of custom-designed functional implants or prostheses made from biocompatible metals [4–6].

As the laser-melted components have to meet strict material requirements regarding mechanical and chemical properties, the process must guarantee their highest density, or controlled porosity. This requires optimising process parameters like laser power, layer thickness, distance between scanning lines, distance between scanning points and scanning time for one point. It results from the so-far performed tests that optimised SLM parameters which can lead to part density amounting to 99.98% [4,7].

Among metallic biomaterials, such as the stainless steels and Co—Cr alloys, Ti and its alloys exhibit the most suitable

* *Corresponding author*. Tel.: +48 71 320 2767; fax: +48 71 321 1235.
E-mail address: bogumila.kuznicka@pwr.wroc.pl (B. Kuźnicka).

1044-5803/$ – see front matter © 2011 Elsevier Inc. All rights reserved.
doi:10.1016/j.matchar.2011.03.006

characteristic for biomedical applications because of their high corrosion resistance, mechanical biocompatibility and specific strength [4,5,8–10].

It is assumed that their excellent corrosion resistance results from formation of a dense and stable passive layer on the material surface when it contacts with air. This native protective oxide film rebuilds spontaneously after being damaged, even in a solution with low oxygen content, and involves low metal ion release even in aggressive environments [11,12].

As recently noted by Niinomi [8], high mechanical biocompatibilities (Young's modulus, as well as tensile strength, ductility, fatigue life, wear properties, functionalities, etc.) should be adjusted to the levels suitable for structural biomaterials used in implants that replace a hard tissue. SLM can potentially build multiporous, as well as multimicrostructural Ti alloy components, e.g. those composed of α, β, $\alpha+\beta$ or α' phases [5].

The Ti—6Al—7Nb alloy is one of the implant materials of a new generation with regard to replacing the controversial vanadium by niobium in its chemical composition. Thanks to the modified chemical composition, this alloy is characterised by a more beneficial set of mechanical properties [13], higher corrosion resistance and biotolerance [14] in comparison with the commonly used Ti—6Al—4V alloy. With respect to microstructure, the Ti—6Al—7Nb alloy belongs to the group of two-phase alloys. In the equilibrium state at room temperature, it is built of hexagonal α phase (stabilised with aluminium) and regular body-centred phase β (stabilised with niobium). Mechanical properties of the alloy strongly depend on morphology and volume fractions of these phases, which in turn are determined by parameters of the manufacturing process [15,16]. This is why a combination of such mechanical properties as plasticity and toughness with significant strength, as well as hardness and elasticity, is of key importance for Ti6Al7Nb components manufactured by the SLM technology. These properties depend not only on composition and size of the initial powder particles, but also on internal structure design and presence of defects in the final product determined by the process parameters and manufacturing strategy [17].

In this work, the influence of the manufacturing strategy on mechanical properties and microstructure of the Ti—6Al—7Nb alloy produced by selective laser melting is discussed. Anisotropy of microstructure and mechanical properties of the fabricated specimens have been investigated in the context of possible production of custom implants made of the Ti—6Al—7Nb alloy.

2. Experimental Procedure

Specimens were fabricated from Ti—6Al—7Nb powder using the SLM Realiser II (MCP-HEK) machine equipped with a continuous wavelength (CW) Ytterbium fibre laser with beam spot size of 180 μm, and maximum power of 100 W. The commercial Ti—6Al—7Nb powder consisted of spherical particles with size distribution determined using SEM micrographs and software MultiScan for image analysis, see Fig. 1.

Chemical composition (in wt.%) of the manufactured specimens was determined by the spectroscopy method as: 5.5% Al, 6.8% Nb, 0.25% Fe, 0.31% Ta, and Ti as the remainder. The contents of the determined substitution elements were in agreement with the ISO 5832-11 Standard. Two kinds of specimens were built up (Fig. 2): flat specimens for a tensile test with the measurement part of 25 × 7 × 3 mm, and cylindrical specimens for a compression test of 5 mm in diameter and 60 mm in length, which were next cut to sections of 7.5 mm in length. The specimens were fabricated assuming a constant scanning strategy: arranging the scanning lines in one layer in parallel to the *x* axis, in parallel to the *y* axis in the subsequent layer, and by applying successive layers in the *z*-direction (Fig. 2). The specimens for the tensile test were made in three series differing in the build direction, as illustrated in Fig. 2. In the first series (A), thickness of the specimens was built-up in the *z*-direction, in the second series (B) — width of the specimens, and in the third series (C) — height of the specimens. The cylindrical specimens for the compression tests were made in two series. In the first series (A/B), diameter of the specimens was built-up in the *z*-direction, and in the second series (C) — heights of the specimens, as can be seen in Fig. 2.

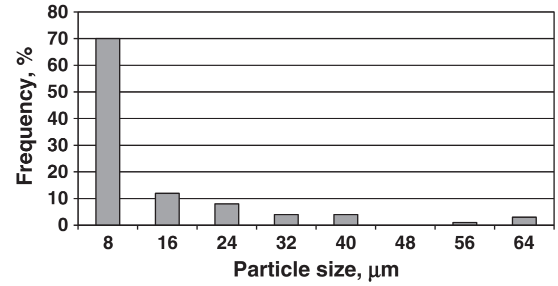


Fig. 1 – Particle size distribution of Ti6Al7Nb powder.

The remaining significant manufacturing parameters for all types of the specimens were selected on the grounds of previously performed research [7], so as to obtain possibly maximum density of the material (not less than 99.95%), and the following were accepted as constants:

- laser power — 100 W,
- distance between scanning lines (named "vectors" [2]) — 100 μm,
- layer thickness — 50 μm,
- and scanning speed — 0.15 m/s (scanning time of one point — 520 μs and distance between scanning points — 80 μm).

Tensile tests were carried out using the MTS 810.23 machine and the MTS 634.31 F-24 extensometer with measuring length of 25 mm, according to EN 10002-1. Compression tests were carried out using INSTRON 1126 testing machine.

The SLM fabricated specimens were tested for their mechanical properties such as tensile yield ($\sigma_{0.2}$) and ultimate strength (σ_t), Young's modulus (E), elongation (ε), ultimate compressive strength (σ_c) and Vickers hardness (HV10).

Examination of microstructure was performed using an optical microscope and Jeol-JSM 5800LV scanning electron microscope equipped with an EDS analysis system. Phases were identified and texture determined by the XRD method using the Siemens D500 X-ray diffractometer. Microscopic