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Evaluation of microstructural development in electron beam melted Ti-6Al-4V

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ARTICLE DATA

Article history:
Received 7 October 2010
Received in revised form
14 November 2011
Accepted 19 December 2011

Keywords:
Ti-6Al-4V
EBM
Microstructure
SEM
TEM
XRD

ABSTRACT

In the current work an investigation of the microstructures of EBM built Ti-6Al-4V test bars has been performed using OM, SEM, TEM and XRD. It has been found that the prior β phase, that formed during the initial solidification, possesses a column shaped morphology with growing direction parallel to built direction. Typical (α+β) structures namely Widmanstätten α platelets with rod-like β phase formed on the interfaces of the fine α grains, have been observed in the columnar prior β grains. Grain boundary α phase was found to be formed around the boundaries of the columnar prior β grains. Different phases present in the parts, especially the BCC β phases have been characterized. The TEM/EDX results indicate very high V composition in the β phase. Results of TEM/SAED and XRD also revealed that a superlattice structure could be present in the β phase. Phase transformation sequence is discussed according to the processing history and the microstructures observed.

1. Introduction

Due to their excellent combination of mechanical and physical properties Titanium and its alloys especially Ti-6Al-4V, are widely used engineering materials in aerospace, automotive, energy and medical implant industries. Metallic materials, in general, are used as implant materials where the hard tissues are to be replaced like dental root or hip joint etc. [1]. In such applications high fatigue life, strength and comparable Young's modulus are important parameters to be considered [2]. Among the metallic biomaterials used for hard tissue replacement, such as stainless steel and Co–Cr alloys, Ti and its alloys exhibit the most suitable characteristics for biomedical applications because of their light weight, specific strength, high biocompatibility, corrosion resistance and human allergic response [1,2]. Their good biocompatibility is due to excellent corrosion resistance and low toxicity owing to instant formation of oxide layer [3]. Ti-6Al-4V is a two-phase (α/β) alloy. Microstructure plays an important role in determination of mechanical properties like strength, creep resistance fracture toughness etc. of alloys [4]. Microstructure of Ti-6Al-4V like any other alloy normally depends on chemical composition, processing history and heat treatment [4,5]. The control of texture and microstructure is necessary to control the physical and mechanical properties of Ti-6Al-4V [6].

Direct digital manufacturing (DDM) is the next embodiment of solid free form fabrication (SFF), additive manufacturing (AM) or rapid prototyping (RP). Different DDM techniques include direct light fabrication (DLF), LASER engineering net shape (LENS), direct LASER deposition (DLD) and electron beam melting (EBM). In all these methods metallic objects are produced directly from computer aided design (CAD) files by melting the metallic powder/wire by a high energy focused beam. EBM is one of such methods. EBM system has been

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doi:10.1016/j.matchar.2011.12.008

described in details by [1,7–9]. EBM systems involve building of three-dimensional fully dense or near net-shape metallic structures/objects layer-by-layer in high vacuum environment. This process involves shaping a powder bed and selectively melting the powder to form a three-dimensional solid object, using high energy focused electron beam and multi-axis motion. Each layer is formed by overlapping several melt beds, which are made by continuously overlaying a new bed of powder over the existing layer. One of the advantages of EBM or any DDM process is the possibility to build complex geometries like downward facing surfaces in cooling channels as single unit avoiding machining and welding etc. EBM process is very energy efficient and applicable to highly reflective materials like Aluminum [7].

It is difficult to predict the microstructures of DDM produced metallic objects due to very complex thermal history [10]. Different scientists have studied the microstructures of Ti-6Al-4V produced by different DDM methods including EBM [1,8,10–14]. In this study we have tried to understand the microstructure at different stages of buildup process in EBM produced Ti-6Al-V and to characterize the different phases by using Optical Microscope (OM), Scanning Electron Microscope (SEM), Transmission Electron Microscope (TEM) and X-ray diffractometer.

2. Materials and methods

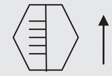
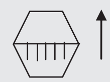
2.1. Materials

In this study the hexagonal test bars were produced from gas atomized Ti-6Al-4V powder of 25–40 μm size. The length of each test bar was 100 mm with the cross-sectional diameter of 8 mm. The buildup time was approximately 10 h and the chamber temperature (build temperature) was approximately 700 °C. The initial cooling rate from melting temperature to 700 °C was very rapid, while from 700 °C to room temperature when the last layer is deposited was very slow and the cooling time in last step was approximately 8 h.

2.2. Specimen preparation

Three types of surfaces related to the build direction were obtained by mechanical cutting of the bars under flowing cooling solution (Table 1). Samples for microscopic studies were prepared by using standard metallographic preparation methods. For OM studies, the specimens of about 10 mm thickness were grinded and polished mechanically for varying time durations to obtain smooth surface. For SEM and TEM studies, the test bars were first sliced into thickness of about 0.2 mm and subsequently grinded to thickness of 0.15 mm. These slices were punched to get 3 mm diameter disks. These samples were electrochemically polished for 50–70 s duration by using Struers double jet unit using electrolyte A3. The electrolyte solution consists of 600 ml methanol, 360 ml 2-butoxyethanol and 60 ml perchloric acid. The polishing voltage and current during the electrochemical polishing process were 35 V and 125 mA respectively. In the final step of specimen preparation all the samples were etched in Kroll's solution (1% HF, 2% HNO_3, balance distilled H_2O) for varying time durations, ranging from 350 to 500 s. Samples prepared for optical micrographic studies were also used for XRD analysis.

Table 1 – Types of surfaces prepared for the microstructural investigations.

Surface type	Surface under study[1]	Description
I		Perpendicular to layer deposition (multiple layers at cross-section)
II		Perpendicular to the layer deposition and Surface type-I (multiple layers along the axis of bar)
III		Parallel to the layer deposition (single layer)

1: with respect to build direction.

In this study the microstructures and different phases present in the hexagonal test bars of Ti-6Al-4V, were studied using Nikon Elipse L150 Optical Microscope (OM), FEI QUANTA 200 Environmental Scanning Electron Microscope (SEM) at 20 kV, PHILLIPS CM200 Transmission Electron Microscope (TEM) and Philips X'Pert diffractometer.

3. Results

3.1. XRD

XRD measurements were carried out in Philips X'Pert diffractometer with Cu, Kα radiations. Diffraction spectrum was taken with thin film collimator (TFC) detector. The XRD pattern was obtained with scan step of 0.01° 2θ, with counting time of 3 s.

Fig. 1 presents the XRD pattern of the sample. Since the known results of the alloy Ti-6Al-4V are not much reported in literature and JCPDS cards are also not available for the alloy, we have to match our pattern for indexing with already published pattern of the alloy in [6,10,15]. The indexing is presented in Table 2. The Bragg's peaks detected in the XRD scan

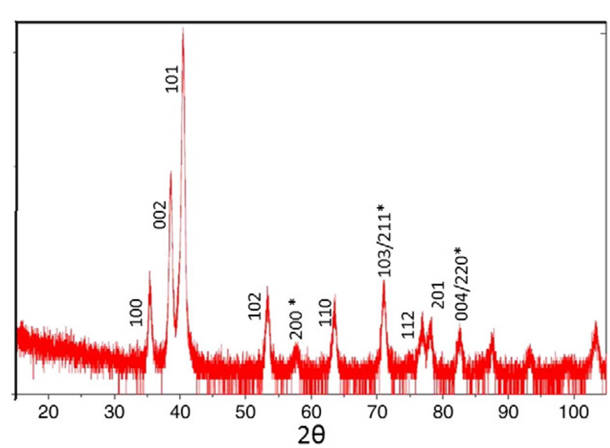


Fig. 1 – XRD pattern for the EBM build Ti-6Al-4V sample.