Materials Science & Engineering A 641 (2015) 323–327

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Short communication

Dynamic tensile behavior of electron beam additive manufactured Ti6Al4V

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ARTICLE INFO

Article history:
Received 27 May 2015
Accepted 23 June 2015
Available online 25 June 2015

Keywords:
Electron microscopy
Powder metallurgy
Plasticity
Strain measurement
Titanium alloys

ABSTRACT

High rate and quasi-static tensile experiments examined strain rate dependence on flow stress and strain hardening of additive manufactured Ti6Al4V. Variations on strain-hardening coefficient indicate that the rate of thermal softening is greater than strain hardening during plastic deformation. Strain rate sensitivity calculations within the plastic strain regime suggest changes in deformation mechanisms. Fractography revealed cup-and-cone fracture for quasi-static samples and shear mechanisms for high rate samples. As-deposited microstructure consisted of bimodal $\alpha+\beta$ with the presence of secondary martensitic phase.

1. Introduction

Additive manufacturing (AM) is an emerging technology where fully functional products are produced directly from a Computer Aided Design (CAD) model [1]. One specific technique, Electron Beam Melting (EBM), is an AM powder-bed fusion procedure that uses a high power electron beam to generate the energy needed for melting conductive pure and/or alloy metal precursor powders. Examples of materials used for EBM manufacturing includes Ti6Al4V, Ti48Al2Cr2Nb, CoCr alloys, H13 steel, Inconel 625 and 718 alloys, Rene 142 alloys, Nb and Fe with Ti6Al4V being the most widely investigated because of its high strength to weight ratio, machinability, heat treatability and excellent corrosion resistance [2,3]. However, Ti6Al4V experiences limited use with applications generally confined to aerospace and medical applications due to higher costs relative to competing materials [4–6].

EBM Ti6Al4V exhibits a mixture of phases containing α plates (hexagonal closed pack, HCP), β (body center cubic, BCC) and α` martensite (HCP). Columnar prior β grains delineated by α grain boundaries (α_{GB}) have been reported along the build direction by many authors [7,8]. The columnar microarchitecture is caused from thermal gradients that exist along the build direction. Al-Bermani et al. [9] observed a transformed $\alpha+\beta$ microstructure, both with colony and Widmanstätten morphology within prior columnar β grains. Likewise, the mean α-lath thickness ranges from 1.4–2.1 μm per published stereological data [10]. Based on X-ray diffractometer (XRD) analysis, Facchini and collaborators [11] concluded that the main constituent is the HCP α/α` phases with small contribution of the β phase (7%). Compared with wrought or cast Ti6Al4V, which exhibits coarse plate-like (acicular) α or equiaxed α/β phase mixture, EBM Ti6Al4V shows finer α due to the intrinsically rapid cooling rate and small melt pool of the EBM process.

Several studies have documented the microstructural development resulting from variations in EBM operational parameters (i.e. scan speed, beam current and voltage, preheating temperature, cooling rates, etc.) [9,12–14]. In fact, variations in microstructures and chemistry have been suggested as causes for disagreements in mechanical properties. For instance, certain studies indicated that properties of EBM Ti6Al4V are comparable to those from conventional processes (wrought, casting) whereas other researchers indicated improved mechanical performance [15,16]. In consequence, enormous efforts are being focused on correlating microstructure to the mechanical response of EBM Ti6Al4V.

Quasi-static tension/compression experiments, hardness experiments and non-destructive nanoindentation analyses, among others techniques, are being used to characterize the EBM Ti6Al4V [9,10,17–19]. The widespread results on mechanical characterization could be attributed to the variation in the build parameters, which result in different morphological features such as composition, structures, pore size, and porosity distribution.

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http://dx.doi.org/10.1016/j.msea.2015.06.069
0921-5093/

Nevertheless, there is consensus that design with build directions parallel to the loading direction are superior to all in regard to strength and stiffness. Likewise, minimizing the number of layers has a tendency to demonstrate greater reliability.

Limited research has been done to examine the strain rate sensitivity of EBM Ti6Al4V alloys. However, data does exist from Ladani et al. [19] in the low strain rate regime that reported the anisotropic mechanical behavior for stain rates from 10^{-2} to $10^{-4}\ s^{-1}$ and compared the data against localized properties obtained using nanoindentation techniques. The work herein is the first to present the strain rate effect on EBM Ti6Al4V mechanical behavior under quasi-static $\left(\dot{\varepsilon} = 1 \times 10^{-3}\ s^{-1}\right)$ and high $\left(\dot{\varepsilon} = 1500\ s^{-1}\right)$ strain rate tensile loading conditions.

2. Materials and methods

In the present study, the ARCAM S12 EBM system located at NASA Marshall Space Flight Center was used to fabricate tensile coupons. Tensile specimens (nominal measurements: 11.88 length, 6.04 mm width and 1.08 mm thick) with flat-built orientation (built direction parallel to the *z*-axis) were built-to-shape. Fine pre-alloyed Ti6Al4V powder, with particle diameter between 45 and 100 μm was used as the feedstock precursor. The nominal chemical composition of the as-supplied powder was 6Al, 4V, 0.03C, 0.10Fe, 0.15O, 0.01 N, 0.003H, balance Ti (wt%). The target pre-heat temperature was set to 730 °C. The scan speed was 0.376 m/s with a beam current of approximately 6 mA. Layer thickness was predefined at 70 μm. The fabrication chamber was kept at 0.1 MPa.

Fabricated Ti6Al4V samples were prepared for microstructural observations with standard metallographic procedures including sectioning, mounting, grinding with SiC papers up to the grit size of 1200, and polishing using diamond suspension down to 0.05 μm. Optical (OM) and Scanning Electron Microscope (SEM) samples were etched in Keller's reagent (2 mL HF, 4 mL HNO_3, and 100 mL H_2O) for 40 s. Both, KEYENCE VHX-1000 series digital microscope and TESCAN LYRA SEM were used for microstructural characterization. Stereological procedures based on ASTM E112 were used for grain size determination [20]. A total of three different locations per sample were analyzed in order to obtain statistical data.

To quantify the EBM Ti6Al4V microstructure–property correlations, a series of tensile tests were performed on flat dog-bone specimens using the same specimen dimensions for both strain rates (gauge length of 5 mm, width of 2 mm, and thickness of 1 mm) so specimen sizes would not influence the percent elongation (EL). Yield strength (YS), ultimate tensile strength (UTS) and EL were determined under quasi-static and high strain rate conditions. Low rate, strain-controlled experiments $\left(\dot{\varepsilon} = 1 \times 10^{-3}\ s^{-1}\right)$ were conducted on an INSTRON 5581 load frame. The load frame was equipped with a 50 KN load cell (±0.4%) while a clip-on extensometer recorded the strain through fracture. Dynamic experiments $\left(\dot{\varepsilon} = 1500\ s^{-1}\right)$ were conducted on a Split-Hopkinson Tension Bar (SHTB) located at the Mississippi State University Center for Advanced Vehicular Systems (MSU-CAVS) as described in [21,22]. For SHTB testing, the specimens were held by 350-margaging steel grips between 12.7 mm diameter 7075-T6 incident and transmission bars instrumented with semiconductor strain gages. Tensile energy was stored by pre-strain section of the incident bar and released by 7075-T6 breaker pins. The tensile data was processed by DAVID software package. All tensile experiments were conducted at room temperature and tested in triplicates ($n = 3$). The TESCAN LYRA SEM performed the fractography analysis.

3. Results and discussion

The bright field 3D OM image in Fig. 1a depicts the as-built microstructure. Fig. 1b and 1d illustrates higher magnification OM micrographs for different planar orientation of the as-built unit cell. As shown in Fig. 1, the bulk microarchitecture exhibits dependence on its orientation with respect to the build axis (*z*-axis). The microstructure is composed of either equiaxed (Fig. 1b) or columnar (Fig. 1d) prior β grains delineated by α_{GB}. The equiaxed

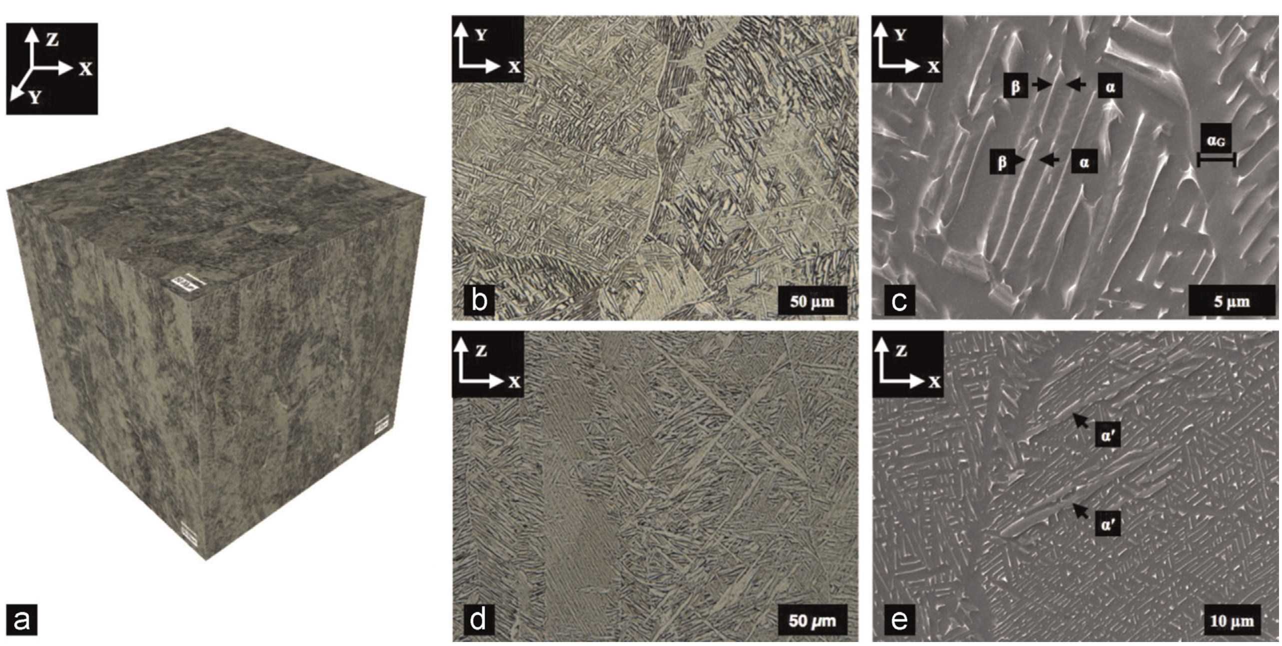

Fig. 1. (a) Bright field 3D OM composite for as-built EBM Ti6Al4V. Plane XY microstructure (b) illustrates equiaxed grains whereas (d) shows the columnar micro-architecture parallel to the built direction. *Z*-axis indicates built direction. α phase are presented as brighter regions whereas β phase is shown as darker fields. (c) and (e) SE SEM micrographs identifying α, β and α` phases and $\boldsymbol{\alpha}_{GB}$ feature.