Materials Science and Engineering A 528 (2011) 4381–4389

Contents lists available at ScienceDirect

Materials Science and Engineering A

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

Dynamic strain aging in low cycle fatigue of duplex titanium alloys

Yi-Hsiang Lin[a], Kan-Hung Hu[b], Fang-Hsin Kao[c], Shing-Hoa Wang[a,*], Jer-Ren Yang[c], Chih-Kuang Lin[d]

[a] Department of Mechanical Engineering, National Taiwan Ocean University, No. 2 Pei Ning Road, Keelung 20224, Taiwan
[b] Institute of Materials Engineering, National Taiwan Ocean University, Keelung 20224, Taiwan
[c] Department of Materials Science and Engineering, National Taiwan University, Taipei 10617, Taiwan
[d] Department of Mechanical Engineering, National Central University, Chung-Li 32001, Taiwan

ARTICLE INFO

Article history:
Received 3 September 2010
Received in revised form 20 January 2011
Accepted 2 February 2011
Available online 17 March 2011

Keywords:
Titanium alloys
Low cycle fatigue
Dynamic strain aging

ABSTRACT

The influence of dynamic strain aging (DSA) on low cycle fatigue (LCF) in duplex Ti-6-4 and SP700 titanium alloys was studied. LCF was performed within the temperature range from 350 °C to 450 °C, at strain rates of 10^{-3} s^{-1} and 10^{-4} s^{-1}, and strain amplitudes of 1.25% and 2%. DSA appeared as serrations at the plastic portion of the cyclic stress–strain hysteresis loop, as well as stress humps appearing in the cyclic stress response (CSR) curve of peak tensile stress response versus cycle number. Strain-induced micro twin formation was only observed in the sample after fatigue with 2% strain amplitude under a 10^{-4} s^{-1} strain rate, indicating that it is a DSA induced phenomenon.

1. Introduction

Titanium alloys are extensively used in a variety of applications due to their good mechanical properties and corrosion resistance [1]. Many investigators [2,3] have studied the mechanical behavior of titanium alloys. Extensive Air Force research on high cycle fatigue (HCF) [4] has shown that the effects of prior loading under low cycle fatigue (LCF) have little or no effect on the subsequent HCF limit stress [5]. The LCF test is the most important test in the area of cyclic plastic strain, as it provides information on the resistance of the material to cyclic stress and on the cracking resistance against cyclic plastic strain. The LCF and elasto-plastic cyclic behavior of materials have received considerable interest in the fields of science and engineering, as repeated cyclic loading with high amplitudes of cyclic stress and strain can severely limit the useful life of many components in a variety of industries [6]. In addition, the LCF is an important consideration in the design of airframe components and high-temperature jet engine systems. Therefore, isothermal LCF tests have been used to assess the performance of materials subjected to thermal transients, and the component behaviors under isothermal LCF testing conditions have been studied [7,8].

The term dynamic strain aging (DSA) refers to an aging process that takes place during plastic deformation. Over a particular range of strain rate and temperature, the interactions between solute atoms and dislocations result in a strong pinning of dislocations responsible for strain aging. Higher stress levels are required to produce further material strain, either to pull dislocations free from the pinning atoms or to nucleate fresh dislocations. Thus, the main effects of dynamic strain aging on the mechanical properties of materials during cyclic tests are an inverse dependence of the peak tensile stress on strain rate, an unusual increase in cyclic hardening and a serrated flow known as the Portevin–Le Chatelier (PLC) effect [9–12,14,15,25]. The appearance of serrations provides information that is useful to determine the kinds of atoms that interact with dislocations to cause DSA. Within a certain regime of temperature and strain rate, serrations in the flow stress–strain curves occur during plastic deformation of alloys containing interstitial or substitutional solutes [16]. The occurrence of DSA has been well-established [13,17,18] to result from solute diffusion into the metal lattice during plastic deformation within a susceptible temperature range. The plastic deformation of engineering alloys is usually associated with the formation of lattice defects including dislocations and voids, and their subsequent movement within their lattice. These dislocations are eventually clustered in the vicinity of their grain boundaries due to the accumulation of interstitial and/or substitutional solute elements before they can migrate to the next grains. Titanium alloy normally contains a small amount of interstitial impurities (H, C, N and O). Titanium shows similar dynamic strain aging behavior to that of steel, with peaks in the flow stress and in the strain hardening rate and minima in ductility over particular temperature ranges. Furthermore, in some cases, the DSA is accompanied by negative strain rate sensitivity from the analysis of the serrated flow [6,19,15]. Dynamic strain aging has been reported to occur for commercially pure (CP) titanium [10,20], several near-α titanium alloys [19,21] and β titanium alloys [22]. DSA

---

* Corresponding author. Tel.: +886 2 24622192x3221; fax: +886 2 24620836.
E-mail address: shwang@ntou.edu.tw (S.-H. Wang).

0921-5093/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.msea.2011.02.013

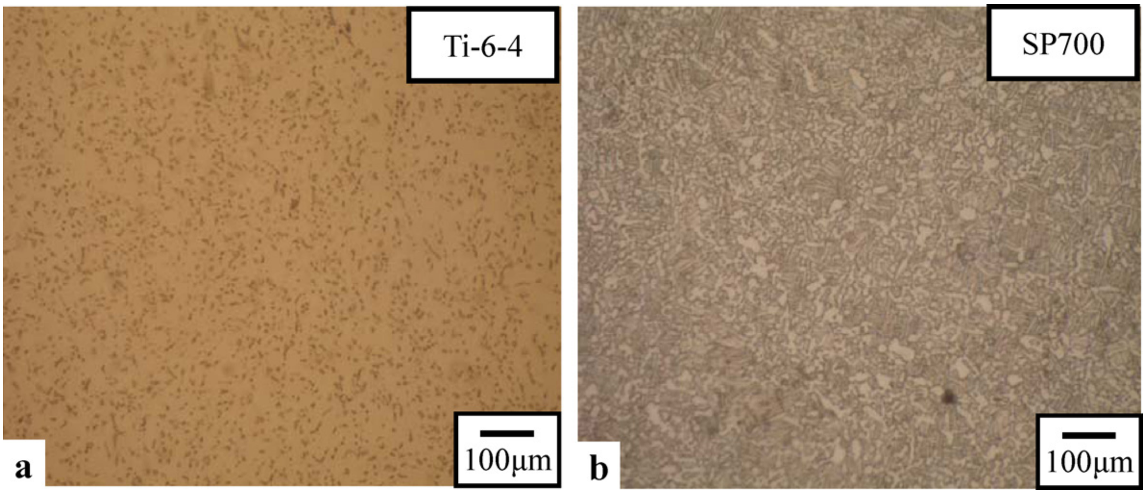

Fig. 1. Optical microstructures of the titanium alloys (a) Ti-6-4 and (b) SP700 alloy.

in CP titanium has been attributed to the interaction between interstitial solute atoms and dislocations [10]. The other investigators have reported that substitutional elements like Al, Zr and Mo cause DSA in α and β titanium alloys [22].

The dynamic strain aging effect of various titanium alloys on tensile behavior has been studied [10,19,21,23–26]. The effects are exhibited in the negative strain rate sensitivity and hardening in DSA at about 600 K. Fewer reports exist on the dynamic strain aging occurring in conjunction with the LCF behavior of Ti-6-4 and SP700 (Ti–4.5Al–3V–2Mo–2Fe) alloys. In addition, the DSA properties of the new duplex titanium alloy SP700 alloy will be compared to those of the Ti-6-4 alloy.

2. Experimental

This study examined the α-rich α + β duplex titanium alloy Ti-6-4 (Ti–6Al–4V) and the β-rich α + β duplex titanium alloy SP700 (Ti–4.5Al–3V–2Mo–2Fe). Table 1 presents the detailed chemical compositions of Ti-6-4 and SP700 used in this study as determined by energy dispersive spectrometry (EDS). α-Rich Ti-6-4 alloys consist of 80 vol.% α phase/20 vol.% β phase, and β-rich SP700 alloys consist of 35 vol.% α phase/65 vol.% β phase. Low cycle fatigue (LCF) tests were conducted in air at 350 °C, 400 °C and 450 °C with two strain amplitudes of 1.25% and 2% and a strain ratio $R = -1$. The round bars of the low cycle fatigue test were 12 mm in diameter and 85.6 mm in length, with a reduced 6.4 mm diameter and 19.2 mm gage length, referring to ASTM E292-01. The tests of DSA occurrence were conducted over 15 or 30 cycles using an MTS 810 machine attached to a heating furnace under fully reversed total strain control mode. The system was heated and was in a state of equilibrium for approximately one hour before the LCF tests were performed. The selected specimens after test at different conditions examined by transmission electron microscopy (TEM) were sliced and sampled within the gage section of the test specimens. The specimens thinned down to 0.06 mm by abrasion with SiC sand paper. The 3 mm disk punched out from the deformed gage length was twinjet electro-polished using a mixture of 5% sulfuric acid and 95% methanol in a temperature between −40 °C and −30 °C at 20 V. The TEM microstructure was observed under model Joel 2000 EXII transmission electron microscope.

Table 1
Composition of Ti-6-4 and SP700 alloys as measured by EDS (wt%).

Materials	Ti	Al	V	Fe	Mo	N	H
Ti–6Al–4V	Balance	6.25	3.8	0.3	–	0.01	0.006
SP700	Balance	4.2	2.8	2.1	2.0	0.02	0.004

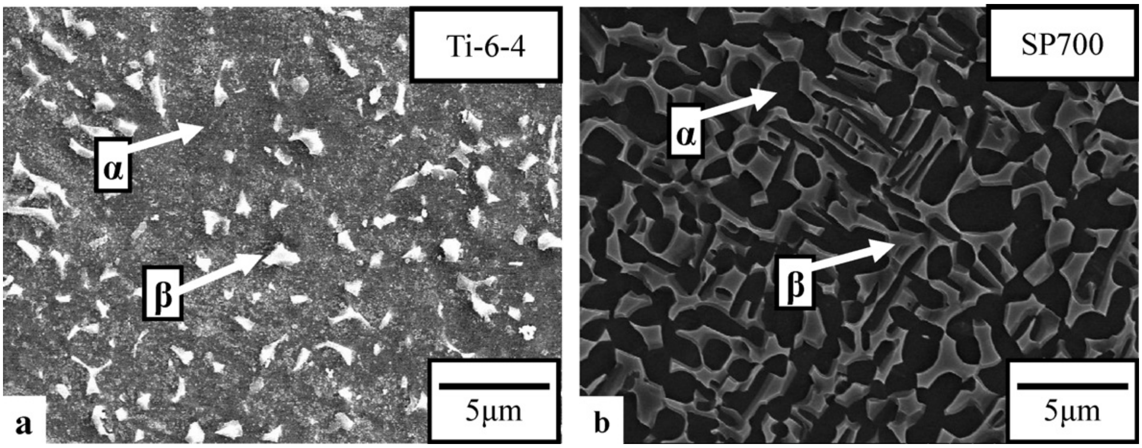

Fig. 2. SEM microstructures of the titanium alloys (a) Ti-6-4 and (b) SP700 alloy.