Materials Science & Engineering A 619 (2014) 290–299

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Microstructures and tensile mechanical properties of Ti–6Al–4V bar/disk fabricated by powder compact extrusion/forging

C. Liang [a], M.X. Ma [a], M.T. Jia [b], S. Raynova [b], J.Q. Yan [a], D.L. Zhang [a,*]

[a] State Key Laboratory of Metal Matrix Composites, School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[b] Waikato Center for Advanced Materials, School of Engineering, University of Waikato, Hamilton, New Zealand

ARTICLE INFO

Article history:
Received 6 May 2014
Received in revised form
19 September 2014
Accepted 20 September 2014
Available online 30 September 2014

Keywords:
Powder metallurgy
Powder compact extrusion
Powder compact forging
Titanium alloy
Mechanical properties
Strain rate sensitivity

ABSTRACT

Ti–6Al–4V (wt%) bar and disk with a density close to 100%, a lamellar structure and oxygen content of 0.44 and 0.51 wt%, respectively, have been made by powder compact extrusion and powder compact forging of HDH Ti–6Al–4V powder respectively. Their microstructure, tensile mechanical properties at different strain rates in the range of 10^{-4}–10^{-1} s^{-1} and the fracture surfaces and longitudinal sections of the tensile test specimens have been studied. It was found that the level of consolidation of the PE/Ti–6Al–4V bar and PF/Ti–6Al–4V disk was very high, as reflected by their high strength and good ductility, small untransformed interparticle boundaries (smaller than 3 μm in sizes), and low volume fraction of cavities ($<1.5\%$) formed by separation of powder particles at the untransformed interparticle boundaries in the specimens tensile tested at a high strain rate of 10^{-2} s^{-1}. The high level of consolidation achieved within a short time through induction heating and extrusion/forging of the Ti–6Al–4V powder compacts suggests that the rate of transforming interparticle boundaries to grain boundaries is very high, and the reasons for this might be formation of new powder particle surfaces through plastic deformation and rapid dissolution of the powder particle surface oxide films. The formation of cavities from the untransformed interparticle boundaries in the PE/Ti–6Al–4V bar and PF/Ti–6Al–4V disk is highly strain rate sensitive with the number and volume fraction of the cavities formed increases significantly with increasing the strain rate.

1. Introduction

As an α/β titanium alloy, Ti–6Al–4V (wt%) alloy has very desirable room temperature and elevated temperature (up to 400 °C) mechanical properties including high strength, good ductility and fracture toughness, and excellent corrosion resistance in a variety of environments. For this reason, it is widely used in industry and accounts for about half of titanium alloy products produced [1–5]. The powder metallurgical route is likely to reduce the cost of making titanium alloy components and structural members by near-net shape forming which minimizes material waste and the cost of post process machining, and, in some cases, also by using low cost powders. For this reason, a large amount of research work has been devoted to studying processes of making titanium alloy parts by powder metallurgy [6–20].

In our research, we utilized rapid powder consolidation routes of powder compact extrusion (PCE) and powder compact forging (PCF) in combination of rapid induction heating of the powder compacts to consolidate relatively low cost Ti–6Al–4V powder made by using a hydriding-dehydriding (HDH) process (the powder is called HDH titanium alloy powder). Thanks to the pressure applied and the large amount of plastic deformation of powder particles facilitated by the process, these powder consolidation routes enable the production of Ti–6Al–4V structural members and shaped components with a high relative density close to 100%. The major issue associated with these rapid powder consolidation techniques is whether all interparticle boundaries of the powder particles are transformed into grain boundaries or interfaces within the short processing time covering induction heating, holding and extrusion/forging of the powder compacts. To address this issue, we studied the microstructures and room temperature tensile mechanical properties and fracture behavior at different strain rates of the Ti–6Al–4V bars and disks produced by PCE and PCF respectively. We hoped that through this study the true nature of the mechanical properties of bulk Ti–6Al–4V alloy produced by powder consolidation routes of PCE and PCF respectively can be elucidated in relation to its microstructure, oxygen content and texture.

* Corresponding author. Tel./fax: +86 21 54743248.
E-mail address: zhangdeliang@sjtu.edu.cn (D.L. Zhang).

http://dx.doi.org/10.1016/j.msea.2014.09.083
0921-5093/

2. Experimental procedure

The starting powder is Ti–6Al–4V alloy powder with an oxygen content of 0.5 wt% and particle sizes of -200 mesh and produced by a hydrogenation-dehydrogenation (HDH) process. For powder consolidation using PCE, the Ti–6Al–4V powder was first die-pressed at 330 °C for 10 min under argon and with a pressure of 730 MPa to produce a cylindrical powder compact with a relative density of 85%. The powder compact was heated under argon to 1250 °C using an induction furnace, and subsequently extruded into a bar with a diameter of 14 mm (called PE/Ti–6Al–4V bar) using a die set kept at 550 °C. The force used in the extrusion was 100 t, and the extrusion ratio was 9:1. For powder consolidation using PCF, the Ti–6Al–4V powder was first die-pressed at 350 °C for 5 min under argon with a pressure of 637 MPa to produce a cylindrical powder compact with a relative density of 83%. The powder compact was heated under argon to 1300 °C using an

Table 1
The oxygen and nitrogen contents (wt%) of the PE/Ti–6Al–4V bar and PF/Ti–6Al–4V disk.

Material	O	N
PE/Ti–6Al–4V	0.44	0.034
PF/Ti–6Al–4V	0.51	0.040

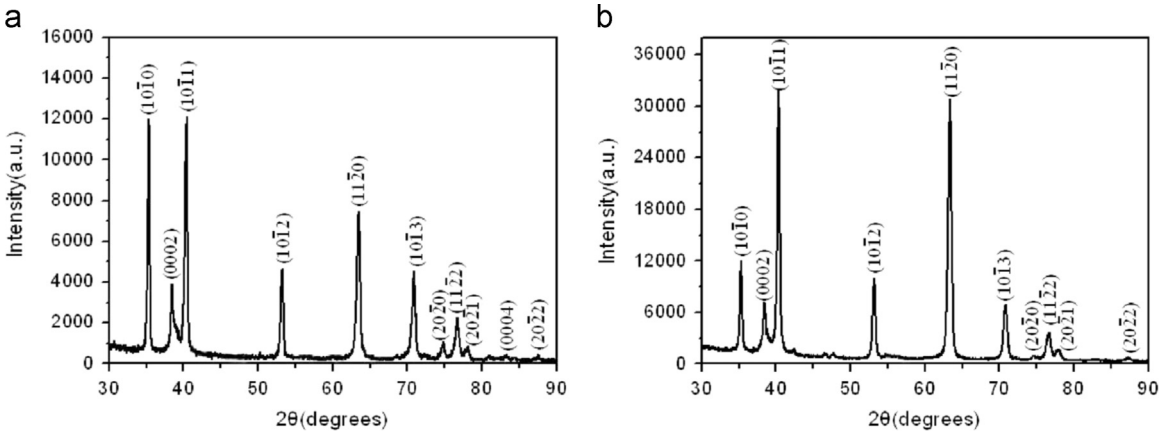

Fig. 1. The XRD patterns of PE/Ti–6Al–4V bar and PF/Ti–6Al–4V disk.

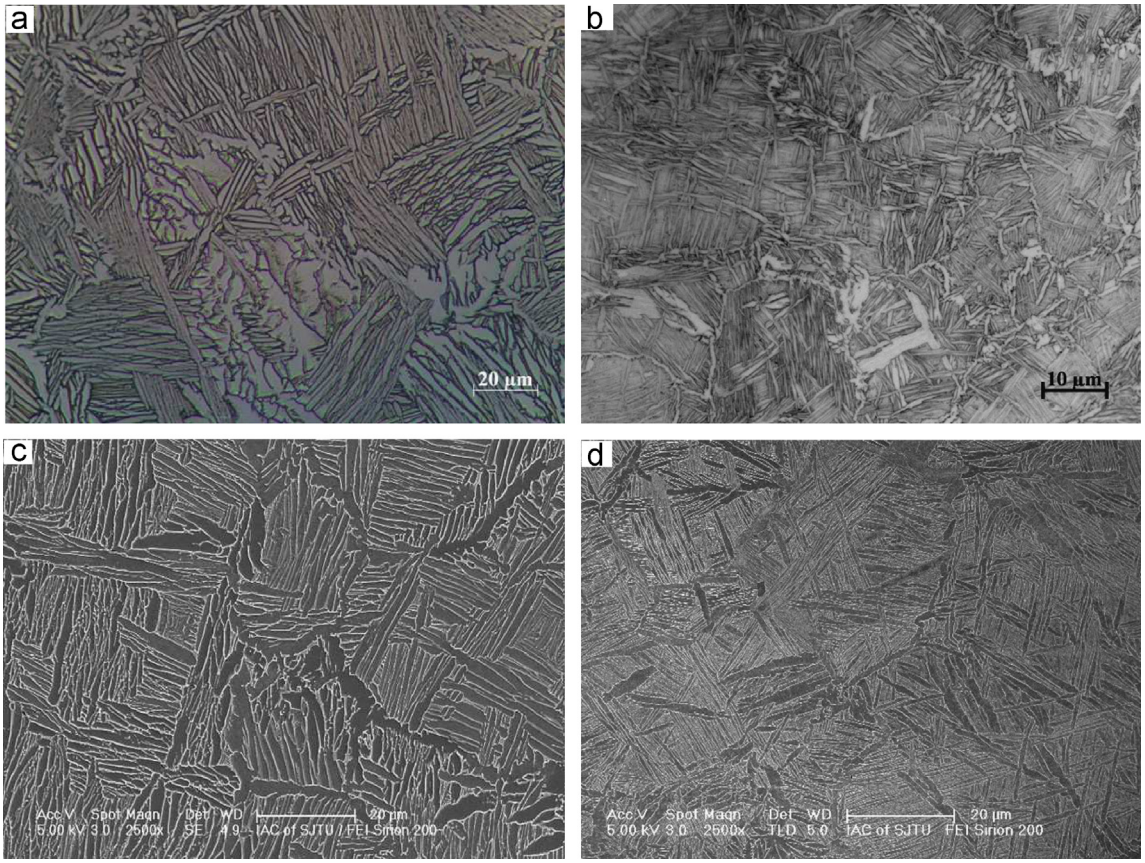

Fig. 2. (a) and (b) Optical microscopy images and (c) and (d) SEM images showing the microstructures of PE/Ti–6Al–4V bar and PF/Ti–6Al–4V disk, respectively.